LSDS-2340
Version 7.0

Department of the Interior
U.S. Geological Survey

Landsat 8-9 Collection 2 Level-2 Provisional Aquatic Reflectance Product Guide

Version 7.0

April 2025

USGS
science for a changing world

Landsat 8-9 Collection 2 Level-2 Provisional Aquatic Reflectance Product Guide

April 2025

Document Owner:

KRISTI SAYLER Digitally signed by KRISTI SAYLER Date: 2025.04.11 09:31:01 -05'00'

_____

Kristi Sayler Date
LSRD Project Manager
U.S. Geological Survey

Approved By:

KAREN ZANTER Digitally signed by KAREN ZANTER Date: 2025.04.11 16:38:30 -05'00'

_____

Karen Zanter Date
LSDS CCB Chair
U.S. Geological Survey

EROS
Sioux Falls, South Dakota

Executive Summary

This product guide describes the characteristics of the Landsat 8-9 Collection 2 Level-2 Provisional Aquatic Reflectance Science Product to facilitate its use in aquatic remote sensing and ocean color applications.

The ocean color, defined as the spectral distribution of reflected visible solar radiation upwelling from beneath the water surface, has revolutionized the field of biological oceanography. The applications of ocean color remote sensing are extensive and fundamental to understanding and monitoring the global ecosystem. The Landsat 8-9 Collection 2 Provisional Aquatic Reflectance is an *experimental science product* with the potential to make a valuable contribution to aquatic science and environmental monitoring capabilities for aquatic ecosystems, especially in coastal environments and inland waters.

This document is under Landsat Satellites Data System (LSDS) Configuration Control Board (CCB) control. Please submit changes to this document, as well as supportive material justifying the proposed changes, via Change Request (CR) to the Configuration Management Tool.

Document History

Document Number	Document Version	Publication Date	Change Number
LSDS-2340	Version 1.0	May 2022	CR 21028
LSDS-2340	Version 2.0	July 2022	CR 21071
LSDS-2340	Version 3.0	February 2023	CR 21320
LSDS-2340	Version 4.0	June 2023	CR 21413
LSDS-2340	Version 5.0	November 2023	CR 21533
LSDS-2340	Version 6.0	December 2024	CR 21807
LSDS-2340	Version 7.0	April 2025	CR 21887

Contents

List of Figures

List of Tables

Section 1 Introduction

1.1 Background

Landsat satellite data have been produced, archived, and distributed by the U.S. Geological Survey (USGS) since 1972. Users rely upon these data for conducting historical studies of land surface change and monitoring the Earth's surface but have shouldered the burden of post-production processing to create application-ready datasets. To alleviate this burden, the USGS has initiated an effort to produce a collection of Landsat Science Products to support land surface change studies. These products include terrestrial variables such as Surface Reflectance, Surface Temperature, Burned Area, and Fractional Snow Covered Area, as well as aquatic variables such as Dynamic Surface Water Extent and Aquatic Reflectance that are suitable for monitoring, assessing, and predicting the Earth surface change over time.

Landsat Collection 2 (C2) marks the second major reprocessing effort on the Landsat archive by the USGS that results in several data product improvements that harness recent advancements in data processing, algorithm development, and data access and distribution capabilities.

This product guide describes the characteristics of the Landsat 8-9 C2 Provisional Aquatic Reflectance (AR) Science Product. Aquatic Reflectance is derived from Landsat 8-9 Operational Land Imager (OLI) Level-1 (L1) reflective bands over water pixels. The Top of Atmosphere (TOA) Reflectance and auxiliary atmospheric data are input to an atmospheric correction algorithm to retrieve the water-leaving radiance at visible wavelengths. The water-leaving radiances are then normalized by downwelling solar irradiance to remove the remaining effects of solar orientation and atmospheric attenuation to produce spectral Remote Sensing Reflectance (R_{rs}) bands. Finally, the R_{rs} bands are normalized by the Bidirectional Reflectance Distribution Function (BRDF) of a perfectly reflecting Lambertian surface (multiplied by π) to produce the dimensionless Aquatic Reflectance. The methodologies used in this algorithm are directly derived from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) Data Analysis System (SeaDAS) package distributed by NASA's Ocean Biology Processing Group (OBPG) and modified by the USGS to process Landsat 8-9 OLI sensor data. For more information about the atmospheric correction algorithm in SeaDAS, please see Mobley et al., 2016 in the References section.

Surface and atmospheric auxiliary data are required for the successful processing of Landsat 8-9 C2 AR Science Products. For Landsat 8-9 AR processing, the auxiliary data includes meteorological variables and ozone data from the Global Modeling and Assimilation Office (GMAO)'s Goddard Earth Observing System (GEOS) for Instrument Teams (GEOS-IT) auxiliary dataset as input for all meteorological (MET) variables.

The latency of the auxiliary data for AR processing of the new Landsat acquisitions is one to two days. Auxiliary data for Aquatic Reflectance processing are retrieved through the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (https://gmao.gsfc.nasa.gov/GMAO_products/GEOS-IT/). More information regarding

the auxiliary input and source can be found in the Landsat 8-9 Collection 2 Level-2 Provisional Aquatic Reflectance Algorithm Description Document (ADD).

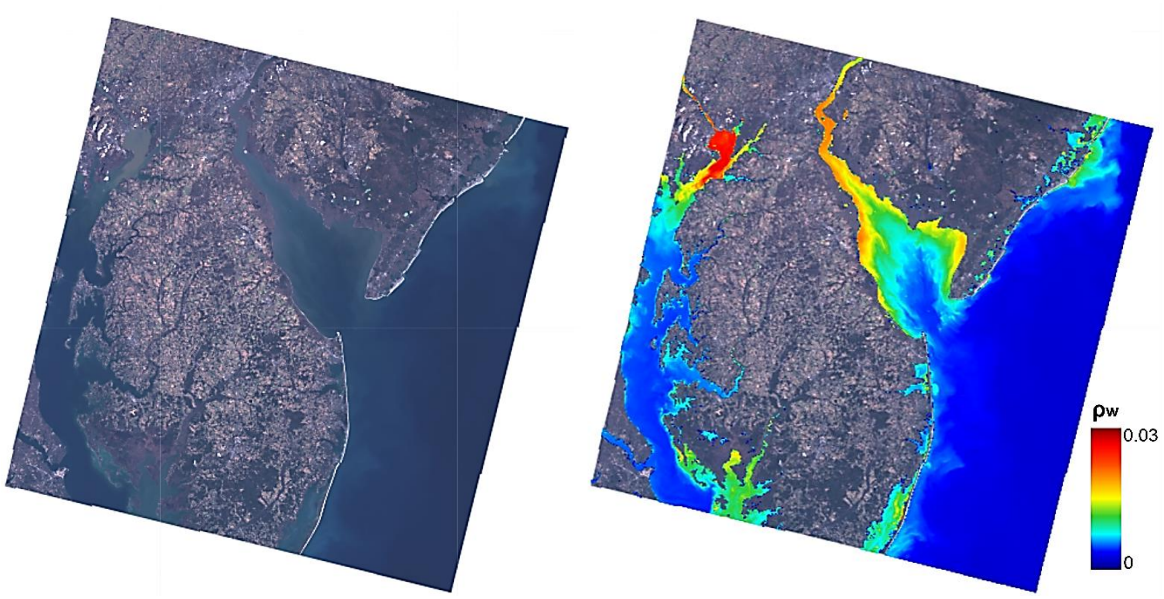

Figure 1-1. Landsat 9 Natural Color Surface Reflectance RGB of Delaware Bay (left) under corresponding Aquatic Reflectance for Band 4 (Red, ρ_w 655nm) (right).

Figure 1-1 shows a comparison of a Landsat 9 Level-2 Surface Reflectance natural color composite image (bands 4,3,2) under corresponding Collection 2 Provisional Aquatic Reflectance Band 4 (Red Band at 655nm) for Delaware Bay, USA (Path 14 Row 33) on February 10, 2022.

C2 Provisional AR Science Products are currently available for Landsat 8 and Landsat 9 OLI data. Thermal data is not required to successfully process Aquatic Reflectance (i.e., both LC08/LC09 and LO08/LO09 data products can be processed).

Landsat 8-9 Provisional AR products are processed for Visible and NIR bands (VNIR) (bands 1-5 for Landsat 8-9 OLI). Intermediate Rayleigh-corrected reflectance (RHORC) for bands 1-7 Visible to Shortwave Infrared (VSWIR) that were used as input for AR processing are also delivered. The product file package includes processing flags (L2_FLAGS) and the associated metadata. Section 3 details the specifications of Landsat 8-9 C2 AR products.

1.2 Purpose and Scope

The primary purpose of this document is to provide a detailed description of Landsat 8-9 C2 Provisional AR Science Products, product characteristics, product packaging, and download accessibility.

The scope of this document is the C2 Provisional AR Science Products generated by the USGS Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA).

1.3 Document Organization

This document contains the following sections:

- Section 1 provides an introduction
- Section 2 provides information about product packaging
- Section 3 provides product characteristics
- Section 4 provides information about product access
- Section 5 provides citation information
- Section 6 provides acknowledgment
- Section 7 provides the contact information of the user services
- Appendix A provides default file characteristics
- Appendix B provides sample metadata fields
- Appendix C contains a list of acronyms
- The References section contains a list of reference documents

Section 2 Product Packaging

2.1 Package Filename

Landsat 8-9 C2 Provisional AR products are delivered in a compressed gzip file (.tar.gz). The package filenames are structured similar to other Landsat products available from ESPA. The following is an example of a typical C2 Landsat Provisional AR package filename.

LXSSPPPRRRYYYYMMDDCCTX-SCyyyymmddhhmmss.tar.gz
(e.g., LC80010892019050602T1-SC20190719150513.tar.gz)

L	Landsat
X	Sensor (“O” = OLI; “C” = OLI/TIRS)
SS	Satellite (“08” = Landsat 8, “9” = Landsat 9)
PPP	Path
RRR	Row
YYYY	Year of acquisition
MM	Acquisition month
DD	Acquisition day
CC	Landsat Collection number (“02” for Collection 2)
TX	Tier (“01” for Tier 1; “02” for Tier 2; “RT” for Real-Time)
SC	Science dataset
yyyy	Year of ESPA processing
mm	Month of ESPA processing
dd	Day of ESPA processing
hh	Hour of ESPA processing
ss	Seconds of ESPA processing

Additional information about product packaging of the science products processed in ESPA is provided in the ESPA On-Demand Interface User Guide.

2.2 Product Filename

Unzipping the AR gzip package produces a tarball (.tar), which will “untar” into 26 individual raster files, and an Extensible Markup Language (XML) (.xml) metadata file. The raster files include five AR bands, seven Rayleigh-corrected Reflectance bands, six auxiliary bands, a processing flags band, the Level-1 pixel quality band, a water mask band, four per-pixel Level-1 solar/viewing zenith and azimuth angles in addition to the scattering angle based on these angles.

The filenames are based on the Landsat Collection 2 Product Identifier (ProductID). The AR band filenames are appended with the suffix “_AR_” followed by a band designation to denote the AR transformation. The Rayleigh-corrected band filenames are appended with the suffix of “_RHORC_” followed by a band designation. Section 3 describes the files included in the AR product in more detail.

The following is an example of a Landsat C2 Provisional AR product filename:

LXSS_LLLL_PPPRRR_YYYYMMDD_yyyymmdd_CX_TX_PROD_BAND.ext
(e.g., LC08_L1TP_015033_20210310_20210317_02_T1_AR_BAND1.TIF)

L	Landsat
X	Sensor (“O” = OLI; “C” = OLI/TIRS)
SS	Satellite (“08” = Landsat 8, “9” = Landsat 9)
LLLL	Processing correction level (“L1TP” = Precision Terrain; “L1GT” = Systematic Terrain; “L1GS” = Systematic)
PPP	Path
RRR	Row
YYYY	Year of acquisition
MM	Month of acquisition
DD	Day of acquisition
yyyy	Year of Level 1 processing
mm	Month of Level 1 processing
dd	Day of Level 1 processing
CX	Collection number (“02” for Collection 2)
TX	Collection category (“RT” = Real-Time; “T1” = Tier 1; “T2” = Tier 2)
PROD	Product (“AR”, “RHORC”)
BAND	Band, such as BAND<1-7>”, “L2_FLAGS”, “NO2_TROPO”, “PRESSURE”, “SAA”, “SZA”, “VAA”, “VZA”, “SCATTANG”, “WATER_VAPOR”, “WINDSPEED”, “WATER_MASK”
ext	File format extension, such as “TIF”, “tif”, “img”, “hdr”, “hdf”, “nc”, “xml”, and “txt”

Section 3 Product Characteristics

Landsat 8-9 C2 Provisional AR products are generated at 30-meter spatial resolution. The default projection system for Landsat science products is Universal Transverse Mercator (UTM), but other projection systems such as Albers Equal Area (AEA), Geographic, and Polar Stereographic (PS) are available through the ESPA on-demand interface. The default file format is Cloud Optimized GeoTIFF (COG; .TIF), but options for delivery include Georeferenced Tagged Image File Format (GeoTIFF), Hierarchical Data Format – Earth Observing System – 2 (HDF-EOS2; .hdf), NetCDF (.nc), or Exelis Visual Information Solutions (ENVI) binary (.img). More information on Landsat output formats supported by ESPA is available in the ESPA On-Demand Interface User Guide.

3.1 Available Products

The files included in Landsat C2 Provisional AR products are listed below:

1. Aquatic Reflectance (AR) – Represents the nondimensional normalized water-leaving remote sensing reflectance, assuming a perfectly Lambertian surface.

2. Rayleigh-corrected Reflectance (RHORC) – Represents the intermediate Rayleigh-corrected reflectance, which is used to generate AR.

3. Atmospheric auxiliary bands (WATER_VAPOR, PRESSURE, WINDSPEED, NO2_TROPO, OZONE) – Represents water vapor, surface pressure, wind speed, tropospheric nitrogen dioxide, and vertical columnar ozone used as input information for atmospheric correction calculations.

4. Elevation (HEIGHT) – Represents the auxiliary digital elevation model used as input for atmospheric correction calculations.

5. Processing Flags (L2_FLAGS) – A bit-packed band that provides per-pixel information about success or failure of processing and validity of sun glint, view angle, solar angle, polarization, chlorophyll-a, etc.

6. Level-1 Pixel Quality Band (QA_PIXEL) – The bit combinations that define certain quality conditions. More information about Pixel Quality Assessment can be found in the Landsat 8-9 Collection 2 Level-2 Science Product Guide.

7. Water Mask (WATER_MASK) – Classified raster consisting of pixels identified as land (0), water (1), cloud (2), cloud shadow (3) and snow (4) used for masking non-water pixels in the RHORC and AR bands.

8. Solar and Sensor angles (SAA, SZA, VAA, VZA, SCATTANG) – Per-pixel Level-1 solar/viewing zenith and azimuth angles in addition to the scattering angle based on these angles.

9. Angle Band Coefficients File (ANG) – Text (.txt) document containing input information to generate the per-pixel sensor and sun viewing angle bands.

10. Metadata – Includes Aquatic Reflectance Science Product information in XML format (Product_ID.xml) and Level-1 metadata both in .txt and XML format.

3.2 Product Specifications

Table 3-1 lists the specifications for each file included in the Landsat C2 Provisional AR product.

Description	Band Name	Range	Valid Range	Scale Factor	Unit	Fill Value	Data Type
Aquatic Reflectance band 1 (Coastal aerosol)	AR_BAND1	-32768 to 32767	0 to 10000	0.00001	Unitless	-9999	INT16
Aquatic Reflectance band 2 (Blue)	AR_BAND2	-32768 to 32767	0 to 10000	0.00001	Unitless	-9999	INT16
Aquatic Reflectance band 3 (Green)	AR_BAND3	-32768 to 32767	0 to 10000	0.00001	Unitless	-9999	INT16
Aquatic Reflectance band 4 (Red)	AR_BAND4	-32768 to 32767	0 to 10000	0.00001	Unitless	-9999	INT16
Aquatic Reflectance band 5 (NIR)	AR_BAND5	-32768 to 32767	0 to 10000	0.00001	Unitless	-9999	INT16
Rayleigh-Corrected Reflectance band 1 (Coastal aerosol)	RHORC_BAND1	-32768 to 32767	0 to 10000	0.0001	Unitless	-9999	INT16
Rayleigh-Corrected Reflectance band 2 (Blue)	RHORC_BAND2	-32768 to 32767	0 to 10000	0.0001	Unitless	-9999	INT16
Rayleigh-Corrected Reflectance band 3 (Green)	RHORC_BAND3	-32768 to 32767	0 to 10000	0.0001	Unitless	-9999	INT16
Rayleigh-Corrected Reflectance band 4 (Red)	RHORC_BAND4	-32768 to 32767	0 to 10000	0.0001	Unitless	-9999	INT16
Rayleigh-Corrected Reflectance band 5 (NIR)	RHORC_BAND5	-32768 to 32767	0 to 10000	0.0001	Unitless	-9999	INT16

Description	Band Name	Range	Valid Range	Scale Factor	Unit	Fill Value	Data Type
Rayleigh-Corrected Reflectance band 6 (SWIR1)	RHORC_BAND6	-32768 to 32767	0 to 10000	0.0001	Unitless	-9999	INT16
Rayleigh-Corrected Reflectance band 7 (SWIR2)	RHORC_BAND7	-32768 to 32767	0 to 10000	0.0001	Unitless	-9999	INT16
Water Vapor	WATER_VAPOR	0 to 65535	0 to 65535	0.0001	g/cm^2	N/A	UINT16
Surface Pressure	PRESSURE	0 to 65535	0 to 65535	0.1	Millibars	N/A	UINT16
Wind Speed	WINDSPEED	0 to 65535	0 to 65535	0.001	m/s	N/A	UINT16
Tropospheric NO2	NO2_ TROPO	-32768 to 32767	0 to 32767	0.01	10^15 molecules/cm^2	N/A	INT16
Ozone	OZONE	0 to 65535	0 to 65535	0.001	atm-cm	65535	UINT16
Elevation	HEIGHT	0 to 2^{31}-1	0 to 90000	0.1	Meters	-32767	INT32
Scattering Angle	SCATTANG	-32768 to 32767	-18000 to 18000	0.01	Degrees	N/A	INT16
Processing Flags	L2_ FLAGS	0 to 2^{31}-1	0 to 2^{31}-1	N/A	N/A	-9999	INT32
Water Mask	WATER_MASK	0-4	0 to 4	N/A	N/A	N/A	UINT8
Level-1 Pixel Quality Assessment	QA_ PIXEL	0 to 65535	1 to 65534	N/A	Bit Index	1 (bit 0)	UINT16
Level-1 Solar Zenith Angle	SZA	-32768 to 32767	-18000 to 18000	0.01	Degrees	N/A	INT16
Level-1 Solar Azimuth Angle	SAA	-32768 to 32767	-18000 to 18000	0.01	Degrees	N/A	INT16
Level-1 Viewing Zenith Angle	VZA	-32768 to 32767	-18000 to 18000	0.01	Degrees	N/A	INT16
Level-1 Viewing Azimuth Angle	VAA	-32768 to 32767	-18000 to 18000	0.01	Degrees	N/A	INT16
Level-2 XML Metadata File	.xml	N/A	N/A	N/A	N/A	N/A	N/A
Level-2 MTL Metadata File	.MTL	N/A	N/A	N/A	N/A	N/A	N/A

Table 3-1. Landsat Provisional AR Product Specifications

3.2.1 Processing Flags

The processing flags (L2_FLAGS) band provides additional per-pixel information about the success or failure of atmospheric correction, as well additional information about high sun glint, water turbidity, coccolithophore blooms, etc. Table 3-2 provides the interpretation of possible pixel values expected in the processing flags band.

Bit	Bit Value	Cumulative Sum	Attribute	Description
0	1	1	ATMFAIL	Atmospheric correction failed
1	2	3	N/A	N/A
2*	4	7	PRODWARN	Intermediate product value falls outside the min/max range
3	8	15	HIGLINT	If glint coefficient > glint threshold (0.005). This is not checked for land or night pixels.
4*	16	31	HILT	Flags high total radiance (Lt) measured by sensor (not used)
5	32	63	HISATZEN	View angle > threshold (60 deg)
6	64	127	N/A	N/A
7	128	255	SEADAS_CLOUD	Cloud based on SeaDAS algorithm
8	256	511	CLOUD_SHADOW	Cloud shadow based on the SeaDAS cloud mask algorithm
9	512	1023	CLOUD	Cloud based on the cloud mask algorithm
10	1024	2047	COCCOLITH	Flagged based on the coccolithophore algorithm coefficients, detects coccolithophore blooms. (Coccolithophores are a group of phytoplanktons that inhabit a wide variety of marine environments and are distinctive by their production of small calcium plates or coccoliths which are organized around each living cell as an outer covering.)
11	2048	4095	TURBIDW	Flags turbid water. If LwB4 / FonomB4 > 0.0012 Where LwB4: water-leaving radiance band 4 value FonomB4: nominal F0 value for band 4 F0: the mean solar flux (unit: $mW \cdot cm^{-2} \cdot \mu m^{-1} \cdot sr^{-1}$)
12	4096	8191	HISOLZEN	Solar angle > threshold (70 deg)
13	8192	16383	Unused	N/A
14	16384	32767	LOWLW	If water-leaving radiance band 3 (LwB3) value < 0.15 (nLwmin)
15	32768	65535	CHLFAIL	Flags a failure in the chlorophyll-a calculation
16	65536	131071	NAVWARN	Mainly used for fill pixels
17	131072	262143	Unused	N/A
18	262144	524287	RRSWARN	R_{rs} < min_valid (0) or R_{rs} > max_valid (0.02) for bands 1-5 (unit: sr^{-1})
19	524288	1048575	MAXAERITER	Number of iterations for the aerosol corrections exceeds the maximum threshold (10)
20	1048576	2097151	MODGLINT	glint coefficient > minimum glint threshold (0.0001)

Bit	Bit Value	Cumulative Sum	Attribute	Description
21	2097152	4194303	CHLWARN	Chlorophyll-a < min_valid (0) or chlorophyll-a > max_valid (100) (unit: mg/m^3)
22	4194304	8388607	ATMWARN	If the value is invalid, then set ATMWARN; also set if MAXAERITER is set. Based on ancillary QC flags (ozone, water vapor, RH, wind speed, surface pressure)
23	8388608	16777215	N/A	N/A
24	16777216	33554431	N/A	N/A
25	33554432	67108863	NAVFAIL	If there is an invalid latitude/longitude value
26*	67108864	134217727	FILTER	Pixel is masked if there are not enough valid pixels in the filter to compute the average
27	134217728	268435455	NEG_RHORC	At least one RHORC band has a negative value for this pixel
28	268435456	536870911	NEG_AR	At least one AR band has a negative value for this pixel
29*	536870912	1073741823	HIPOL	If degree of polarization for any band is > hipol (0.5)
30*	1073741824	2147483647	PRODFAIL	Processing failure (chlorophyll-a retrieval for this pixel failed, data values are outside the valid range, too many bands, etc.)

Key: *These bits are not used in Landsat implementation of SeaDAS
N/A = Not Applicable

Table 3-2. Landsat Provisional AR Processing Flags (L2_FLAGS) Bit Index

3.2.2 Water Mask

A WATER_MASK band is created and delivered in the AR product package to reference which pixels were identified as land, water, cloud, cloud shadow and snow in the classification process. Table 3-3 provides information on how to interpret the class of each pixel. Please refer to the Landsat 8-9 Collection 2 Level-2 Provisional Aquatic Reflectance Algorithm Description Document for more information on the water masking process.

Value	Description
0	Land / Fill (Level-2)
1	Water (Level-2 & Level-1 QA_PIXEL)
2	Cloud (Level-1 QA_PIXEL)
3	Cloud Shadow (Level-1 QA_PIXEL)
4	Snow (Level-1 QA_PIXEL)

Table 3-3. Landsat Provisional AR WATER_MASK Band Interpretation

3.2.3 Metadata

Each Landsat C2 Provisional AR product is accompanied by an XML-based metadata file. The metadata fields included in the XML are listed in Appendix B.

3.3 Caveats and Constraints

1. Current Landsat 8-9 C2 AR Science Products are considered provisional. The atmospheric correction algorithm and subsequent output products have not been completely validated. Most preliminary validation efforts are conducted using the Ocean Color component data of the Aerosol Robotic Network (AERONET) (Pahlevan et al., 2017) representing moderately coastal waters. The performance of the algorithm over highly turbid and eutrophic inland water bodies requires further verification and/or improvement. For additional information about the preliminary validation details, see the References section.

2. C2 AR products are currently available only for Landsat 8 and Landsat 9 C2 Operational Land Imager (OLI) data; the capability to process Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 4-5 Thematic Mapper (TM) data likely will be added in the future.

3. An across-track non-uniformity artifact may be visible in Landsat 8-9 C2 Provisional AR products. This non-uniformity is mainly due to slight differences in the viewing geometries of odd and even Focal Plane Modules (FPM) of OLI in along-track direction (Morfitt et al., 2015). In effect, one set of detectors are forward-looking (looking toward the sun) and the others backward-looking (looking away from the sun) as satellite travels in its orbit. This difference in viewing angles results in collecting different reflected radiances from the water surface and ambient aerosols (Pahlevan et al., 2017). The effect is more pronounced toward the eastern portion of the OLI images a) when the solar elevation angle is higher and/or b) under hazy conditions.

4. The Landsat 8-9 C2 Provisional AR uses an algorithm developed internally at EROS to assess each pixel for the presence of surface water. This procedure may result in omission and commission classification errors. In this case, commission error will trigger AR processing for misclassified non-water pixels It is advised that analysis of any surface water pixels -- not only those identified by the classification -- be done under the supervision of an analyst.

5. The QA_PIXEL band is used for masking cloud, cloud shadow and snow. The RHORC and AR bands may include instances where NoData values appear over valid water pixels. The NoData pixels are usually due to misclassified clouds resulting from the Fmask operation over water. For more information on Fmask algorithm, see https://www.usgs.gov/landsat-missions/cfmask-algorithm. Any NoData pixel in the AR that has valid RHORC value is due to aerosol correction failure.

6. The processing flags (L2_FLAGS) band provides useful information about the status of AR processing. More details about the processing flags band are provided in Section 3.2.1.

Section 4 Product Access

Landsat 8-9 C2 Provisional AR products can be requested through the USGS EROS Science Processing Architecture (ESPA) On-demand Interface (https://espa.cr.usgs.gov/). ESPA offers additional customization services such as reprojection, spatial subsetting, and pixel resizing. More information about ESPA's processing options can be found in the ESPA On-Demand Interface User Guide.

Section 5 Citation Information

There are no restrictions on the use of Landsat Science Products. It is not a requirement of data use, but the following citation may be used in publication or presentation materials to acknowledge the USGS as a data source and to credit the original research.

Landsat Collection 2 Provisional Aquatic Reflectance Science Product courtesy of the U.S. Geological Survey.

Franz, B.A., Bailey, S.W., Kuring, N., & Werdell, P.J. (2015). Ocean color measurements with the Operational Land Imager on Landsat-8: implementation and evaluation in SeaDAS. Journal of Applied Remote Sensing, 9(1), 096070. https://doi.org/10.1117/1.JRS.9.096070

Pahlevan, N., Schott, J.R., Franz, B.A., Zibordi, G., Markham, B., Bailey, S., Schaaf, C.B., Ondrusek, M., Greb, S. & Strait, C.M. (2017). Landsat 8 remote sensing reflectance (R_{rs}) products: Evaluations, intercomparisons, and enhancements. Remote sensing of environment, 190, 289-301. https://doi.org/10.1016/j.rse.2016.12.030

Reprints or citations of papers or oral presentations based on USGS data are welcome to help the USGS stay informed of how data are being used. These can be sent to the contact information provided in Section 7.

Section 6 Acknowledgment

The Landsat Collection 2 Provisional Aquatic Reflectance algorithm is based on the SeaDAS system that was developed at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) by the Ocean Biology Processing Group (OBPG).

Section 7 User Services

Landsat Science Products and associated interfaces are supported by User Services staff at the USGS Earth Resources Observation and Science (EROS) Center. Questions or comments regarding Landsat Science Products or interfaces are welcome and can be sent via email or by phone.

USGS EROS User Services
Email: custserv@usgs.gov
Phone: 800-252-4547

USGS Landsat Missions Website (LMWS)
https://www.usgs.gov/landsat-missions

User support is available Monday through Friday from 8:00 a.m. – 4:00 p.m. Central Time. Inquiries received outside of these hours are addressed during the next business day.

Appendix A Default File Characteristics

A typical Landsat Provisional AR naming convention and file size are illustrated below.

Description	Example File Size (Kbytes)	Example File Name
Aquatic Reflectance Bands (5)	57,300	LC08_L1TP_161042_20171008_20200903_02_T1_AR_BAND*.TIF
Rayleigh-Corrected Reflectance Bands (7)	37,500	LC08_L1TP_161042_20171008_20200903_02_T1_RHORC_BAND*.TIF
Water Vapor	7,610	LC08_L1TP_161042_20171008_20200903_02_T1_WATER_VAPOR.TIF
Wind Speed	4,920	LC08_L1TP_161042_20171008_20200903_02_T1_WINDSPEED.TIF
Surface Pressure	1,840	LC08_L1TP_161042_20171008_20200903_02_T1_PRESSURE.TIF
Tropospheric NO2	1,360	LC08_L1TP_161042_20171008_20200903_02_T1_NO2_TROPO.TIF
Ozone	416	LC08_L1TP_161042_20171008_20200903_02_T1_OZONE.TIF
Height	5,610	LC08_L1TP_161042_20171008_20200903_02_T1_HEIGHT.TIF
Processing Flags	6,180	LC08_L1TP_161042_20171008_20200903_02_T1_L2_FLAGS.TIF
Water Mask	201	LC08_L1TP_161042_20171008_20200903_02_T1_WATER_MASK.TIF
Level-1 Quality Pixel Assessment (QA)	380	LC08_L1TP_161042_20171008_20200903_02_T1_QA_PIXEL.TIF
Level-1 Solar Zenith Angles	1,820	LC08_L1TP_161042_20171008_20200903_02_T1_SZA.TIF
Level-1 Solar Azimuth Angles	1,820	LC08_L1TP_161042_20171008_20200903_02_T1_SAA.TIF
Level-1 Viewing Zenith Angles	2,070	LC08_L1TP_161042_20171008_20200903_02_T1_VZA.TIF
Level-1 Viewing Azimuth Angles	5,610	LC08_L1TP_161042_20171008_20200903_02_T1_VAA.TIF
Scattering Angle	6,860	LC08_L1TP_161042_20171008_20200903_02_T1_SCATTANG.TIF
Metadata	18	LC08_L1TP_161042_20171008_20200903_02_T1.xml

Table A-1. Example Landsat Provisional AR Files

Appendix B Level-2 Metadata Fields

Example of global XML metadata:

```
<global_metadata>
        <data_provider>USGS/EROS</data_provider>
        <satellite>LANDSAT_8</satellite>
        <instrument>OLI_TIRS</instrument>
        <acquisition_date>2020-02-06</acquisition_date>
        <scene_center_time>22:33:12.4730669Z</scene_center_time>
        <level1_production_date>2020-08-23T13:31:42Z</level1_production_date>
        <solar_angles zenith="44.487141" azimuth="59.728600" units="degrees"/>
        <earth_sun_distance>0.986056</earth_sun_distance>
        <wrs system="2" path="77" row="92"/>
        <product_id>LC08_L1TP_077092_20200206_20200823_02_T1</product_id>
        <lpgs_metadata_file>LC08_L1TP_077092_20200206_20200823_02_T1_MTL.txt</lpgs_metadat
        a_file>
        <corner location="UL" latitude="-44.959660" longitude="164.750220"/>
        <corner location="LR" latitude="-47.083320" longitude="167.898360"/>
        <bounding_coordinates>
        <west>164.740098</west>
        <east>167.898565</east>
        <north>-44.925761</north>
        <south>-47.120140</south>
        </bounding_coordinates>
        <projection_information projection="UTM" datum="WGS84" units="meters">
        <corner_point location="UL" x="480300.000000" y="-4978500.000000"/>
        <corner_point location="LR" x="720000.000000" y="-5218500.000000"/>
        <grid_origin>CENTER</grid_origin>
        <utm_proj_params>
        <zone_code>58</zone_code>
        </utm_proj_params>
        </projection_information>
        <orientation_angle>0.000000</orientation_angle>
</global_metadata>
```

Example of Aquatic Reflectance band XML metadata:

```
<band product="aq_refl" source="level1" name="ar_band1" category="image" data_type="INT16" nlines=
"8001" nsamps="7991" fill_value="-9999" scale_factor="0.00001000" band_center="0.443">
        <short_name>LC08AR</short_name>
        <long_name>band 1 aquatic reflectance</long_name>
<file_name>LC08_L1TP_077092_20200206_20200823_02_T1_AR_BAND1.TIF</file_name>
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>unitless</data_units>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>
```

Example of Rho_rc band XML metadata:

```
<band product="aq_refl" source="level1" name="rhorc_band1" category="image" data_type="INT16" nlin
es="8001" nsamps="7991" fill_value="-9999" scale_factor="0.00010000" band_center="0.443">
        <short_name>LC08RHORC</short_name>
        <long_name>band 1 Rayleigh-corrected reflectance</long_name>
```

```
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_RHORC_BAND1.TIF</file_nam
        e>
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>unitless</data_units>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>
```

Example of Auxiliary bands metadata

```
<band product="aq_refl" source="GMAO GEOS-IT
file" name="water_vapor" category="auxiliary" data_type="UINT16" nlines="8001" nsamps="7991" fill_val
ue="65535" scale_factor="0.00010000">
        <short_name>LC08WV</short_name>
        <long_name>water vapor</long_name>
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_WATER_VAPOR.TIF</file_nam
        e>
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>g cm^-2</data_units>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>

<band product="aq_refl" source="GMAO GEOS-IT
file" name="pressure" category="auxiliary" data_type="UINT16" nlines="8001" nsamps="7991" fill_value=
"65535" scale_factor="0.10000000">
        <short_name>LC08PRES</short_name>
        <long_name>surface pressure</long_name>
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_PRESSURE.TIF</file_name>
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>millibars</data_units>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>

<band product="aq_refl" source="ETOPO1" name="height" category="auxiliary" data_type="INT32" nline
        s="8001" nsamps="7991" fill_value="-32767" scale_factor="0.10000000">
        <short_name>LC08ELEV</short_name>
        <long_name>terrain elevation</long_name>
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_HEIGHT.TIF</file_name>
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>meters</data_units>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>

<band product="aq_refl" source="GMAO GEOS-IT
        file" name="ozone" category="auxiliary" data_type="UINT16" nlines="8001" nsamps="7991" fill_v
        alue="65535" scale_factor="0.00100000">
        <short_name>LC08OZONE</short_name>
        <long_name>ozone concentration</long_name>
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_OZONE.TIF</file_name>
```

```
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>cm</data_units>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>

<band product="aq_refl" source="GMAO GEOS-IT
        file" name="windspeed" category="auxiliary" data_type="UINT16" nlines="8001" nsamps="7991"
        fill_value="65535" scale_factor="0.00100000">
        <short_name>LC08WIND</short_name>
        <long_name>wind speed</long_name>
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_WINDSPEED.TIF</file_name>
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>m s^-1</data_units>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>

<band product="aq_refl" source="Static NO2
        climatology" name="no2_tropo" category="auxiliary" data_type="INT16" nlines="8001" nsamps="
        7991" fill_value="-32767" scale_factor="0.01000000">
        <short_name>LC08NO2TROPO</short_name>
        <long_name>tropospheric nitrogen dioxide</long_name>
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_NO2_TROPO.TIF</file_name>
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>10^15 molecules cm^-2</data_units>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>

<band product="aq_refl" source="level1" name="scattang" category="auxiliary" data_type="INT16" nlines
        ="8001" nsamps="7991" fill_value="-32768" scale_factor="0.01000000">
        <short_name>LC08SCATTANG</short_name>
        <long_name>scattering angle</long_name>
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_SCATTANG.TIF</file_name>
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>degree</data_units>
        <valid_range min="-18000.000000" max="18000.000000"/>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>
```

Example of Processing Flags metadata

```
<band product="aq_refl" name="l2_flags" category="qa" data_type="INT32" nlines="8001" nsamps="799
        1" fill_value="-9999" scale_factor="1.00000000">
        <short_name>LC08ARFLAG</short_name>
        <long_name>aquatic reflectance processing flags</long_name>
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_L2_FLAGS.TIF</file_name>
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
```

```
        <data_units>quality/feature classification</data_units>
        <bitmap_description>
        <bit num="0">ATMFAIL</bit>
        <bit num="1">N/A</bit>
        <bit num="2">PRODWARN</bit>
        <bit num="3">HIGLINT</bit>
        <bit num="4">HILT</bit>
        <bit num="5">HISATZEN</bit>
        <bit num="6">N/A</bit>
        <bit num="7">SEADAS_CLOUD</bit>
        <bit num="8">CLOUD_SHADOW</bit>
        <bit num="9">CLOUD</bit>
        <bit num="10">COCCOLITH</bit>
        <bit num="11">TURBIDW</bit>
        <bit num="12">HISOLZEN</bit>
        <bit num="13">N/A</bit>
        <bit num="14">LOWLW</bit>
        <bit num="15">CHLFAIL</bit>
        <bit num="16">NAVWARN</bit>
        <bit num="17">N/A</bit>
        <bit num="18">RRSWARN</bit>
        <bit num="19">MAXAERITER</bit>
        <bit num="20">MODGLINT</bit>
        <bit num="21">CHLWARN</bit>
        <bit num="22">ATMWARN</bit>
        <bit num="23">N/A</bit>
        <bit num="24">N/A</bit>
        <bit num="25">NAVFAIL</bit>
        <bit num="26">FILTER</bit>
        <bit num="27">NEG_RHORC</bit>
        <bit num="28">NEG_AR</bit>
        <bit num="29">HIPOL</bit>
        <bit num="30">PRODFAIL</bit>
        </bitmap_description>
        <app_version>ESPA_AQ_REFL_GEOS-IT (Collection 2)</app_version>
        <production_date>2024-11-15T17:32:24Z</production_date>
</band>
```

Example of Water Mask metadata

```
<band product="aq_refl" name="water_mask" category="qa" data_type="UINT8" nlines="8001" nsamps="
        7991">
        <short_name>LC08LWMASK</short_name>
        <long_name>water mask: uses internal water algorithm</long_name>
        <file_name>LC08_L1TP_077092_20200206_20200823_02_T1_WATER_MASK.TIF</file_name
        >
        <pixel_size x="30" y="30" units="meters"/>
        <resample_method>none</resample_method>
        <data_units>quality/feature classification</data_units>
        <valid_range min="0.000000" max="4.000000"/>
        <class_values>
        <class num="0">land/fill</class>
        <class num="1">Level-2 water</class>
        <class num="2">Level-1 QA_PIXEL cloud</class>
        <class num="3">Level-1 QA_PIXEL shadow</class>
        <class num="4">Level-1 QA_PIXEL snow</class>
```

```
        </class_values>
        <app_version>MASK_LAND_WATER_v1.0.0</app_version>
        <production_date>2024-11-15T18:33:30Z</production_date>
</band>
```

Appendix C Acronyms

AEA	Albers Equal Area
AERONET	Aerosol Robotic Network
ANG	Angle band coefficients file extension
AR	Aquatic Reflectance
BRDF	Bidirectional Reflectance Distribution Function
C2	Collection 2
CCB	Configuration Control Board
CFMask	C Function of Mask
COG	Cloud Optimized GeoTIFF
CR	Change Request
ENVI	Exelis Visual Information Solutions
EROS	Earth Resources Observation and Science
ESPA	EROS Science Processing Architecture
ETM+	Enhanced Thematic Mapper Plus
FPM	Focal Plane Module
GEOS	Goddard Earth Observing System
GEOS-IT	GEOS for Instrument Teams
GeoTIFF	Georeferenced Tagged Image File Format
GES DISC	Goddard Earth Sciences Data and Information Services Center
GMAO	Global Modeling and Assimilation Office
GSFC	Goddard Space Flight Center
HDF-EOS2	Hierarchical Data Format – Earth Observing System (version 2)
HDR	Header
INT	Integer
INT16	16-bit signed integer
L1	Level-1
L2	Level-2
L1GS	Level-1 Geometric Systematic
L1GT	Level-1 Systematic Terrain
L1TP	Level-1 Terrain Precision
LMWS	Landsat Missions Website
LSDS	Land Satellites Data System
m	meter
MSI	Multispectral Instrument
NA	Not Applicable
NASA	National Aeronautics and Space Administration
NC	NetCDF File Format
NIR	Near Infrared
OBPG	Ocean Biology Processing Group
OLI	Operational Land Imager
pixel_qa	Pixel Quality Assessment

PS	Polar Stereographic
QA	Quality Assessment
RHORC	Rayleigh-corrected reflectance
Rrs	Remote Sensing Reflectance
RT	Real-Time
SAA	Solar Azimuth Angle
SeaDAS	SeaWiFS Data Analysis System
SeaWiFS	Sea-viewing Wide Field-of-View Sensor
SWIR	Shortwave Infrared
SZA	Solar Zenith Angle
T1	Tier 1
T2	Tier 2
TIRS	Thermal Infrared Sensor
TM	Thematic Mapper
TOA	Top of Atmosphere
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
VAA	Viewing Azimuth Angle
VNIR	Visible and Near Infrared
VSWIR	Visible to Short Wavelength Infrared
VZA	Viewing Zenith Angle
XML	Extensible Markup Language

References

Please see https://www.usgs.gov/landsat-missions/landsat-acronyms for a list of acronyms.

Franz, B.A., Bailey, S.W., Kuring, N., & Werdell, P.J. (2015). Ocean color measurements with the Operational Land Imager on Landsat-8: implementation and evaluation in SeaDAS. Journal of Applied Remote Sensing, 9(1), 096070. https://doi.org/10.1117/1.JRS.9.096070

Gordon, H.R., & Wang, M. (1994). Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: a preliminary algorithm. Applied optics, 33(3), 443-452. https://doi.org/10.1364/AO.33.000443

Mobley, C.D., Werdell, J., Franz, B., Ahmad, Z., & Bailey, S. (2016). Atmospheric correction for satellite ocean color radiometry. NASA Tech. Memo, NASA/TM-2016-217551, p. 85 https://ntrs.nasa.gov/search.jsp?R=20160011399

Morfitt, R., Barsi, J., Levy, R., Markham, B., Micijevic, E., Ong, L., Scaramuzza, P. and Vanderwerff, K., 2015. Landsat-8 Operational Land Imager (OLI) radiometric performance on-orbit. Remote Sensing, 7(2), pp.2208-2237. https://doi.org/10.3390/rs70202208

Pahlevan, N., Mangin, A., Balasubramanian, S.V., Smith, B., Alikas, K., Arai, K., Barbosa, C., Bélanger, S., Binding, C., Bresciani, M. and Giardino, C., 2021. ACIX-Aqua: A global assessment of atmospheric correction methods for Landsat-8 and Sentinel-2 over lakes, rivers, and coastal waters. *Remote Sensing of Environment*, *258*, p.112366. https://doi.org/10.1016/j.rse.2021.112366

Pahlevan, N., Schott, J.R., Franz, B.A., Zibordi, G., Markham, B., Bailey, S., Schaaf, C.B., Ondrusek, M., Greb, S. & Strait, C.M. (2017). Landsat 8 remote sensing reflectance (Rrs) products: Evaluations, intercomparisons, and enhancements. Remote sensing of environment, 190, 289-301. https://doi.org/10.1016/j.rse.2016.12.030

Pahlevan, N., & Schott, J.R. (2013). Leveraging EO-1 to evaluate capability of new generation of Landsat sensors for coastal/inland water studies. IEEE Journal of selected topics in applied earth observations and remote sensing, 6(2), 360-374. https://doi.org/10.1109/JSTARS.2012.2235174

USGS/EROS. LSDS-2339. Landsat 8-9 Collection 2 Level-2 Provisional Aquatic Reflectance Algorithm Description Document.