Harmonized Landsat Sentinel-2 (HLS) Product User's Guide

Product Version 1.4

Principal Investigator: Dr. Jeffrey G. Masek, NASA/GSFC

Web site: http://hls.gsfc.nasa.gov

Correspondence email address: Jeffrey.G.Masek@nasa.gov

Prepared by S. Skakun, J. Ju, M. Claverie, J.-C. Roger,
E. Vermote, B. Franch, J. L. Dungan, J. Masek

Document Version: 1.4

December, 2018

Table of Contents

Acronyms

AROP	Automated Registration and Orthorectification Package
BRDF	Bidirectional Reflectance Distribution Function
BT	Brightness temperature
CMG	Climate Modelling Grid
ETM+	Enhanced Thematic Mapper Plus
GDAL	Geospatial Data Abstraction Library
GLS	Global Land Survey
HDF	Hierarchical Data Format
HLS	Harmonized Landsat and Sentinel-2
KML	Keyhole Markup Language
MGRS	Military Grid Reference System
MSI	Multi-Spectral Instrument
NBAR	Nadir BRDF-normalized Reflectance
OLI	Operational Land Imager
QA	Quality assessment
RSR	Relative spectral response
SDS	Scientific Data Sets
SR	Surface reflectance
SZA	Sun zenith angle
TM	Thematic Mapper
TOA	Top of atmosphere
UTM	Universal Transverse Mercator
WRS	Worldwide Reference System

1 Introduction

The Harmonized Landsat and Sentinel-2 (HLS) project is a NASA initiative to produce a Virtual Constellation (VC) of surface reflectance (SR) data from the Operational Land Imager (OLI) and Multi-Spectral Instrument (MSI) onboard the Landsat 8 and Sentinel-2 remote sensing satellites, respectively. The combined measurement enables global observations of the land every 2-3 days at moderate (<30 m) spatial resolution. The HLS project uses a set of algorithms to obtain seamless products from OLI and MSI: atmospheric correction, cloud and cloud-shadow masking, spatial co-registration and common gridding, illumination and view angle normalization and spectral bandpass adjustment. The HLS data products can be regarded as the building blocks for a "data cube" such that a user may examine any given pixel through time, and treat the near-daily reflectance time series as though it came from a single sensor.

Product Citation: Claverie, M., Ju, J., Masek, J. G., Dungan, J. L., Vermote, E. F., Roger, J.-C., Skakun, S. V., & Justice, C. (2018). The Harmonized Landsat and Sentinel-2 surface reflectance data set. *Remote Sensing of Environment*, *219*, 145-161. (https://doi.org/10.1016/j.rse.2018.09.002).

Note that this paper is based on the previous version (1.3) of the HLS product.

2 New in v1.4

HLS v1.4 builds on v1.3 by updating and improving processing algorithms, expanding spatial coverage, and providing validation. Particular updates are as follows:

- *New sites*. New sites have been added, increasing the total number of sites from 91 to 120, and increasing the number of tiles from 1047 to 4090. HLS now covers the whole of North America.
- *Product format*. The product is delivered in the HDF-EOS format. With a bug fix for this version, the HLS file format is now GDAL-compatible.
- *Input data*. HLSv1.4 uses Landsat 8 Collection-1 input data and includes data from Sentinel-2B (2017-).
- *Atmospheric correction*. LaSRCv3.5.5 has been applied for both Landsat 8 and Sentinel-2 data. This version fixes an aerosol interpolation scheme for Sentinel-2 data to remove occasional blockiness and "pinholes". LaSRCv3.5.5 has been validated for both Landsat 8 and Sentinel-2 within the CEOS ACIX-I (Atmospheric Correction Inter-Comparison eXercise, http://calvalportal.ceos.org/projects/acix).
- *Spectral response functions for Sentinel-2A*. Updated MSI Relative Spectral Response (RSR, version 2.0) functions for Sentinel-2A's bands 1 and 2.
- *Temporal Coverage and Latency*. Version 1.4 moves toward "keep up" processing. The intent is to continually update products with <7 day latency. Users are cautioned however that HLS is still a research product.

3 Products overview

3.1 Input data

The Operational Land Imager (OLI) sensor is a moderate spatial resolution multi-spectral imager onboard the Landsat 8 satellite, in a sun-synchronous orbit (705 km altitude) with a 16-day repeat cycle. The sensor has a field of view of 15 degrees (approximately 185 km). The OLI sensor has 9 bands and its data is co-registered with that of the 2-band instrument TIRS (Thermal Infrared Sensor) onboard the same Landsat 8 satellite. The native resolution for OLI is 30 m and for TIRS is 100 m, although both OLI and TIRS products are distributed with 30m GSD. HLS v1.4 uses Landsat 8 Collection-1[1] Level-1 top-of-atmosphere (TOA) product, including Tier-1 (high-quality L1TP) and Tier-2 (primarily L1GT, and some L1GS and L1TP).

The Sentinel-2 Multi-Spectral Instrument (MSI) is onboard the Sentinel-2A and -2B satellites orbiting the Earth at 786 km altitude. The ground sampling distance varies with the spectral bands: 10 m for the visible and the broad NIR bands, 20 m for the red edge, narrow NIR and SWIR bands, and 60 m for the atmospheric bands. The sensor has a 20.6° field of view corresponding to an image swath width of approximately 290 km. Table 1 provides an overview of Landsat 8 and Sentinel-2 characteristics. HLS v1.4 uses Level-1C (L1C) TOA product.

Table 1: Input data characteristics

<table>
<tr><th colspan="2"></th><th>Landsat 8/OLI-TIRS</th><th>Sentinel-2A/MSI</th><th>Sentinel-2B/MSI</th></tr>
<tr><td colspan="2">Launch date</td><td>February 11, 2013</td><td>June 23, 2015</td><td>March 7, 2017</td></tr>
<tr><td colspan="2">Equatorial crossing time</td><td>10:00 a.m.</td><td>10:30 a.m.</td><td>10:30 a.m.</td></tr>
<tr><td colspan="2">Spatial resolution</td><td>30 m (OLI) / 100 m (TIRS)</td><td colspan="2">10 m / 20 m / 60 m (see spectral bands)</td></tr>
<tr><td colspan="2">Swath / Field of view</td><td>180 km / 15°</td><td colspan="2">290 km / 20.6°</td></tr>
<tr><td rowspan="8">Spectral bands (central wavelength)</td><td>Ultra blue</td><td>443 nm</td><td colspan="2">443 nm (60 m)</td></tr>
<tr><td>Visible</td><td>482 nm, 561 nm, 655 nm</td><td colspan="2">490 nm (10 m), 560 nm (10 m),
665 nm (10m)</td></tr>
<tr><td>Red edge</td><td>-</td><td colspan="2">705 nm (20 m), 740 nm (20 m),
783 nm (20 m)</td></tr>
<tr><td>NIR</td><td>865 nm</td><td colspan="2">842 nm (10 m), 865 nm (20 m)</td></tr>
<tr><td>SWIR</td><td>1609 nm, 2201 nm</td><td colspan="2">1610 nm (20 m), 2190 nm (20 m)</td></tr>
<tr><td>Cirrus</td><td>1373 nm</td><td colspan="2">1375 nm (60 m)</td></tr>
<tr><td>Water Vapor</td><td>-</td><td colspan="2">945 nm (60 m)</td></tr>
<tr><td>Thermal</td><td>10.9 µm, 12 µm</td><td colspan="2">-</td></tr>
</table>

[1] Landsat Collections — https://landsat.usgs.gov/landsat-collections

3.2 Overall HLS processing flowchart

The processing (Figure 1) starts with orthorectified TOA reflectance data from Sentinel-2 (L1C) and Landsat 8 (L1TP, L1GT) and generates three products: S10, S30 and L30. A detailed description of methods applied for processing and harmonizing Landsat 8 and Sentinel-2 data is described in Section 4.

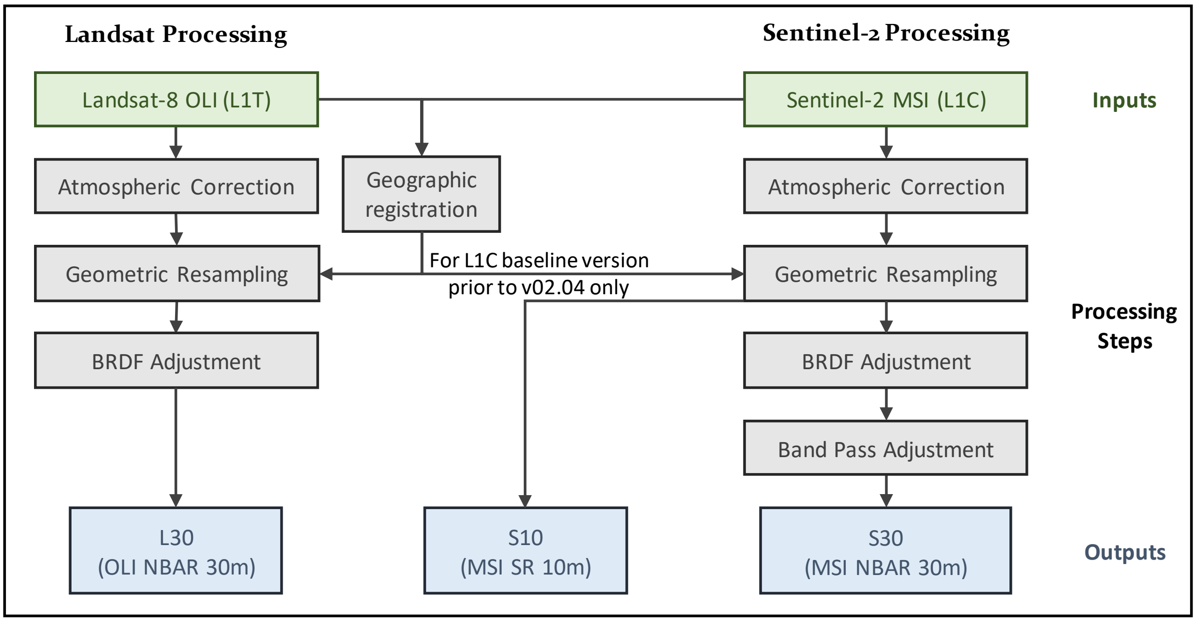


Figure 1: HLS science algorithm processing flow

3.3 Products specifications

The HLS suite contains three products:

- **S10**: MSI surface reflectance at full (native) resolutions (i.e. 10 m, 20 m and 60 m).
- **S30**: MSI harmonized surface reflectance resampled to 30 m into the Sentinel-2 tiling system and adjusted to Landsat 8 spectral response function.
- **L30**: OLI harmonized surface reflectance and TOA brightness temperature resampled to 30m into the Sentinel-2 tiling system.

The S10 product is atmospherically corrected, full spatial-resolution Sentinel-2 MSI surface reflectance. The geolocation of the images in processing baselines prior to 02.04 was adjusted slightly for better coregistration to a reference image per tile of minimal cloud cover from processing base 02.04. No other correction is applied, and the full spatial resolution (i.e. 10 m, 20 m, and 60 m) of the individual MSI bands is preserved. The product is intended for users requiring both the full spatial resolution of Sentinel-2 and the same LaSRC atmospheric correction approach used operationally for Landsat 8/OLI. Note that due to storage limitations S10 products are not archived. Interested users may contact the HLS management for on-demand delivery of S10 products for special test cases.

The S30 and L30 products provide 30 m Nadir BRDF-Adjusted Reflectance (NBAR) derived from MSI and OLI data, respectively. The S30 products are derived from S10 products and resampled to 30 m, BRDF normalized using a locally fixed, latitude-dependent solar angle and nadir view, and spectrally adjusted to match Landsat 8/OLI spectral bandpasses. The L30 products are derived from Landsat 8/OLI SR products, and registered to the same per-tile reference images used for S30 and gridded into the Sentinel-2 tiling system, and BRDF-normalized in the same way as S30. Note that the S30 and L30 products are gridded to the same resolution and tiling system, and thus are "stackable" for time series analysis. Product specifications are given in Table 2.

Table 2: HLS products specifications

Product Name	**S10**	**S30**	**L30**
Input sensor	Sentinel-2A/B MSI	Sentinel-2A/B MSI	Landsat-8 OLI/TIRS
Spatial resolution	10-20-60 m	30 m	30 m
BRDF-adjusted	No	Yes (except for bands 01, 05, 06, 07, 09, 10)	Yes
Bandpass-adjusted	No	Adjusted to OLI-like but no adjustment for Red Edge or water vapor	No
Projection	UTM	UTM	UTM
Tiling system	MGRS (110*110)	MGRS (110*110)	MGRS (110*110)

3.4 Spectral bands

All Landsat-8 OLI and Sentinel-2 MSI reflective spectral bands nomenclatures are retained in the HLS products (Table 3).

Table 3: HLS spectral bands nomenclature

Band name	**OLI band number**	**MSI band number**	**HLS band code name L8**	**HLS band code name S2**	**Wavelength (micrometers)**
Coastal Aerosol	1	1	band01	B01	0.43 – 0.45*
Blue	2	2	band02	B02	0.45 – 0.51*
Green	3	3	band03	B03	0.53 – 0.59*
Red	4	4	band04	B04	0.64 – 0.67*
Red-Edge 1	–	5	–	B05	0.69 – 0.71**
Red-Edge 2	–	6	–	B06	0.73 – 0.75**
Red-Edge 3	–	7	–	B07	0.77 – 0.79**
NIR Broad	–	8	–	B08	0.78 –0.88**
NIR Narrow	5	8A	band05	B8A	0.85 – 0.88*
SWIR 1	6	11	band06	B11	1.57 – 1.65*
SWIR 2	7	12	band07	B12	2.11 – 2.29*
Water vapor	–	9	–	B09	0.93 – 0.95**
Cirrus	9	10	band09	B10	1.36 – 1.38*

Thermal Infrared 1	10	–	band10	–	10.60 – 11.19*
Thermal Infrared 2	11	–	band11	–	11.50 – 12.51*

* from OLI specifications (may vary for S10 product which follow MSI specifications);
** from MSI specifications

3.5 Output projection and gridding

HLS has adopted the tiling system used by Sentinel-2. The tiles are in the Universal Transverse Mercator (UTM) projection, and are 109,800 m (110km nominally) on a side. The tiling system is aligned with the UTM-based Military Grid Reference System (MGRS). The UTM system divides the Earth's surface into 60 longitude zones, each 6° of longitude in width, numbered 1 to 60 from 180° West to 180° East. Each UTM zone is divided into latitude bands of 8°, labeled with letters C to X from South to North. One mnemonic is that latitude bands N and later refer to Northern Hemisphere. Each 6°×8° polygon (grid zone) is further divided into the 110km ×110km Sentinel-2 tiles labeled with letters. For example, tile 11SPC is in UTM zone 11, latitude band S (in Northern Hemisphere), and labeled P in the east-west direction and C in the south-north direction within grid zone 11S. There is an overlap of either 7980m or 8040m between two adjacent tiles of the same UTM zone. The overlap between two adjacent tiles both straddling a UTM zone boundary may be substantial. A KML file produced by ESA showing the location of all Sentinel-2 tiles is available at
https://sentinel.esa.int/documents/247904/1955685/S2A_OPER_GIP_TILPAR_MPC__20151209T095117_V20150622T000000_21000101T000000_B00.kml

One difference is that HLS uses a UTM convention of keeping the Y coordinate for the Southern Hemisphere negative with no need to indicate which hemisphere is used for UTM zone. This convention is used for USGS Landsat data distribution, and also for the HDF-EOS format, in which the HLS data are stored. In contrast, a lot of spatial data handling tools use another convention of adding 10,000,000 meters to make the southern coordinate positive (i.e. use of a false northing 10,000,000) and indicating which hemisphere to avoid confusion. These tools may textually report a Southern Hemisphere dataset with a false-northing 0 and no indication of hemisphere as being in Northern Hemisphere, but correctly handle the geolocation of the data in processing.

4 Algorithms description

4.1 Spatial co-registration of input data

Our objective in HLS is to maintain the geodetic accuracy requirement of the Sentinel-2 images (<20 m error, 2σ) and improve the multi-temporal co-registration among Sentinel-2 images and between Sentinel-2 and Landsat 8 images (<15 m 2σ) for the 30 m products. This specification supports time series monitoring of small fields, man-made features, and other spatially heterogeneous cover types.

Two issues impede our ability to directly register Landsat 8 and Sentinel-2 imagery without additional processing. First, while the relative co-registration of Landsat 8/OLI imagery is quite accurate (<6.6m, Storey et al. 2014), the absolute geodetic accuracy varies with the quality of the Global Land Survey 2000 (GLS2000) ground control around the world. In some locations, the GLS geodetic accuracy can be in error by up to 38 m (2σ, Storey et al. 2016). As a result, Sentinel-2/MSI and Landsat 8/OLI Level-1 products may not align to sub-pixel precision for those locations (Storey et al. 2016). Second, an error in the yaw characterization for the MSI L1C images processed before v02.04 (May 2016) caused misregistration between the edges of MSI images acquired from adjacent orbits (ESA 2018). The misregistration of up to 2.8 pixels at 10 m resolution between Sentinel-2A images from adjacent orbits has been observed by Skakun et al. (2017) and Yan et al. (2018). Although the issue was fixed with L1C version 02.04 (yielding to a measured absolute geolocation of less than 11m at 95.5% confidence, ESA 2018), archived data from 2015-2016 will continue to have this error until the entire archive is reprocessed by ESA.

We selected for each HLS tile our own reference image, an MSI image of processing L1C baseline version 02.04 with minimal cloud cover. MSI images were selected as reference since MSI absolute geodetic accuracy is better than OLI (Storey et al. 2014; Storey et al. 2016). Then we used the Automated Registration and Orthorectification package (AROP, Gao et al. 2009), to align all Landsat 8 and pre-v02.04 MSI imagery to the reference image of each tile. The NIR band (B5 for OLI and B8A for MSI) was used by AROP in the cross-correlation analysis to identify tie points.

The Automated Registration and Orthorectification Package (AROP) for Landsat (Gao et al. 2009) was adapted for Sentinel-2 data processing, and is used to warp and co-register an image to a reference image. Based on a large number of tie points derived from cross-correlation of small areas (chips), AROP yields a 1 degree polynomial describing the transformation of coordinates between the two images (eq. 1). These polynomials are used in co-registration (section 3.6).

$$\begin{cases} x' = a_1 + a_2 x + a_3 y \\ y' = b_1 + b_2 x + b_3 y \end{cases} \tag{1}$$

where (x, y) and (x', y') correspond to the coordinates of the original and the warped image, respectively, and $a_{1,2,3}$ and $b_{1,2,3}$ are AROP coefficients estimated using ordinary least squares. If an image has high cloud or snow cover or no distinct features to be exploited, AROP may not be able to identify enough tie points (>=10 pairs) or confidently provide a transformation. In these cases, the original geolocation information is used in registration with no AROP attempt for correction, and this is indicated by “0 tie point” in the product metadata.

The Landsat-8 surface reflectance is resampled using cubic convolution interpolation for the AROP derived coordinate transformation. The 30 m Sentinel-2 surface reflectance is derived from S10, by resampling all S10 bands to 30m. The 10 m pixels are resampled to 30m by averaging the nine 10 m values within a 30 m square. The 20 m bands are resampled to 30 m by averaging with area-based weights 4/9, 2/9, 2/9, and 1/9 for the four 20 m pixels overlapping the intended 30 m pixel. The reflectance of a 60 m pixel is replicated to the four intended 30 m pixel locations.

4.2 Atmospheric correction

The same atmospheric correction algorithm is applied to both sensors data — Land Surface Reflectance Code (LaSRC), developed by Eric Vermote (NASA/GSFC) (Vermote et al., 2016). LaSRC is based on the 6S radiative transfer model and a heritage from the MODIS MCD09 products (Vermote and Kotchenova 2008) as well as the earlier LEDAPS algorithm implemented for Landsat-5 and Landsat-7 (Masek et al. 2006). A detailed description of the method is given in Vermote et al. (2016), and results of surface reflectance validation for Landsat 8 and Sentinel-2 within CEOS ACIX-I are provided in Doxani et al. (2018).

HLSv1.4 uses LaSRC v3.5.5.

4.3 Cloud masks

HLS provides per-pixel cloud, shadow, snow, and water masks. The Landsat-8 mask of cloud, cloud-shadow, snow and water is a union of the mask derived from the LaSRC atmospheric correction tool introduced in 4.2, and the mask in the USGS Landsat TOA data (i.e. the BQA file).

The Sentinel-2 mask of cloud, cloud-shadow, snow and water mask is a union of LaSRC mask and the mask generated from the Fmask algorithm which has been adapted from (Zhu et al. 2015). Fmask is run on 30 m aggregated TOA reflectance.

4.4 View and illumination angles normalization

The S30 and L30 Nadir BRDF-Adjusted Reflectance (NBAR) products are surface reflectance normalized for the view and illumination angles. The view angle is set to nadir and the illumination is set based on the center latitude of the tile.

The *c*-factor global 12 month fixed BRDF technique, introduced by Roy et al. (2016), is used to perform the BRDF normalization. It consists of a unique set of BRDF coefficients, i.e., a constant BRDF shape, derived from a large number of pixels in the MODIS 500m BRDF product (MCD43) that are globally and temporally distributed (more than 15 billion pixels). The technique has been evaluated using ETM+ data off-nadir (i.e. on the overlap areas of adjacent swaths, Roy et al. 2016) and MSI data (Roy et al. 2017). The technique is applied on OLI and MSI bands equivalent to MODIS ones; MSI red-edge spectral bands are, therefore, not normalized. BRDF coefficients for the three kernels (isotropic, volumetric and geometric) are shown in the Table 4. The kernel definitions are described in the ATBD of MOD43 product (Strahler et al. 1999).

Table 4: BRDF coefficients used for the c-factor approach (Roy et al. 2016)

MODIS band	f_{iso}	f_{geo}	f_{vol}	Equivalent HLS code name
1 (red)	0.169	0.0227	0.0574	RED
2 (NIR)	0.3093	0.033	0.1535	NIR1, NIR2
3 (blue)	0.0774	0.0079	0.0372	BLUE
4 (green)	0.1306	0.0178	0.058	GREEN
6 (1.6μm)	0.343	0.0453	0.1154	SWIR1
7 (2.1μm)	0.2658	0.0387	0.0639	SWIR2

$$\rho(\lambda, \theta^{Norm}) = c(\lambda) \times \rho(\lambda, \theta^{sensor}) \tag{2}$$

$$c(\lambda) = \frac{f_{iso}(\lambda) + f_{geo}(\lambda) \times K_{geo}(\theta^{Norm}) + f_{vol}(\lambda) \times K_{vol}(\theta^{Norm})}{f_{iso}(\lambda) + f_{geo}(\lambda) \times K_{geo}(\theta^{sensor}) + f_{vol}(\lambda) \times K_{vol}(\theta^{sensor})} \tag{3}$$

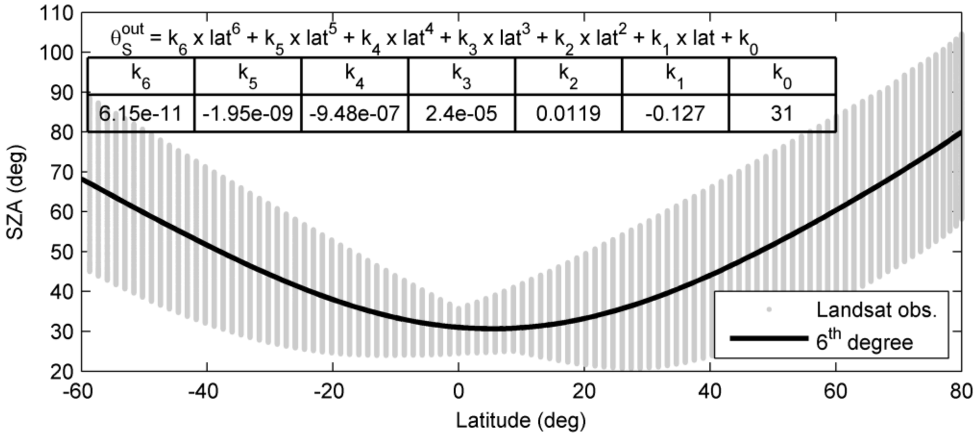
where: $\theta^{Norm} \Leftrightarrow (\theta_v = 0, \theta_s = \theta_s^{out}, \Delta\varphi = 0)$

$\theta_{sensor} \Leftrightarrow (\theta^{sensor} = \theta_v^{sensor}, \theta_s = \theta_s^{sensor}, \Delta\varphi = \Delta\varphi^{sensor})$

The S30 and L30 reflectance products are normalized for per-pixel view and per-tile illumination angles. This normalization is applied to all S30 and L30 optical bands, except the MSI red-edge bands and the cirrus and water vapor bands, for which no MODIS BRDF information is available. The view angle is set to nadir and the solar zenith angle is fixed through time but varies for each tile based on the latitude.

OLI and MSI equator crossing time are close: nominally 10:00AM and 10:30AM, respectively. Following findings of Zhang et al. (2016), a constant sun zenith angle (SZA) per location, named θ_s^{out}, was derived. The SZA follows a 6th degree polynomial as a function of the latitude. The polynomial was calibrated using Landsat-8 archive (Figure 2). A single θ_s^{out} value per tile is defined based on the tile central latitude and eq. 4 (where k_i values are given in Figure 2). Consequently, the output SZA for S30 and L30 products varies latitudinally for the tile center but is constant throughout the year for any given tile.

$$\theta_s^{out} = \sum_{i=0}^{6} k_i \times Lat^i \quad (4)$$



k_6	k_5	k_4	k_3	k_2	k_1	k_0
6.15e-11	-1.95e-09	-9.48e-07	2.4e-05	0.0119	-0.127	31

Figure 2: Sun zenith angle (SZA) and central latitude of all the scenes of the Landsat-8 archive. The line corresponds to the overall fit using a 6th degree polynomial.

4.5 Bandpass adjustment

The small differences between MSI and OLI equivalent spectral bands need to be adjusted. The OLI spectral bandpasses are used as reference, to which the MSI spectral bands are adjusted. The bandpass adjustment is a linear fit between equivalent spectral bands. The slope and offset coefficients were computed based on 500 hyperspectral spectra selected on 160 globally distributed Hyperion scenes processed to surface reflectance and used to synthesis MSI and OLI bands. MSI's RSRs correspond to the version v2.0. The spectral differences between MSI onboard Sentinel-2A (S2A) and Sentinel-2B (S2B) are accounted. Note that the S2A CA and Blue bands RSRs correspond to S2B RSRs. The coefficients are given in Table 5, and scatterplots are given in Figure 3 and Figure 4.

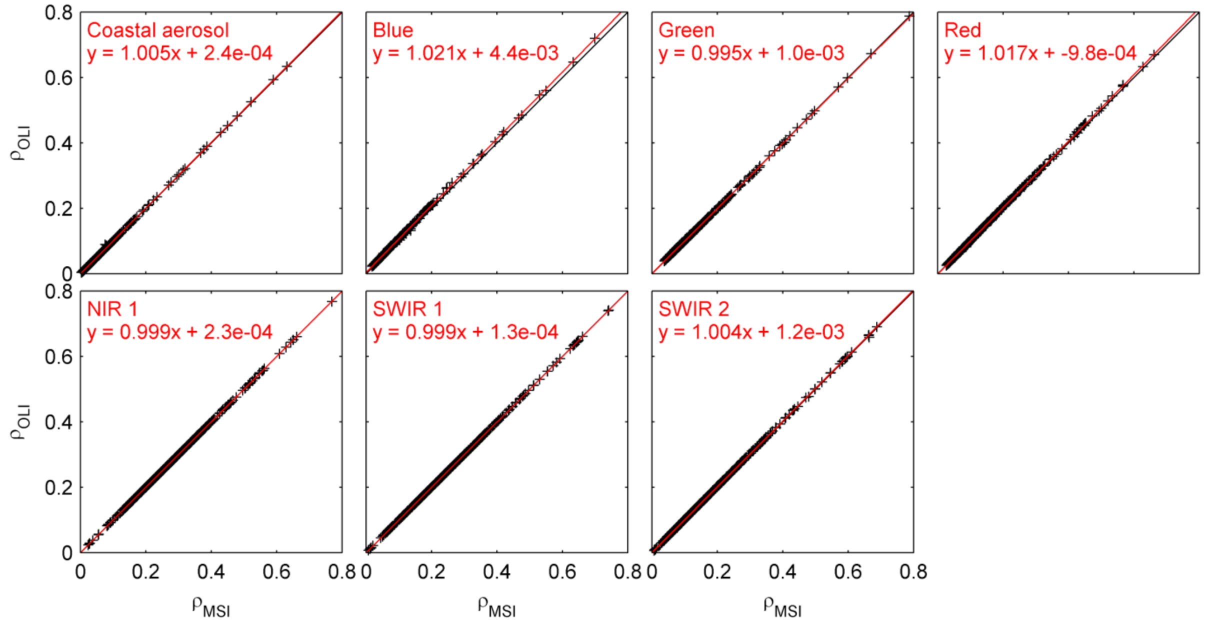


Figure 3: Sentinel-2A MSI vs OLI surface reflectance for the seven equivalent bands, using a synthetic dataset built with 500 surface reflectance spectra from Hyperion.

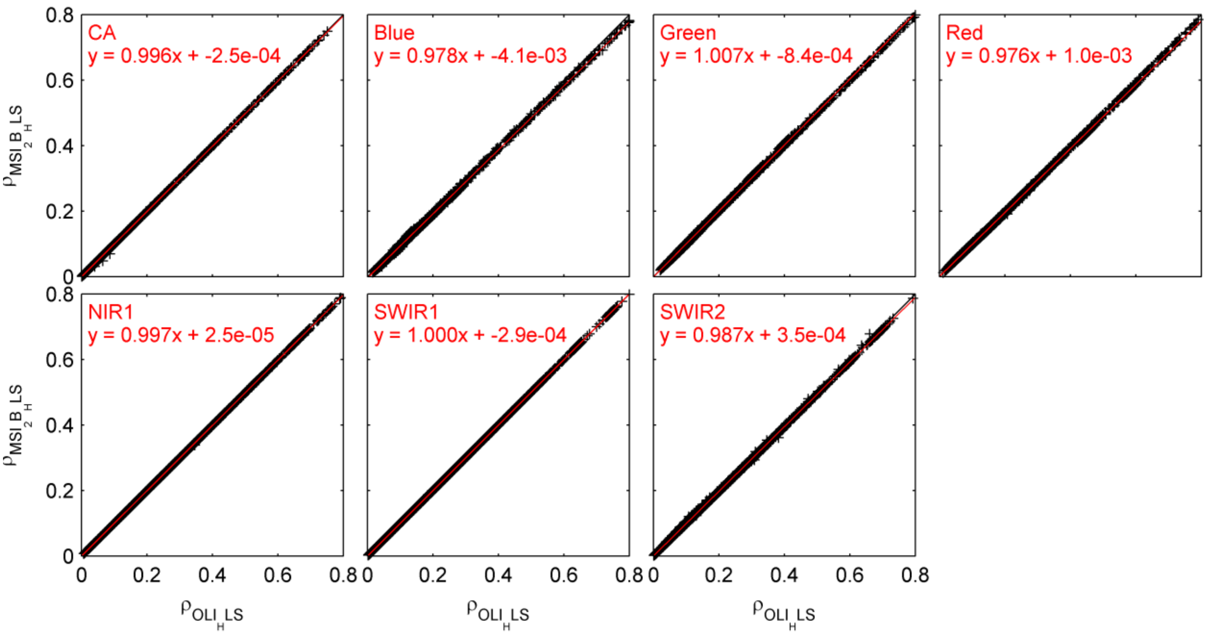


Figure 4: Same as Figure 3, but for Sentinel-2B.

$$\rho_{OLI} = a \times \rho_{MSI} + b \tag{5}$$

Table 5: Bandpass adjustment coefficients

			Sentinel-2A		Sentinel-2B	
HLS Band name	OLI band number	MSI band number	Slope (a)	Intercept (b)	Slope (a)	Intercept (b)
CA	1	1	0.9959	-0.0002	0.9959	-0.0002
BLUE	2	2	0.9778	-0.004	0.9778	-0.004
GREEN	3	3	1.0053	-0.0009	1.0075	-0.0008
RED	4	4	0.9765	0.0009	0.9761	0.001
NIR1	5	8A	0.9983	-0.0001	0.9966	0.000
SWIR1	6	11	0.9987	-0.0011	1.000	-0.0003
SWIR2	7	12	1.003	-0.0012	0.9867	0.0004

4.6 Spatial resampling

HLS products are resampled over the MGRS grid. Depending on the product, several resampling methods are utilized.

S10 - Sentinel-2 full resolution

S10 products are processed and delivered at full spatial resolution. No resampling is used.

S30 - Sentinel-2 at 30 m

The following resampling methods are used depending on the spatial resolution of the S10 data:

- S10 10 m bands are resampled to 30m using a boxcar method,
- S10 20 m bands are resampled to 30m using an area weighted average method,
- S10 60 m bands are resampled to 30m using a nearest neighbor method (i.e. split).

L30 - Landsat-8 gridded over the MGRS tiling system

Due to the spatial shift observed between Landsat-8 and Sentinel-2 data, AROP was used for registering L30 products to S30 products. The following resampling methods are used depending on the input L2A data (i.e. Landsat-8 surface reflectance in WRS grid):

- transform UTM coordinates of each pixel using AROP polynomial regression (eq. 1),
- If Landsat-8 and MGRS tile have a different UTM zone, transform Landsat-8 UTM coordinates of each pixel to MGRS tile UTM coordinates.
- Retrieve the gridded value in the MGRS grid using a cubic convolution method.

Note on the QA layer resampling

QA layers are created during the atmospheric correction processing, performed at 10 m over the MGRS grid for Sentinel-2 and at 30 m over the WRS path-row grid for Landsat. The resample of the QA is performed per information (i.e. for each bit). Depending on the product type, a different strategy is used:

- S10: A simple nearest neighbor method (i.e. split) from 20 m to 10 m is used.
- S30: 10 m QA are resampled to 30m using a boxcar method. S30 pixel bit value is set to 0 if only all the nine S10 pixels bit values are set to 0.
- L30: using a 2x2 window (i.e. 4 closest pixels), the L30 pixel bit value is set to 0 if only at least 3 pixels bit values are set to 0. If 2 or more pixel bit value is set to 1, the L30 pixel bit value is set to 1.

5 Selected regions

Following user requests, HLS v1.4 includes 120 regions (Figure 5), corresponding to a total of 4090 MGRS tiles. Table 6 and Figure 5 provide the list of regions and geographical distribution of tiles.

Table 6: List of regions and associated codes

Code	Region	Code	Region	Code	Region
ABI	Abisko	**GDG**	Guangdong	**PAL**	Palouse
ABO	ABoVE	**GDS**	Great Dismal Swamp	**PAM**	Pampas
ACR	ACRE	**GOD**	East and West Godavari	**PAY**	Paysandu
ALB	Albuera Dehesa	**GOI**	Goias	**PDB**	Pardubice
AUS	Styria	**GXI**	Guangxi	**POK**	Pokhara
BAH	Bahia	**HBB**	Hubbard Brook	**POT**	Potohar
BAI	Buenos Aires	**HE1**	Heilongjiang-1	**PPR**	Prarie Pothole Region
BAK	Bakersfield	**HE2**	Heilongjiang-2	**PUN**	Punjab
BAN	Bangalore	**HUL**	Hulunber	**RCO**	Rio Colorado
BAR	Bartlett	**HVF**	Harvard Forest	**REA**	Rosemount Agricultural Experiment Station
BDP	Budapest	**IND**	Odisha | West Bengal	**RRV**	Railroad Valley
BE	Belgium	**IOW**	Iowa LTAR	**RUS**	Russel Sage
BGD	Chittagong	**IRL**	Ireland	**SA**	South Africa
BIT	Bitterroot Valley	**ISF**	Iowa South Fork Watershed	**SAS**	South-East Asia
CAA	Caagazu	**ISP**	Ispra	**SC**	South Carolina
CAB	Cabauw	**ISR**	Israel	**SCR**	Santa Cruz
CAR	Caribbean	**KEN**	Kenya	**SEA**	South East Australia
CAU	Caucasus	**KS**	Kansas	**SED**	South East Dakota
CEN	Central Plains Experimental Range	**LAH**	Lahore	**SHA**	Shandong
CHK	Chatham-Kent	**LB4**	Lybia-4	**SKU**	Skukuza
COB	Cobecore	**LCW**	Least Chub Wetland	**SLT**	Sevilleta Long Term Ecological Research site
COL	Columbus	**LEB**	BekaaValley	**SOD**	Sodankyla
COW	Coweeta	**LET**	Lethbridge	**SOR**	Sorriso
CRA	Carpentras-La Craux	**MAR**	Marocco	**STA**	Staffordshire
CSI	Casselman Saint-Isidore	**MAU**	Maun	**THA**	Thailand
CSR	Campania Region Southern Italy	**MBO**	Monte Bondone	**TIF**	Tifton
CYP	Cyprus	**ME**	Maine	**TOR**	Toravere
CZE	Czech	**MEZ**	Mezaira	**TUC**	Tucuman
DAH	Dahra field site	**MMR**	Myanmar | Magway | Ayeyarwady | Bago | Yangon | Mandalay	**TZ**	Tanzania
DE	Germany	**MNE**	Mead NE	**UDR**	Upper Deschutes River

Code	Region	Code	Region	Code	Region
DEP	Delmarva Peninsula	**MON**	Mongu	**UIE**	U of Ill. Energy Farm
DON	Donana	**NA**	North_America	**UKR**	Ukraine
EVE	Everglades	**NEA**	North East Arkansas	**UMB**	U of Mich. Biological Station
FAJ	Fajemyr	**NID**	Nile Delta	**VAI**	Vaira Ranch
FAQ	Aquitaine	**NOR**	Norunda	**VMD**	Mekong
FCE	Centre	**NOS**	Norway Spruce	**VRR**	Red River
FR	France	**NWG**	Northwest Georgia	**WNU**	Gangneung_WNU
FTB	Fontainebleau	**NWI**	North Wisconsin	**YAK**	Yakutsk-Larch
FUJ	Fujian	**NWO**	North West Ohio	**YAQ**	YaquiValley
GBL	Gambella	**OSR**	Observatoire Spatial Regional	**YUM**	Yuma

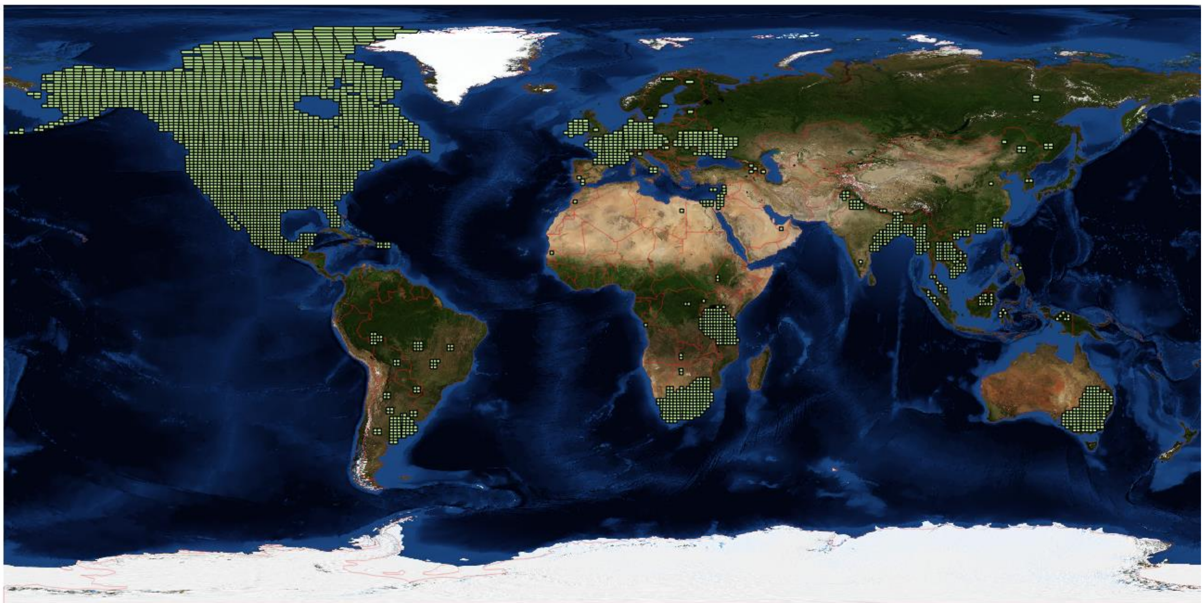


Figure 5: Distribution of 4090 MGRS tiles covered in HLS v1.4. Background image is NASA Blue Marble product

6 Products formats

6.1 Files format

HLS products are stored in the Hierarchical Data Format (HDF)-4 format, with internal compression. Each HDF file contains metadata including geoferencing information, as well as data sets on spectral band and QA band. Each HDF file is also accompanied by an ENVI ASCII text header file containing georeferencing information.

6.2 S10

The S10 product contains MSI surface reflectance at full spatial resolution. Table 7 lists all the Scientific Data Sets (SDS) of the S10 product.

Table 7: list of the SDS of the S10 product (SR = Surface Reflectance, TOA Refl. = Top-of-Atmosphere Reflectance)

SDS name	MSI band number	Units	Data type	Scale	Fill value	Spatial Resolution	Description
B01	1	reflectance	int16	0.0001	-1000	60	SR
B02	2	reflectance	int16	0.0001	-1000	10	SR
B03	3	reflectance	int16	0.0001	-1000	10	SR
B04	4	reflectance	int16	0.0001	-1000	10	SR
B05	5	reflectance	int16	0.0001	-1000	20	SR
B06	6	reflectance	int16	0.0001	-1000	20	SR
B07	7	reflectance	int16	0.0001	-1000	20	SR
B08	8	reflectance	int16	0.0001	-1000	20	SR
B8A	8A	reflectance	int16	0.0001	-1000	10	SR
B09	9	reflectance	int16	0.0001	-1000	60	TOA Refl.
B10	10	reflectance	int16	0.0001	-1000	60	TOA Refl.
B11	11	reflectance	int16	0.0001	-1000	20	SR
B12	12	reflectance	int16	0.0001	-1000	20	SR
QA (Table 10)	-	none	uint8	-	255	10	Quality bits

6.3 S30

The product S30 contains MSI surface reflectance at 30 m spatial resolution. Table 8 lists all the SDS of the S30 product.

Table 8: list of the SDS of the S30 product (SR = Surface Reflectance, NBAR = Nadir BRDF-Adjusted Reflectance, TOA Refl. = Top of Atmosphere Reflectance)

SDS name	MSI band number	Units	Data type	Scale	Fill value	Spatial Resolution	Description
B01	1	reflectance	int16	0.0001	-1000	30	SR
B02	2	reflectance	int16	0.0001	-1000	30	NBAR
B03	3	reflectance	int16	0.0001	-1000	30	
B04	4	reflectance	int16	0.0001	-1000	30	
B05	5	reflectance	int16	0.0001	-1000	30	SR
B06	6	reflectance	int16	0.0001	-1000	30	
B07	7	reflectance	int16	0.0001	-1000	30	
B08	8	reflectance	int16	0.0001	-1000	30	NBAR
B8A	8A	reflectance	int16	0.0001	-1000	30	
B09	9	reflectance	int16	0.0001	-1000	30	TOA Refl.
B10	10	reflectance	int16	0.0001	-1000	30	
B11	11	reflectance	int16	0.0001	-1000	30	NBAR
B12	12	reflectance	int16	0.0001	-1000	30	
QA (Table 10)	-	none	uint8	-	255	30	Quality bits

6.4 L30

The product L30 contains Landsat-8 OLI surface reflectance and TOA TIRS brightness temperature gridded at 30 m spatial resolution over the MGRS tiling system. Table 9 lists all the SDS of the L30 product.

Table 9: list of the SDS of the L30 product (SR = Surface Reflectance, NBAR = Nadir BRDF-normalized Reflectance, TOA Refl. = Top of Atmosphere Reflectance, TOA BT = Top of Atmosphere Brightness temperature)

SDS name	OLI band number	Units	Data type	Scale	Fill value	Spatial Resolution	Description
band01	1	reflectance	int16	0.0001	-1000	30	NBAR
band02	2	reflectance	int16	0.0001	-1000	30	
band03	3	reflectance	int16	0.0001	-1000	30	
band04	4	reflectance	int16	0.0001	-1000	30	
band05	5	reflectance	int16	0.0001	-1000	30	
band06	6	reflectance	int16	0.0001	-1000	30	
band07	7	reflectance	int16	0.0001	-1000	30	
band09	9	reflectance	int16	0.0001	-1000	30	TOA Refl.
band10	10	degree °C	int16	0.01	-1000	30	TOA BT
band11	11	degree °C	int16	0.01	-1000	30	
QA (Table 10)	-	none	uint8	-	255	30	Quality bits

6.5 Quality Assessment layer

Quality Assessment (QA) SDS of the 3 products follows the same bit structure described in Table 10.

Table 10: Description of the bits in the one-byte Quality Assessment layer for the 3 products. Bits are listed from the MSB (bit 7) to the LSB (bit 0)

Bit number	QA description	Bit combination	Description
7-6	Aerosol Quality	00	Climatology
		01	Low
		10	Average
		11	High
5	Water	1	Yes
		0	No
4	Snow/ice	1	Yes
		0	No
3	Cloud shadow	1	Yes
		0	No
2	Adjacent cloud	1	Yes
		0	No
1	Cloud	1	Yes
		0	No
0	Cirrus	1	Yes
		0	No

Note that due to the union of masks from multiple sources, values of bits 0-5 may not be mutually exclusive, i.e., two bits may both be set to 1 for the same pixel. See Appendix A on how to decode the QA bits with simple integer arithmetic.

Users are advised to mask out Cirrus, Cloud and Adjacent cloud pixels. Users requiring high quality land surface reflectance values with the lowest uncertainties should also mask out Aerosol Quality pixels with High impact, in addition to cloud and adjacent cloud pixels, recognizing that doing so will decrease the number of observations available for analysis. Users with less strict requirements and intending to provide additional post-processing steps, such as time-series filtering/fitting or incorporating quality information into higher-level algorithms, may use surface reflectance values identified as high aerosol and mark them as lower quality compared to other pixels.

6.6 Metadata dictionary

Metadata about the product are encapsulated in the HDF file. Those metadata can be extracted, for example through GDAL command `gdalinfo`, or HDF command `ncdump -h`. The metadata fields are:

- ACCODE: LaSRC version, e.g. LaSRCS2AV3.5.5 or LaSRCL8V3.5.5
- AngleBand: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 [for S10/S30]
- arop_ave_xshift(meters): Average X-shift in meter computed over the HLS tile [L30/S30]
- arop_ave_yshift(meters): Average Y-shift in meter computed over the HLS tile [L30/S30]
- arop_ncp: Number of control point found by AROP [L30/S30]
- arop_rmse(meters): RMSE of co-registration to the reference image
- arop_s2_refimg: S10 product name used as based image for AROP [L30/S30]
- cloud_coverage: cloud coverage per tile
- DATASTRIP_ID: Datastrip name in the SAFE file [S30/S10]
- DATA_TYPE: Landsat 8 Levele-1 product, e.g. L1GT [L30]
- HLS_PROCESSING_TIME: HLS Processing date and time [S30/S10/L30]
- HORIZONTAL_CS_CODE: Projection code in EPSG format, e.g. EPSG:32618 [S30/S10]
- HORIZONTAL_CS_NAME: Projection name, e.g. WGS84 / UTM zone 18N [S30/S10/L30]
- L1C_IMAGE_QUALITY: Sentinel-2 L1C product quality control, including the following quality controls: "SENSOR", "GEOMETRIC", "GENERAL", "FORMAT" and "RADIOMETRIC", related to the following value: "PASSED" or "FAILED". The "NONE" metadata value means all quality controls were set to PASSED [S30]
- L1_PROCESSING_TIME: Input Level-1 product processing date [S30/S10/L30]
- LANDSAT_PRODUCT_ID: Landsat-8 product ID name, e.g. LC08_L1GT_014033_20170103_20170218_01_T2 [L30]
- LANDSAT_SCENE_ID: Landsat-8 scene ID name, e.g. LC80140332017003LGN01 [L30]
- MEAN_SUN_AZIMUTH_ANGLE: Mean Sun Azimuth Angle in degree of the input data [S30/S10/L30]
- MEAN_SUN_ZENITH_ANGLE: Mean Sun Zenith Angle in degree of the input data [S30/S10/L30]
- MEAN_VIEW_AZIMUTH_ANGLE: Mean View Azimuth Angle in degree of the input data [S30/S10]
- MEAN_VIEW_ZENITH_ANGLE: Mean View Zenith Angle in degree of the input data [S30/S10]
- NBAR_Solar_Zenith: Mean Sun Zenith Angle in degree of the HLS product after BRDF-adjustment [S30/L30]
- NCOLS: Number of columns [S30/S10/L30]
- NROWS: Number of rows [S30/S10/L30]
- PROCESSING_BASELINE: processing baseline for Sentinel-2, e.g. 02.04 [S10/S30]
- PRODUCT_URI: Tile directory name in the SAFE (Sentinel Standard Archive Format for Europe) file [S30/S10]
- SENSING_TIME: Image sensing date/time, e.g. 2017-01-06T16:00:50.223Z [S30/S10/L30]
- SENSOR: Input Sensor [S10/L30]
- SPACECRAFT_NAME: remote sensing satellite, e.g. Sentinel-2A [S10/S30]
- spatial_coverage: Percentage of HLS tile with data [S30/S10]

– SPATIAL_RESOLUTION: HLS spatial resolution in meter [S30/S10/L30]
– TILE_ID: Sentinel-2 tile identifier, e.g. S2A_OPER_MSI_L1C_TL_MTI__20170106T205741_A008059_T18SUJ_N02.04 [S10/S30]
– TIRS_SSM_MODEL: TIRS SSM encoder position model (Preliminary, Final or Actual) see http://landsat.gsfc.nasa.gov/?p=12294 [L30]
– TIRS_SSM_POSITION_STATUS [L30]
– ULX: X-coordinate of the Upper-left corner of the Upper-left pixel [S30/S10/L30]
– ULY: Y-coordinate of the Upper-left corner of the Upper-left pixel [S30/S10/L30]
– USGS_SOFTWARE = "LPGS_2.6.2" ;

S10/S30 products have also bandpass adjustment coefficients:

– MSI band 01 bandpass adjustment slope and offset=0.995900, -0.000200
– MSI band 02 bandpass adjustment slope and offset=0.977800, -0.004000
– MSI band 03 bandpass adjustment slope and offset=1.005300, -0.000900
– MSI band 04 bandpass adjustment slope and offset=0.976500, 0.000900
– MSI band 11 bandpass adjustment slope and offset=0.998700, -0.001100
– MSI band 12 bandpass adjustment slope and offset=1.003000, -0.001200
– MSI band 8a bandpass adjustment slope and offset=0.998300, -0.000100

6.7 File naming

All the spectral measurements and QA data from a given sensor on a day for a tile are saved in a single HDF, named with the following naming convention:

HLS.<*HLS_Product*>.T<*Tile_ID*>.<*year*><doy>.v<*version_number*>.hdf

where:

– <*HLS_Product*> is the HLS product type (S10, S30 or L30) [3 symbols]
– <*Tile_ID*> is the MGRS Tile ID [5 digits]
– <*Year*> is the sensing time year [4 digits]
– <*Doy*> is the sensing time day of year [3 digits]
– <*Version_number*> is the HLS version number (e.g., 1.2, major and minor changes reflected in the first and second digits respectively) [3 digits]

For example:

– HLS.S30.T18SUJ.2017006.v1.4.hdf
– HLS.L30.T18SUJ.2017003.v1.4.hdf

6.8 Product access

The S30 and L30 files are available at https://hls.gsfc.nasa.gov/data/. The v1.4 data directory structure is slightly different from that of v1.3, as follows:

<*HLS_Product*>/<*year*>/<*Tile_subdir*>/

where

<*HLS_Product*> is the HLS product type (S30 or L30) [3 characters]

<*Year*> is the sensing time year [4 digits]

<*Tile_subdir*> is sub-directory path for an HLS Tile ID decomposed into 4 parts. For example, tile 11SPC corresponds to a sub-directory 11/S/P/C/; L30 data of 2018 for tile 11SPC are at https://hls.gsfc.nasa.gov/data/v1.4/L30/2018/11/S/P/C/

A Bash script is made available at the HLS website to help download the products for an environment where either the Linux command *wget* or *curl* is available. See Appendix B for the script usage.

S10 products are available upon request for special test cases.

7 Quality Control

An evaluation of the S30 and L30 products has been pursued. It follows the methodology of the cross-comparison of surface reflectance with MODIS Climate Modelling Grid (CMG) products (MOD09CMG) involving BRDF and spectral adjustment (Claverie et al. 2015). The results are gathered into HTML tables which show overall scores of the cross-comparison for each product, and individual QA graphics are linked in the table (Figure 6). For each tile and each site (Table 6), html tables and overall scatter plots are provided. True color Quick-look images are also produced for each L30 and S30 products at [60m spatial resolution](#) (Figure 7), highlighting the main QA layers: Water, snow, cloud, cirrus, and shadow. Links to the quick-look images are provided in the HTML tables.

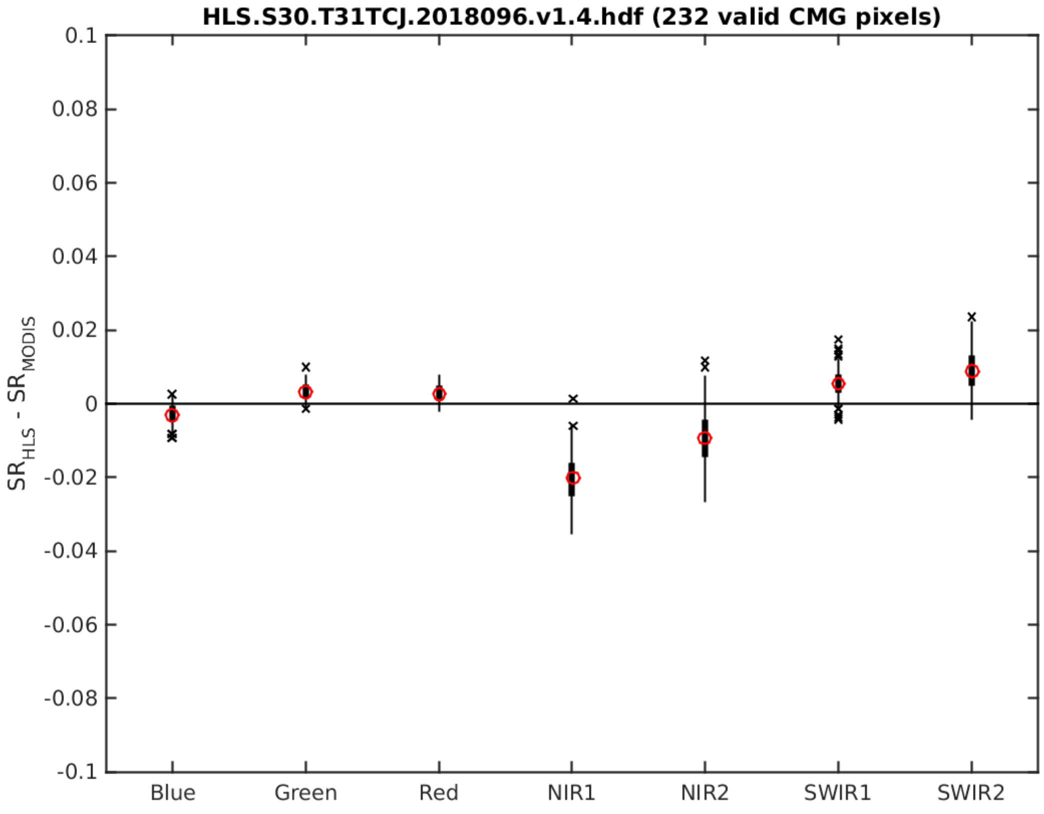


Figure 6: QA of a sample S30 product (HLS.S30.T31TCJ.2018096.v1.4.hdf). Boxplots show, for each spectral band, the deviation between HLS and MODIS surface reflectance. The median is displayed with the red circle, the bold line represents the 1st and 3rd quartiles, and the outliers are displayed with black crosses.

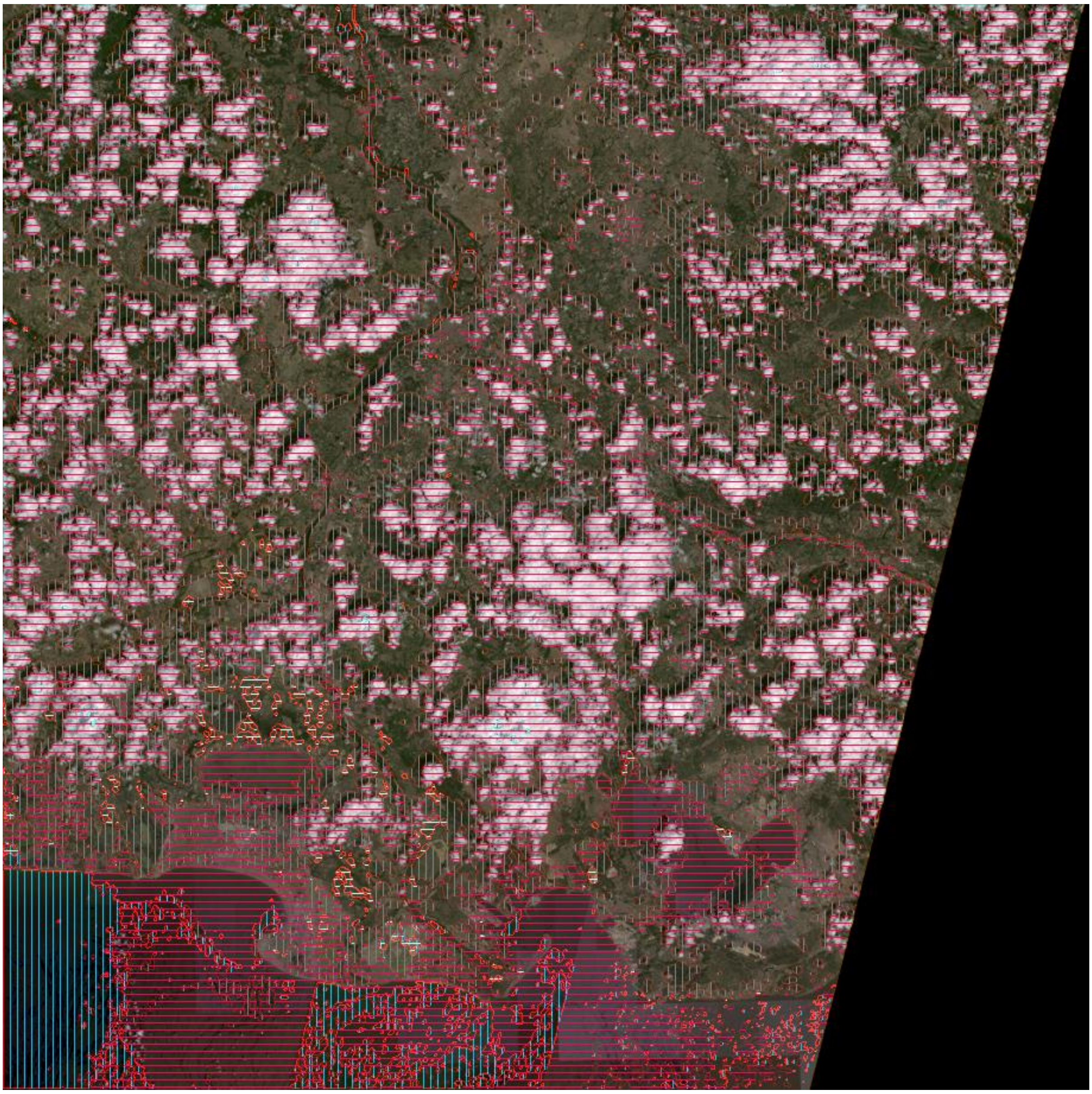


Figure 7: Quick-look of a sample S30 product, using Red, NIR and SWIR 1.6 spectral bands. Water bodies are delineated with blue lines, snow with yellow, cloud with red, cirrus clouds with magenta, and shadow with grey. Interiors of listed bodies are dashed.

Looking at the performance of downstream products that could be in turn be compared to independent "truth", can provide additional evidence of the performance of the HLS surface reflectance product. The Landsat and Sentinel 2 class of sensors by themselves could not derive albedo, which by definition necessitates the integration of several different viewing geometries. However, the albedo can be estimated using MODIS by the inversion of the BRDF (Schaaf et al., 2002). By combining MODIS BRDF information and Landsat data and spatially disaggregating the coarse resolution information, one can derive a reasonable estimate of a HLS spatial scale Broadband Albedo, as shown by several authors by comparison to flux tower measurements (Franch, B., et al., 2014a, Shuai, Y., et al., 2011). The Franch et al. (2014a) algorithm derives a Landsat surface albedo based on the BRDF parameters estimated from the MODIS CMG surface reflectance product (M{O,Y}D09) using the VJB method (Vermote et al., 2009;

Franch et al., 2014b). The algorithm uses a Landsat unsupervised classification to disaggregate the BRDF parameters to the HLS spatial resolution. The method of Franch et al. (2014a) is directly applied to the HLS product from 2013 to 2017 over five SURFRAD sites (i.e. Desert Rock, Table Mountain, Bondville, Goodwin Creek and Penn State University). The results are presented in Figure 8 showing separately the statistics for Landsat (red) and Sentinel 2 (blue). Figure 8 shows a good agreement of both Landsat and Sentinel 2 products with field measurements with similar correlation coefficients. The Landsat albedo shows slightly better statistics than the Sentinel 2 albedo with s difference in RMSE of 0.003 (on the order of 1%) and a slope nearer to one. However, given the statistical significance of the data analyzed and the lower number of Sentinel 2 data, both sensors show equivalent performance. These errors are equivalent to the errors showed in Franch et al. (2014a) for Landsat TM and ETM+ and in Vermote et al. (2016) for Landsat 8.

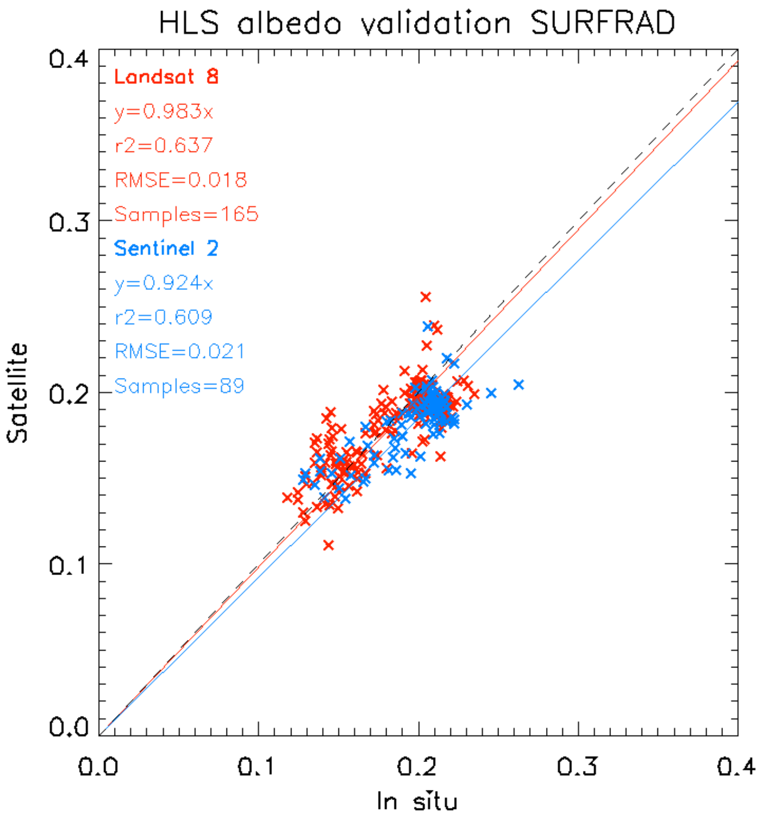


Figure 8: Validation of the HLS surface albedo using Franch et al. (2014a) method.

8 Known issues

- Fmask for Sentinel-2 can generate erroneous results, particularly for hazy conditions, thin clouds, cloud edges, and bright urban areas. Distinction between snow and cloud pixels can be inaccurate due to the lack of thermal data.
- The LaSRC cloud mask often confuses cloud with bright urban areas. Users are cautioned to examine other cloud masking options for urban areas.

References

Claverie, M., Vermote, E., Franch, B., & Masek, J. (2015). Evaluation of the Landsat-5 TM and Landsat-7 ETM + surface reflectance products. *Remote Sensing of Environment, 169,* 390-403.

Claverie, M., Ju, J., Masek, J.G., Dungan, J.L., Vermote, E.F., Roger, J.-C., Skakun, S.V., & Justice, C.O. (2018). The Harmonized Landsat and Sentinel-2 surface reflectance data set, in press, *Remote Sensing of Environment*.

Doxani, G., Vermote, E., Roger, J. C., Gascon, F., Adriaensen, S., Frantz, D., ... & Louis, J. (2018). Atmospheric correction inter-comparison exercise. *Remote Sensing*, *10*(2), 352.

ESA (2018). Sentinel-2 Data Quality Report S2-PDGS-MPC-DQR.

Franch, B., Vermote, E.F., Claverie, M., (2014a). Intercomparison of Landsat albedo retrieval techniques and evaluation against in situ measurements across the US SURFRAD network. *Remote Sensing of Environment*, 152, 627-637.

Franch, B., Vermote, E. F., Sobrino, J. A., & Julien, Y. (2014b). Retrieval of surface albedo on a daily basis: Application to MODIS data. *IEEE Transactions on Geoscience and Remote Sensing*, 52(12), 7549-7558.

Gao, F., Masek, J.G., & Wolfe, R.E. (2009). Automated registration and orthorectification package for Landsat and Landsat-like data processing. *Journal of Applied Remote Sensing, 3(1),* 033515.

Masek, J. G., Vermote, E. F., Saleous, N. E., Wolfe, R., Hall, F. G., Huemmrich, K. F., ... & Lim, T. K. (2006). A Landsat surface reflectance dataset for North America, 1990-2000. *IEEE Geoscience and Remote Sensing Letters*, *3*(1), 68-72.

Roy, D. P., Li, J., Zhang, H. K., Yan, L., Huang, H., & Li, Z. (2017). Examination of Sentinel-2A multi-spectral instrument (MSI) reflectance anisotropy and the suitability of a general method to normalize MSI reflectance to nadir BRDF adjusted reflectance. *Remote Sensing of Environment*, *199*, 25-38.

Roy, D.P., Zhang, H.K., Ju, J., Gomez-Dans, J.L., Lewis, P.E., Schaaf, C.B., Sun, Q., Li, J., Huang, H., & Kovalskyy, V. (2016). A general method to normalize Landsat reflectance data to nadir BRDF adjusted reflectance. *Remote Sensing of Environment, 176*, 255-271.

Schaaf, C. B., Gao, F., Strahler, A. H., Lucht, W., Li, X., Tsang, T., ... & Lewis, P. (2002). First operational BRDF, albedo nadir reflectance products from MODIS. *Remote Sensing of Environment*, *83*(1-2), 135-148.

Shuai, Y., Masek, J. G., Gao, F., & Schaaf, C. B. (2011). An algorithm for the retrieval of 30-m snow-free albedo from Landsat surface reflectance and MODIS BRDF. *Remote Sensing of Environment*, *115*(9), 2204-2216.

Skakun, S., Roger, J. C., Vermote, E. F., Masek, J. G., & Justice, C. O. (2017). Automatic sub-pixel co-registration of Landsat-8 Operational Land Imager and Sentinel-2A Multi-Spectral Instrument images using phase correlation and machine learning based mapping. *International Journal of Digital Earth*, *10*(12), 1253-1269.

Storey, J., Choate, M., & Lee, K. (2014). Landsat 8 Operational Land Imager On-Orbit Geometric Calibration and Performance. *Remote Sensing, 6*, 11127-11152

Storey, J., Roy, D. P., Masek, J., Gascon, F., Dwyer, J., & Choate, M. (2016). A note on the temporary misregistration of Landsat-8 Operational Land Imager (OLI) and Sentinel-2 Multi Spectral Instrument (MSI) imagery. *Remote Sensing of Environment*, *186*, 121-122.

Strahler, A.H., Lucht, W., Schaaf, C.B., Tsang, T., Gao, F., Li, X., Lewis, P., & Barnsley, M. (1999). MODIS BRDF/Albedo Product: Algorithm Theoretical Basis Document Version 5.0. In M. documentation (Ed.). Boston.

Vermote, E., Justice, C. O., & Bréon, F. M. (2009). Towards a generalized approach for correction of the BRDF effect in MODIS directional reflectances. *IEEE Transactions on Geoscience and Remote Sensing*, *47*(3), 898-908.

Vermote, E., Justice, C., Claverie, M., & Franch, B. (2016). Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. *Remote Sensing of Environment*, *185*, 46-56.

Vermote, E. F., & Kotchenova, S. (2008). Atmospheric correction for the monitoring of land surfaces. *Journal of Geophysical Research: Atmospheres*, *113*(D23).

Yan, L., Roy, D. P., Li, Z., Zhang, H. K., & Huang, H. (2018). Sentinel-2A multi-temporal misregistration characterization and an orbit-based sub-pixel registration methodology. *Remote Sensing of Environment*, *215*, 495-506.

Zhang, H.K., Roy, D.P., & Kovalskyy, V. (2016). Optimal Solar Geometry Definition for Global Long-Term Landsat Time-Series Bidirectional Reflectance Normalization. *IEEE Transactions on Geoscience and Remote Sensing*, *54*, 1410-1418.

Zhu, Z., Wang, S., & Woodcock, C.E. (2015). Improvement and expansion of the Fmask algorithm: cloud, cloud shadow, and snow detection for Landsats 4-7, 8, and Sentinel 2 images. *Remote Sensing of Environment*, *159*, 269-277.

Acknowledgment

We thank Feng Gao for providing and spending many hours adapting the AROP code for HLS with quick turnaround. We also thank Jan Dempewolf for offering his Python script which works around the GDAL-incompatible issue in HLS v1.3 and it has proved very useful for many people. We also thank Shuang Li, Min Feng, and Mark Broich for GDAL-test HLS v1.4.

Appendix A. How to decode the bit-packed QA

Quality Assessment (QA) encoded at the bit level provides concise presentation but is less convenient for users new to this format. This appendix shows how to decode the QA bits with simple integer arithmetic and no explicit bit operation at all. An analogy in the decimal system illustrates the idea. Suppose we want to get the digit of the hundreds place of an integer 3215. First divide the integer by 10^2 (i.e. 100) to get an integer quotient 32, then the digit of the ones place (the least significant digit) of the quotient is what we want. By computing 32 – ((32 / 10) * 10), we get 2, the digit in the hundreds place of 3215. (Note that in integer arithmetic 32/10 evaluates to 3.) The same idea applies to binary integers. Suppose we get a decimal QA value 100, which translates into binary 01100100, indicating that the aerosol level is low (bits 6-7), it is water (bit 5), and adjacent to cloud (bit 2). Suppose we want to find whether it is water, by examining the value of bit 5. It can be achieved in two steps:

- Divide 100 by 2^5 to get the quotient, 3 in this case for integer arithmetic
- Find the value of the least significant bit of the quotient by computing 3 – ((3/2) * 2), which is 1

The pixel is water based on the QA byte. Note that Step 2 above is essentially an odd/even number test. All the bits can be decoded with a loop.

Appendix B. A Bash script to download HLS data

A Bash script available at the HLS home page can be used to download the HLS data in a Bash shell environment which has either the *wget* or the *curl* command. The script can download for a single tile ID, or multiple tile IDs given in a text file, for all the years or a given year. Download the script and make it executable. The script works in three ways.

```
$  ~/bin/download.hls.sh  -t 11SPC   /tmp/mydata/
```

This downloads all the years of L30 and S30 data for tile 11SPC into /tmp/mydata/, saved as

```
/tmp/mydata/11SPC/2013/L30/*hdf

/tmp/mydata/11SPC/2014/L30/*hdf

…

/tmp/mydata/11SPC/2015/S30/*hdf

…
```

```
$   ~/bin/download.hls.sh  -t 11SPC -y 2017  /tmp/mydata/
```

This downloads L30 and S30 for year 2017 only.

```
$   ~/bin/download.hls.sh  -t mytiles  -y 2017  /tmp/mydata/
```

In this example a text file named *mytiles* is given to specify multiple 5-character tile IDs delimited by white space characters (space, tab, or newline). Without the -y option, data of all years will be downloaded for all the specified tiles.

The script downloads data incrementally. If an earlier downloading process has been interrupted, the invocation of the same command skips the already downloaded files and continues with the new files. This also applied to daily routine download (e.g. a cron job).