



AirHARP2 Data Quality Statement, Version R0

Brent A. McBride^{1,2,*}, Xiaoguang Xu^{1,2,3}, Noah Sienkiewicz^{1,3}, Anin Puthukuddy^{1,2}, and J. Vanderlei Martins^{1,2,3} (PI)

¹*Earth and Space Institute, University of Maryland Baltimore County, Baltimore MD 21250*

²*Goddard Earth Sciences and Technology (GESTAR II), 5523 Research Park Drive Suite #140
Baltimore, MD 21228*

³*Department of Physics, University of Maryland Baltimore County, Baltimore MD 21250*

*Correspondence to Brent McBride at mcbride1@umbc.edu

Campaign

Name	NASA PACE Postlaunch Airborne eXperiment (PACE-PAX)
Dates	05 Aug – 05 Oct 2024
Locations	Edwards AFB (ER-2)
ER-2 Remote Sensing Instruments (Colocated Datasets with AirHARP2)	RSP, PICARD, SPEXone, PRISM, HSRL-2

AirHARP2 Overview of Data Calibration and Processing to L1C

Data Delivery Version	R0
Detector Corrections	31 Mar 2025
Polarimetric Calibration	31 Mar 2025
Radiometric Calibration	31 Mar 2025
Spectral Calibration	31 Mar 2025

Table of Contents

Introduction.....	3
Overview	3
AirHARP2 instrument	3
Calibration	4
Detector Corrections	4
Polarimetric Sensitivity.....	5
Radiometric Calibration	5
Known Data Quality Issues.....	6
Data Examples.....	7
References	13

Introduction

Overview

The Airborne Hyper-Angular Rainbow Polarimeter (AirHARP2) instrument is a multi-angle imaging polarimeter instrument designed, developed, and supported by the Earth and Space Institute (ESI) at the University of Maryland Baltimore County (UMBC) in Baltimore, MD, USA.

AirHARP2 participated in the NASA Plankton Aerosol Cloud ocean Ecosystem (PACE) Post-launch Airborne eXperiment (PACE-PAX, Knobelspiesse et al. 2023) from 5 August to 5 October 2024. AirHARP2 was one of six remote sensing payloads on the NASA ER-2 high altitude research aircraft during PACE-PAX. AirHARP2 was specifically solicited for this campaign as a proxy for the HARP2 instrument on the NASA PACE mission (Martins et al. 2024, McBride et al. 2024b). PACE underflights were prioritized during the campaign to maximize data intercomparison opportunities between AirHARP2 and HARP2, as well as the other remote sensing, in-situ, and ocean-based assets throughout the California and eastern Pacific Ocean domain.

In this document, we will discuss the AirHARP2 instrument, the calibration and processing that goes on in the background to produce the publicly available L1C data, known data quality issues, data examples, and links to how to parse the L1C data. This is a “living document” that will be updated with every new data release version.

AirHARP2 instrument

The AirHARP2 instrument is a wide-field of view (FOV) imaging polarimeter. It is a near 1:1 copy of the HARP2 instrument on the NASA PACE mission. AirHARP2 samples at four nominal spectral channels: 440 (15), 550 (9), 670 (11), and 870 (40) nm. These channels are distributed over 90 discrete cross-track regions of the detector. 670 nm has 60 views forward-to-aft, with $\sim 2^\circ$ mean separation in viewing zenith angle. The other three channels have 10 views each, with $\sim 12^\circ$ mean separation in viewing zenith angle. As the instrument flies, the detectors take sequential images. Data in a given view are stitched together along-track to make a pushbroom of the scene from that specific angle. The AirHARP2 FOV spans 114° (94°) along-track (cross-track), with a nadir full-resolution pixel size of ~ 20 m from ER-2 altitude of 20 km. This translates to a 62 (43) km single-image along-track (cross-track) swath. The science data acquisition of AirHARP2 employs onboard binning technique, known as modified time-delayed integration (MTDI). The footprint of binned pixel on the ground is in the range of 100-200 meters depending on the field of view.

The L1C data product is calibrated, geolocated, and multi-view colocated spectral radiances ($\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$). At each pixel, AirHARP2 produces total intensity (I) and orthogonal components of linearly polarized radiance along 0-90° axes (Q) and 45-135° axes (U). These metrics are combined in other derived products: the degree of linear polarization

(DOLP) and the angle of linear polarization (AOLP). The L1C data product was designed by the PACE project with the three PACE instruments in mind: OCI, HARP2, and SPEXone. The PACE L1C georegisters all three instrument data onto a common latitude-longitude grid and spatial resolution (5.2 km). The AirHARP2 L1C follows the same processing heritage, though in R0 is not co-registered with other ER-2 assets or at a common spatial resolution. Like HARP2, L1C granules are segmented into 5-minute observations, but at a 250 m spatial resolution in R0. More on the L1C data product are in the following sections.

Some version RA draft datasets still exist on the LARC server. They contain a preliminary calibration, are not quality-assured, and are not suitable for publications.

Calibration

Detector Corrections

The calibration of AirHARP2 translates pixel-level detector counts to meaningful quantities of energy ($\text{W m}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$) for I, Q, and U Stokes parameters. The AirHARP2 pre-flight calibration campaign took place at NASA Goddard Space Flight Center from 28 June to 19 July 2024. For most activities, the broadband integrating sphere source “Grande” at the NASA GSFC Radiometric Calibration Facility was used, in conjunction with the Goddard Laser for Absolute Measurement of Radiance (GLAMR) for high resolution spectral radiances and response function. The radiometric calibration of both spheres is traceable to the National Institute of Standards and Technology (NIST) and are re-calibrated multiple times a year (Barsi, private communication).

The calibration pipeline follows from the first AirHARP (McBride et al. 2024a) and HARP2 (Sienkiewicz et al. 2024) heritage, as well as theoretical optical modeling (Fernandez-Borda et al. 2009). AirHARP2 detectors are commercial CCDs and therefore, require corrections for background, non-linearity, flatfield, and defects. These are done using a variety of observations. Background correction is performed by measuring zero illumination at flight integration time. Non-linearity involves the comparison between sphere spectral radiances and measurements of the sphere aperture at various stable lamp levels. Flatfield is a measure of pixel-to-pixel relative response and characterized by “stepping” the sphere around the AirHARP2 FOV at a single lamp level. This is compared against a single-shot of the sphere aperture with the internal diffuser actuated. The cross-track structure of the flatfield is smoothed to reduce noise, and defects are characterized simultaneously (≥ 6 -sigma outliers). Identified defect pixels are validated vicariously on full-FOV marine stratocumulus observations from PACE-PAX. The calibration is dynamic, in the sense that each leg has associated in-flight darks for each CCD. This is done in the heritage of HARP2 V3 processing. There are several other detector corrections, including a correction for elevated background in the heritage of HARP2. However, the details on these will be expanded on in future data quality statements and publications.

Polarimetric Sensitivity

After these corrections, we characterize the pixel-level polarimetric sensitivity of AirHARP2. Incident light is portioned to three AirHARP2 detectors through an optimized Phillips prism. Prism coatings and glass angles send 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 sensitive to either 0, 45, or 90° linearly polarized light over the entire focal plane array (FPA). Lab-generated polarization and co-aligned detector counts are used to derive the *characteristic matrix* **C** (Fernandez-Borda et al. 2009). **C** is a mathematical object that translates corrected detector counts to normalized Stokes parameters (Q/I, U/I).

The polarization calibration involves a wire-grid polarizer on a mechanized rotational stage at the aperture of an integrating sphere (*degree of linear polarization, or DOLP* < 0.005). The polarizer is rotated perpendicular to the AirHARP2 optical axis at incremental angles. AirHARP2 laboratory DOLP uncertainty is estimated at 0.005 for all channels. **C**-coefficients are derived at nadir in the version R0 data release. However, this test is done at various FOVs, and allows for a proper full-FOV characterization of **C**. A full-FOV version of **C** will be part of a future data release.

Radiometric Calibration

The radiometry of AirHARP2 includes spectral response, absolute calibration, and crosstalk correction. Spectral response testing identifies the channels that AirHARP2 accepts and rejects, as well as the shape function of the in-band response. This was characterized using the GLAMR sphere at NASA GSFC with incremental spectral steps between 300 - 900 nm. In data version R0, the AirHARP2 SRF is defined using the corrected GLAMR scans and in-band response.

Table 1. Characteristics of the AirHARP2 SRF based on GLAMR testing and nadir observations

Nominal Band Center (Width) [nm]	Derived Band Center (Width) [nm]	F_0 ($\text{W m}^{-2} \mu\text{m}^{-1}$)	HARP2 Sens. Avg. (BC/BW/ F_0)
440 (10)	440.5 (15.1)	1843.7	440.2/15.8/1843.7
550 (10)	549.2 (9.3)	1871.3	549.6/9.4/1871.7
670 (10)	664.2 (10.6)	1530.5	664.6/10.4/1530.5
870 (40)	864.7 (40.0)	956.0	865.6/40.2/963.5

Absolute radiometry is the final step of the calibration process. The AirHARP2 instrument measures the illumination of the NASA Grande broadband sphere over a range of FEL lamp levels. Each lamp is radiometrically calibrated and traceable to NIST. Therefore, the slope

of the correlation between the calibrated radiances of each lamp and the relative intensity of the AirHARP2 measurement at each lamp (after the matrix **C** is applied to corrected sensor data) is the *radiometric gain factor*. This value gives absolute units ($\text{W m}^{-2} \text{um}^{-1} \text{sr}^{-1}$) to the Stokes parameters (I, Q, U), and is applied directly to the matrix **C** in processing. The full treatment of the AirHARP2 calibration is split between Sienkiewicz et al. (2024) and McBride et al. (2024).

Known Data Quality Issues

Polarimetric systematic biases (Q, U, DOLP)

Multi-angle intercomparisons with RSP and validation with GRASP over clean ocean and desert targets during PACE-PAX suggests potential systematic polarization bias in AirHARP2 calibration in version R0. This is most evident at 870 nm DOLP and impacts the other bands to a lesser extent. **We advise caution when using AirHARP2's polarization products in version R0. The AirHARP2 cal/val team is currently assessing and applying corrections.** We are working towards a full mission reprocess with an updated calibration in version R1.

Along-track striping

AirHARP2 L1C pushbrooms, specifically for Q, U, and DOLP may contain stable along-track striping. These stripes are more evident over dim scenes and vary by pushbroom. Our flatfield product, which is the pixel-to-pixel relative response and vignetting correction, uses an empirical data smoothing function that may not be exactly tuned to the high frequency signals present in every PACE-PAX dataset. AirHARP2 did not take in-flight flatfield measurements, so addressing temperature-related changes between flight and lab is a challenge and may require further empirical (or vicarious) corrections. The AirHARP2 cal/val team is currently assessing impacts and will include a full-mission update in the version R1.

CCD1 failure on 09/27 and 09/29

On 09/27 and 09/29, the AirHARP2 CCD1 failed to acquire meaningful data for some of the flight due to an electrical anomaly. CCD1 is the detector sensitive to S-polarization and is therefore critical to the calculation of I, Q, and U. Without CCD1, we cannot produce the Stokes parameters, DOLP, or AOLP. Affected data is not archived on the LARC server for data version R0 (though some is available at RA), and the missing data for CCD1 is unrecoverable. In all cases, the CCD1 recovered from the anomalies mid-flight to take valid data for the remainder. Therefore, these datasets may have missing data in I, Q, U, and DOLP between valid data acquisitions.

MTDI compression as a result of backwards orientation

The AirHARP2 polarimeter was unintentionally mounted to the superpod of the ER-2 backwards during PACE-PAX integration. In other words, the heading direction of the imagery is at image bottom, for all datasets taken during PACE-PAX. This typically has no consequence on data quality or geometry. However, the modified time-delay integration

(MTDI) scheme used to compress the AirHARP2 data on-board prior to storage is asymmetric. It requires the top of the image synced with the heading direction for optimal performance.

Because AirHARP2 data is captured backwards, we expect anywhere between a factor of 2 – 4 degradation in image quality in the along-track direction. These estimates come from sensitivity testing at UMBC post-campaign. There is no impact in the cross-track direction. Intercomparisons with RSP and validations with GRASP at 125, 250, and 500 m L1C spatial resolution suggest that 250 m is the minimum achievable resolution without introducing additional spatial noise from MTDI. This impact is more evident over land and heterogeneous areas than ocean. **All AirHARP2 PACE-PAX L1C is processed at 250 m in version R0.**

The HARP2 instrument operates the same MTDI scheme on-orbit as AirHARP2, however, HARP2 is correctly aligned (i.e. heading direction is synced with image top). Therefore, HARP2 operates optimally and as expected with respect to MTDI.

Geolocation uncertainty

AirHARP2 pixels are registered to the spheroid Earth surface, taking into account the ground surface elevations based on the GEBCO-2020 (the General Bathymetric Chart of the Oceans) terrain model at a resolution of 15 arc-second adopted by the Ocean Color Science Software (OCSSW, <https://oceandata.sci.gsfc.nasa.gov/ocssw>). The geolocation makes use of AirHARP2 IMU and ER2 attitude logs, combining GPS and roll/pitch attitudes from AirHARP2 and Yaw attitudes from ER2. Boresight offsets, which account for mounting and internal optical axis bias, are interactively characterized by matching the geolocated AirHARP2 pushbroom with the Google Earth map data.

As of version R0, we have estimated our geolocation error to be up to 250 m on average (± 1 L1C pixel). This may differ slightly from pushbroom to pushbroom, and deviate at wide FOV angles along- and cross-track. We are continuing to refine this estimate for the forthcoming update version R1.

Data Examples

The following imagery shows a projected AirHARP2 near-nadir pushbrooms for in red-green-blue (left column, 'RGB') and red-nir-blue (right column, "RNB"). Total radiance (Stokes parameter I) is shown in the top row, and polarized radiance ($\sqrt{Q^2 + U^2}$) on the bottom row. For both fields, brighter pixels are larger values (and vice versa). The timestamp of the capture is given in the subtitle (top center), and the projected axes are latitude (y) and longitude (x).

Figure 1. California Central Valley capture on 09/26/2024. Square farm land pops in the radiance RNB (top right). The scene has relatively low polarization (bottom).

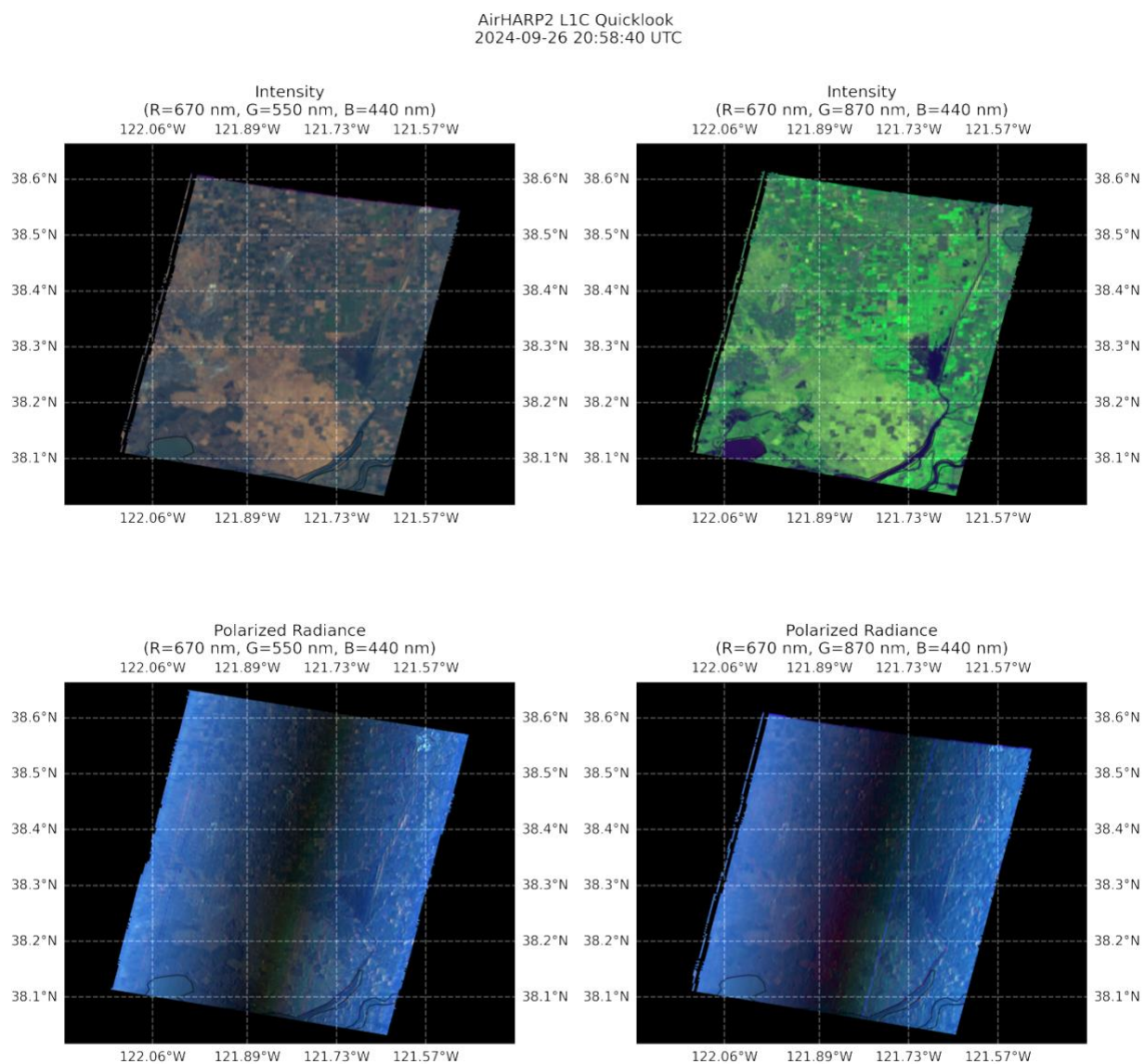


Figure 2. Overflight of San Francisco and the bay area on 09/30/2024.

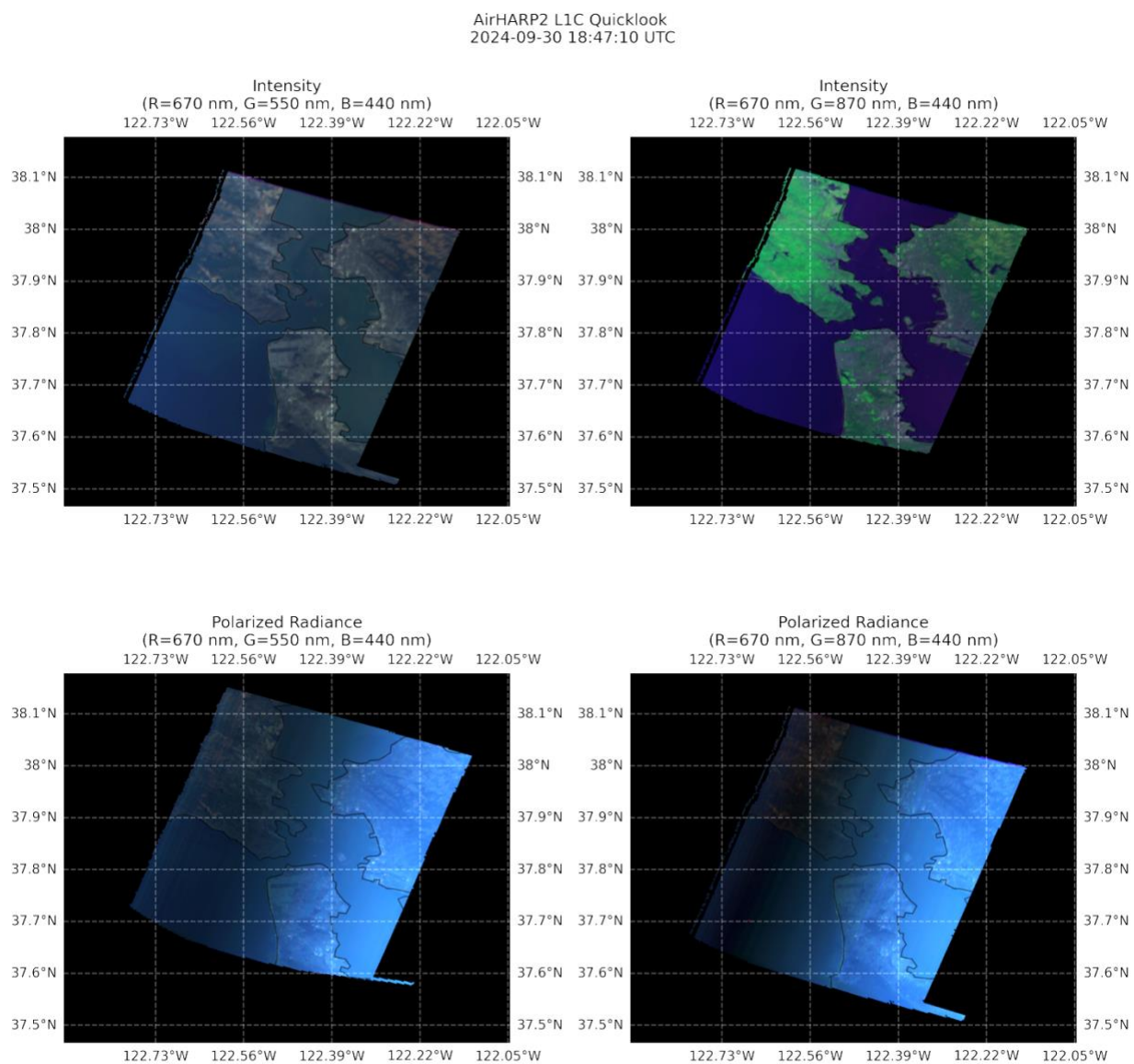


Figure 3. Railroad Valley capture on 09/30/2024. This dry lake is popular for vicarious radiometric calibration of remote sensors. The lake appears to be depolarized as well.

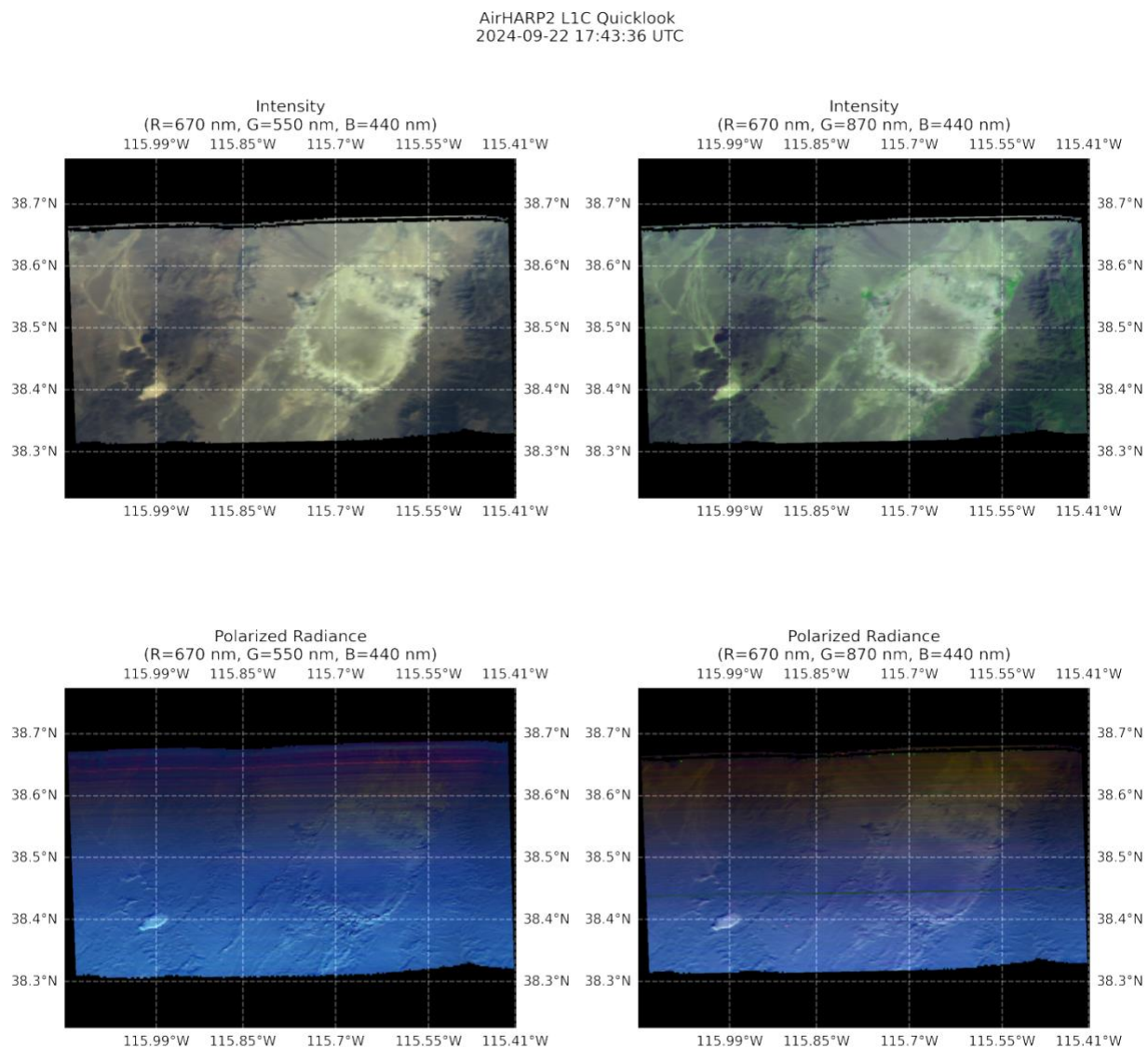


Figure 4. Marine stratus capture on 09/04/2024. In polarized light, liquid water clouds generate a rainbow at certain geometries. This signal encodes the droplet size distribution at cloud top and requires high-density along-track observations to decode the information content in the oscillations. The subsolar point, or *glory*, is also visible as a bright stripe in the RGB intensity (upper left) and a green stripe in the RNB polarized reflectance (lower right)

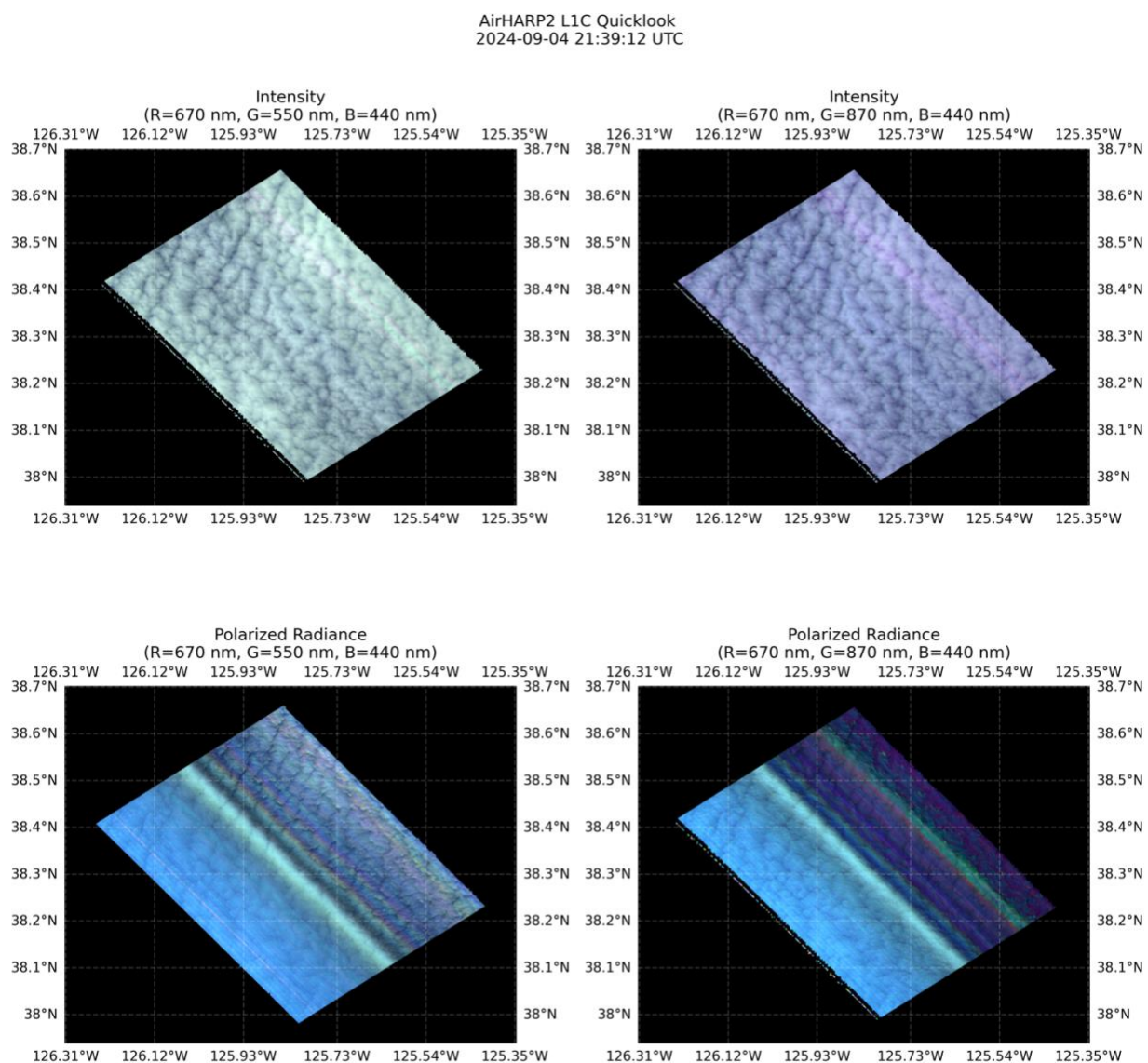
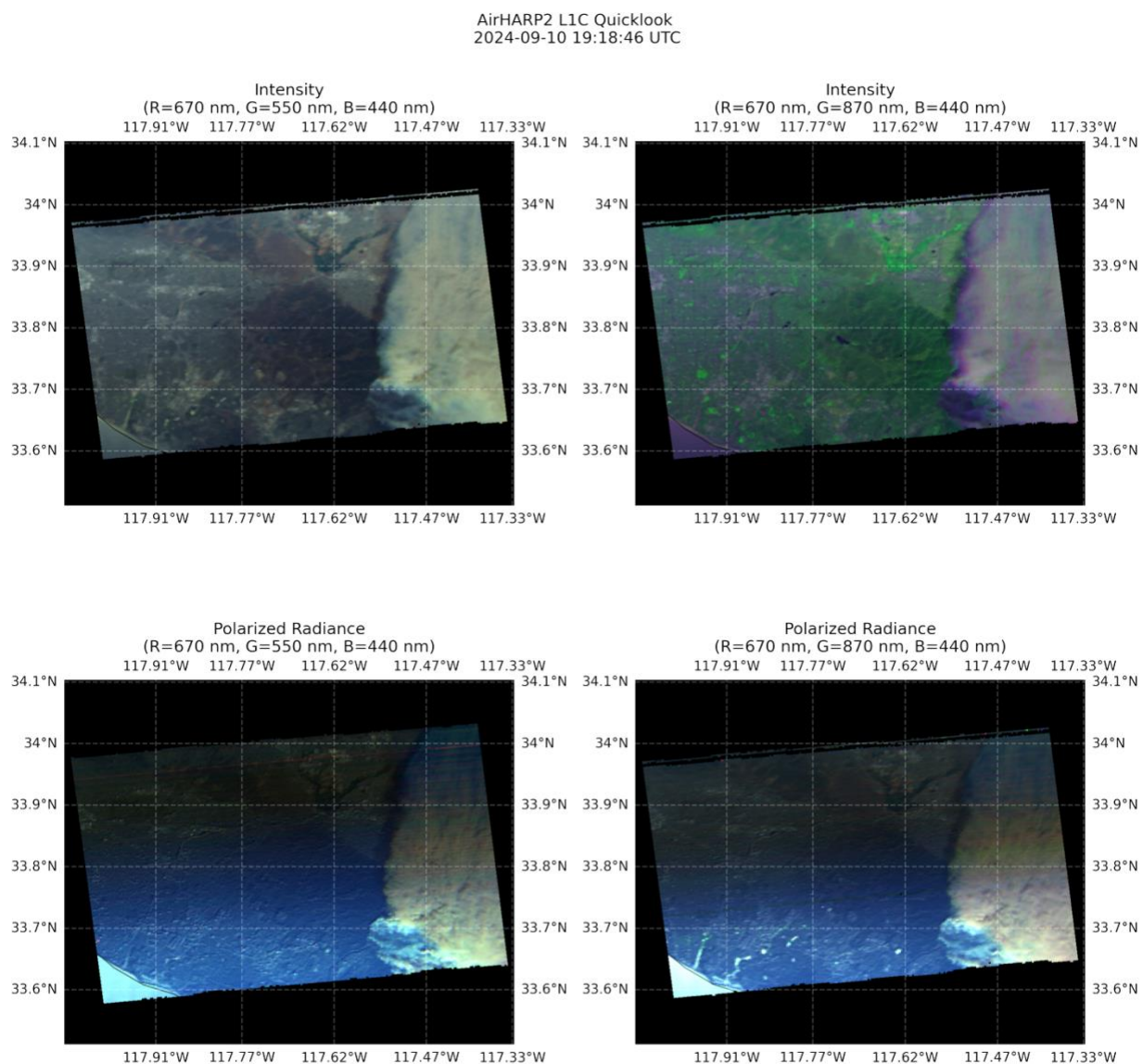


Figure 5. The massive aerosol plume from the Bridge Fire on 09/10/2024. The dark patch in the lower right of the RNB radiance (upper right image) is the burn scar left by the fire.



References

Allen, J. G., and Knobelspiesse, K. D. : PACE Level 1C user's guide. Last retrieved on 20 May 2025 at https://oceancolor.gsfc.nasa.gov/files/PACE_L1C_Users_Guide.pdf.

Fernandez-Borda, R., Waluschka, E., Pellicori, S., Martins, J. V., Ramos-Izquierdo, L., Cieslak, J. D., and Thompson, P.: Evaluation of the polarization properties of a Philips-type prism for the construction of imaging polarimeters, in: Polarization Science and Remote Sensing IV, SPIE Optical Engineering + Applications, 2–6 August 2009, San Diego, California, USA, edited by: Shaw, J. A. and Tyo, J. S., Proc. SPIE, 7461, 746113, <https://doi.org/10.1117/12.829080>, 2009.

Knobelspiesse, K. D., Patt., F. S., Montes, M. A., Bailey, S. W., Cairns, B., Franz, B. A., Gao, M., and Sayer, A. M.: PACE Technical Report Series, Volume 12. The PACE Level 1C Data Format. NASA/TM.-2024-219027/Vol.12. Eds. Cetinic, I., McClain, C. R., and Werdell, P. J. Last retrieved on 20 May 2024 at https://oceancolor.gsfc.nasa.gov/files/NASA_TM2024219027v12_PACE_Level_1C_Format.pdf, 2024.

Knobelspiesse, K. D., Cairns, B., Cetinic, I., Craig, S., Franz, B. A., Gao, M., Ibrahim, A., Mannino, A., Sayer, A. M., and Werdell, P. J. : PACE Technical Report Series, Volume 11. The PACE Postlaunch Airborne eXperiment (PACE-PAX). NASA/TM.-2023-219027/Vol.11. Eds. Cetinic, I., McClain, C. R., and Werdell, P. J. Last retrieved on 20 May 2024 at https://pace.oceansciences.org/docs/PACETM_vol11.pdf, 2023.

Martins, J. V., Fernandez-Borda, R., Puthukkudy, A., Xu, X., Sienkiewicz, N., Smith, R. E., McBride, B. A., Dubovik, O., and Remer, L. A.: First results and on-orbit performance of the Hyper-Angular Rainbow Polarimeter on the PACE satellite, Proc. SPIE 13192, Sensors, Systems, and Next-Generation Satellites XXVIII, 131920C (20 November 2024); <https://doi.org/10.1117/12.3034008>, 2024.

McBride, B. A., Martins, J. V., Cieslak, J. D., Fernandez-Borda, R., Puthukkudy, A., Xu, X., Sienkiewicz, N., Cairns, B., and Barbosa, H. M. J.: Pre-launch calibration and validation of the Airborne Hyper-Angular Rainbow Polarimeter (AirHARP) instrument, Atmos. Meas. Tech., 17, 5709–5729, <https://doi.org/10.5194/amt-17-5709-2024>, 2024a.

McBride, B. A., Sienkiewicz, N., Xu, X., Puthukkudy, A., Fernandez-Borda, R., and Martins, J. V.: In-flight characterization of the Hyper-Angular Rainbow Polarimeter (HARP2) on the NASA PACE mission, Proc. SPIE 13192, Sensors, Systems, and Next-Generation Satellites XXVIII, 131920H (20 November 2024); <https://doi.org/10.1117/12.3033680>, 2024b.

Sienkiewicz, N., Martins, J. V., McBride, B. A., Xu, X., Puthukkudy, A., Smith, R., and Fernandez-Borda, R.: HARP2 Pre-Launch Calibration Overview: The Effects of a Wide Field of View, EGU sphere [preprint], <https://doi.org/10.5194/egusphere-2024-2024>, 2024.