Moderate Resolution Sensor Interoperability Framework

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Moderate Resolution Sensor Interoperability Framework Initiative

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Introduction

This initiative addresses the Committee on Earth Observation Satellites (CEOS) strategic objective to support complementarity and compatibility among the increasing number of Earth observing systems in the moderate (10-100m) resolution class for optical and SAR sensors and the data received from them.

This framework paper for moderate (10-100m) resolution interoperability identifies data production and use issues that need to be considered for the successful implementation of multi-sensor interoperable time series.

The scope of the initiative is restricted to moderate (10-100m) resolution sensors designed for global monitoring of land and associated water features. However, CEOS agencies should feel free to explore other sensor interoperability combinations including other resolutions, and non-land related applications using the framework.

The initial focus is on optical sensors with an emphasis on surface reflectance products, but the framework will accommodate inclusion of SAR and higher-level products. Case studies exploring data production alternatives and a wide range of use cases are crucial to the success of the initiative. Lessons learned and good practices will be captured in appendices to this document, referenced papers and revisions of this document.

The goal of interoperability is to enable the use of complementary sensors to achieve a coherent single data stream to enable characterization of change on the Earth's surface through time.

As products, including high-level products, covering long time periods are developed, the integration of these products requires verification and validation of their interoperability, such as: *when can these products be compared, when can't they be compared and under what conditions?* Sources of variability of data through time is confounded by geolocation accuracies, spatial resolution, radiometric and spectral differences as well as atmospheric effects and natural variability of the surface features and instrument differences. This interoperability initiative is an attempt to identify sources of variability that scientists and land managers should consider when comparing multi sensor products through time, to enable the coherent use of multi-sensor data streams and increasing the richness, density and depth of the image time series. Interoperable metadata are critical for data discovery and access, and for the maintenance and updating of image databases, such as dense multi-sensor time series stored in data cubes.

There are three underlying requirements for achieving multi-sensor interoperability.

The first requirement is to provide methodologies to determine the uncertainties for input and combined products with an initial focus on optical surface reflectance products, but including SAR and higher-level products, such as classed products. The intent is to understand the uncertainties at each step of production, for example allocating uncertainty to at-sensor products, atmospheric corrections, illumination and view angle corrections, band difference corrections and classification, as appropriate. Case studies can demonstrate the methodologies for creating multi-sensor data streams.

The second requirement is to determine the acceptable uncertainties for specific applications as identified by the user community. The use cases will provide lessons learned for estimating uncertainties for thematic applications and methodologies.

The third requirement is to establish interoperable per-scene and per-pixel metadata for use in data discovery and as analytical filters. Metadata can be used to identify available scenes, quality of the data and to determine data gaps where clear pixels are not available.

The long-term MRI outcomes are to provide

1) **recommendations to data producers for product evolution to meet interoperability requirements, and**
2) **good practices and guidance for the user community adapting and using multiple sensors products within single data streams.**

The MRI framework is organized into four components: general metadata, per-pixel metadata, data measurements and geolocation. Within each of these components are a set of interoperability concepts for which alternative solutions are identified, threshold verifications are discussed and target next steps are proposed. The framework is a living document and interoperability tool that will evolve as products evolve and as use cases are implemented. We seek feedback from both data producers and data users to establish and expand on these concepts, alternates, thresholds and targets. The MRI document needs to continue to evolve. The producer and user communities are in a period of rapid change as dense time series of 10-100 meter analysis ready data become increasingly easy to access.

We encourage close cooperation among space agencies toward the development of well documented and validated compatible methodologies and products to enable interoperability allowing access, where possible to free-and-open methodologies and inputs. By understanding and describing the challenges of interoperability, the goal is to support CEOS agencies on the development of products and to guide the user community in the use of the products within multi-sensor environments.

Background

The Future Data Architectures (FDA) CEOS Chair initiative and the CEOS Analysis Ready Data for Land (CARD4L) LSI-VC activity complement the objectives of this initiative. The Group on Earth Observations (GEO) the Global Forest Observation Initiative (GFOI) and GEO Global Agricultural Monitoring (GEOGLAM) activities can provide user feedback on acceptable application-specific requirements.

"CEOS Analysis Ready Data for Land (CARD4L) are satellite data that have been processed to a minimum set of requirements and organized into a form that allows immediate analysis with a minimum of additional user effort and interoperability both through time and with other datasets [1]."

Future Data Architectures seeks for Earth observation data to bridge the gap between data, application and user. *"The data management and analysis challenges arising from the explosion in free and open data volumes can be overcome with the high-performance ICT infrastructure, technologies and architectures now available. These solutions have great potential to streamline data distribution and management for providers while simultaneously lowering the technical barriers for users to exploit the data to its full potential."[2]*

The Working Group on Calibration Validation (WGCV) and the Working Group on Information

Systems & Services (WGISS) are foundational to this initiative. The core expertise and coordination of these interoperability activities reside at this level for science data and metadata interoperability respectively. MRI is an LSI-VC activity with access to CEOS agency development and science teams and to team members who represent the requirements of GFOI, GEOGLAM and other thematic user communities.

The MRI team includes members associated with LSI-VC, WGCV, WGISS, GFOI, GEOGLAM, FDA and CARD4L representing space agencies and user communities. Relationships are needed between the MRI Initiative, and R&D and capacity building teams to understand and communicate the benefits and challenges of multi-sensor interoperability for the user communities.

The framework will identify data and metadata characteristics for data products that may affect multi-sensor applications. Table 1 provides a high-level summary of many CEOS agency 10-100 meter data sources [3].

Table 1: 10-100 Meter Resolution Sensor Characteristics Summarized [4]

	Platform	Instrument	Radiometry	Pixel size	FOV	Life	References
Optical	Landsat	MSS	Visible, NIR	79 m	15°	1972-2008	[5-7]
		TM, ETM+	Visible, NIR, SWIR, Thermal	30 m	15°	1982	[8, 9]
		OLI/TIRS	Visible, NIR, SWIR, Cirrus, Thermal	30m	15°	2013	[10]
	Sentinel 2	MSI	Visible, NIR, SWIR, Cirrus	10/20/60 m	21°	2015	
	Terra	ASTER	Visible, NIR, SWIR, Thermal	15/30/90m		1999	[11]
	SPOT	HRV	Visible, NIR	20m			[12, 13]
		HRVIR, HRG	Visible, NIR, SWIR	10/20m			
	CBERS	MUX, WFI, IRS	Visible, SWIR, NIR, Thermal	20/40/64/80m			[14]
	ResourceSat	AWIFS, LISS-III	Visible, NIR, SWIR	56/23.5m	50°/15°		[15]
	EO-1	Hyperion	Visible, NIR, SWIR				[16, 17]
SAR	Sentinel 1	C-band				2016	
	Radarsat 2	C-band					
	JERS-1	L-band	HH polarization	25m		1993-1998	[18]
	ALOS-1/2	L-band	HH+HV	25m		2007	[18]
	TerraSAR-X TanDEM-X	X-band					

The case studies will quantify the uncertainties associated with the multi-sensor data sets used in the case study applications. Knowledge of the uncertainties for each sensor can be used within future data architectures and analysis ready data definitions to promote uptake of new methodologies and technologies. Lessons learned can guide the use of products by users, product development by agencies, and lead to new case studies to further refine uncertainties needed to support the interoperability of products.

The case studies will document, publish, and communicate to the community the objectives and intended uses of the interoperable products. The initial case study will involve documenting and advancing current Landsat-Sentinel-2 interoperability. Future case studies will evolve, if the decision is to continue the initiative.

Framework

This living multi-sensor interoperability framework document will evolve as products, technology and user applications evolve. Some sensors are very similar and more easily made interoperable. However, some sensors have significant differences, and the differences between these sensors must be identified and cross-calibration factors be produced to enable the datasets to be used together. Interoperability solutions may include one or both of two common paths:

1) Changes to operational products or post processing methodologies to create interoperable products
2) Accommodation to inherent differences between products

Changes to products include radiometric cross calibration to standard references, and acceptance of compatible geographic reference grid, DEMs, BRDF models, and atmospheric models. Where appropriate the same models and references can be adopted, otherwise differences between the references and methodologies need to be quantified and documented. These changes are considered **harmonization**.

Accommodations to inherent differences include pixel size, field of view, different spectral response curves, view and solar angle variations, and available bands. Accommodation may include resampling and scaling products to provide a comparable merged product or robust and flexible application methodologies designed to accommodate the differences. Many of the new trending methodologies, such as Continuous Change Detection and Classification (CCDC), take advantage of the increased temporal density to implement robust outlier logic [19-27]. Accommodation has the best results if all possible attempts are made to harmonize the products as early as possible in the product production flow to take advantage of space agency expertise, and to focus user expertise requirements on applications rather than data pre-processing. Modification of the products to create a consistent time series product is considered **homogenization**.

The CARD4L product family specifications strive toward creating products that meet the criteria for single sensor intra-product analysis to minimize the specialized knowledge needed to preprocess the data prior to multi-sensor analysis. If two products are sufficiently similar, for example, possessing similar pixel size and spectral bands, then they can be used interoperably for many applications. Otherwise, steps are needed to harmonize and homogenize the products to make them interoperable. These homogenization steps may be application specific. Both harmonization and homogenization are independent of implementation. The implementation may include the creation of discrete products or may be virtual implementation within a model. Key to success is knowledge of the uncertainty of the individual source products, combined data streams and user requirements.

The four components underlying the MRI framework and the CARD4L specifications are 1) general metadata, 2) per-pixel metadata, 3) measurements, and 4) geolocation. Table 2 summarizes consequences associated with moderate resolution sensor interoperability items. These MRI items will be discussed in further detail in the component sections that follow as will current threshold requirements and future targets for improvement plus some initial recommendations.

Table 2: MRI Item Summary with Interoperability Consequences.

Component	Items	Consequences
General Metadata	Coordinate Reference System	Different pixel sizes, origins and projections require the data be spatially resampled. Larger differences will cause larger changes in radiometry.
	Reference grid accuracy	Different and less accurate reference grids will cause greater uncertainty in spatial alignment of pixels.
	Geometric accuracy and temporal consistency	Absolute spatial RMSE distributions and temporal spatial consistency for each sensor are needed to establish the joint distribution for multi-sensor time series.
	Spectral bands	Different bands between sensors require methodologies that can adapt to band availability.
	Spectral response curves	Different spectral response curves may exist for similar bands between sensors causing land surface dependent variability.
	Radiometric Accuracy	Biases and uncertainty need to be minimized between sensors using spectrally uniform references and opportunities for simultaneous imaging.
	Revisit time & lifetime	Multi-sensor data sets can increase the length of the time series and increase the density of the time series
	Field of View	The greater the swath width or Field of View the more importance needs to be placed on illumination and viewing geometry and on the DEM used.
	Mean Local Time	Different mean local times between sensors and over the lifetime of a sensor will be reflected in the reflectance values
Per-Pixel Metadata	Clouds	Verified and validated cloud masks are needed to estimate radiometric contamination for specific and known cloud characteristics.
	Cloud Shadow	Verified and validated cloud shadow masks are needed to estimate radiometric contamination for specific and known cloud characteristics.
	Land/water mask	Land and water masks provide useful information for other radiometric corrections.
	Snow & Ice masks	Snow/ice mask assists in pixel filters and illumination and viewing geometry corrections. Known confusion, such as with clouds, need to be documented.
	DEM	The required accuracy of the DEM is dependent upon the corrections implemented, swath width and pixel size.
	Terrain Shadow mask	Terrain shadow masks are needed to estimate radiometric contamination associated with shadows. Known confusion such as with water and cloud shadow needs to be quantified.
	Illumination and Viewing geometry	Solar illumination angles are needed for reflectance calculations. Solar and View angles are needed for BRDF related corrections.
	Data Quality	No data, saturated, contaminated, terrain occlusion pixels need to be identified.
Data Measurements	Measurements	Absolute calibrated measurement units with or without corrections below
	Measurement normalization	Radiometry viewed through time is significantly impacted by variation in solar and viewing angles
	Aerosol, water vapor and Ozone corrections	Different atmospheric models can introduce significant between sensor variability.
	SBAF corrections	Different spectral response curves will introduce differences between products.

Component	Items	Consequences
Geolocation	Geometric Corrections	Residual misregistration between images introduces variability in the radiometry measurements
	Resampling	The number and type of spatial resampling will impact the radiometric signal

Each of these components is discussed in more detail in the following sections. The concepts and alternatives will be explored along with specific thresholds and next steps toward meeting targets to further improve interoperability. General and per-pixel metadata typically serve as input to radiometric and geometric methodologies.

The results of the MRI initiative will support the CARD4L description document [1]. CARD4L identifies information needed for a product to be considered Analysis Ready Data [28] for the user community. The CARD4L Product Family Specifications define threshold and target information needed to provide a minimal Analysis Ready Data product [29-31]. Thresholds identify minimum current and verifiable product requirements. Targets identify a product evolutionary path – how can agencies continue to improve products.

The threshold information is either now in use in operational products or is known and documented within the community. Products that meet all CARD4L threshold requirements are considered analysis-ready for scientific analysis or decision-making.

Products that meet CARD4L target requirements further reduce the overall product uncertainties, increase accuracy and enhance broad-scale applications requiring interoperable products. The target information is often under development and not widely implemented in operational products. The target requirements anticipate continuous improvement of methods and evolution of community expectations which are both normal and inevitable in a developing field. Over time, *target* specifications may (and subject to due process) become accepted as *threshold* requirements.

Below are MRI specific thresholds and targets addressing concerns and recommendations for achieving multi-sensor interoperability. The MRI team comprised of WGCV, WGISS and other agency experts can, through the MRI framework and case studies, assist in the identification, explanation and justification of CARD4L targets and thresholds through the consideration of MRI requirements. Closing the discussion for each framework item below are recommendations and notes (*in italic*) for consideration of users and producers of multi-sensor data sets.

General Metadata

General metadata is provided at the product or scene level. Product level metadata should, as a minimum, be documented in user guides and published literature. Scene-level metadata should be available in a machine-readable format, since this information is needed to filter specific scenes for inclusion in analysis. The general metadata table below identifies MRI thresholds and targets (Table 3).

The overall threshold objective for general metadata is to bundle machine readable metadata with the product, while the target objective for general metadata is the adoption of the either the OGC metadata standard or the ISO 19115-2 standard for Geographic information – Metadata – Part 2: Extensions for imagery and gridded data. The threshold objective of machine readable metadata is met by most products.

Table 3: General Metadata

Items	Threshold Verification	Target, Next steps
Coordinate Reference System	Document pixel sizes, origins and map projections in machine readable format.	Document in standardized metadata format. When practical establish common origins and map projections.
Reference grid accuracy	Document absolute accuracy of reference data. Reference grid uncertainty contribution to geometric accuracy should be minimized.	Document relationships among reference databases in operational use. Share reference databases when possible. Adopt common accuracy metric.
Geometric accuracy	Document uncertainty of each individual product and the methodologies used.	Document in standardized metadata format. Total uncertainty when combined with reference grid uncertainty should be on the order of 1/3 pixel. Adopt common accuracy metric.
Spectral bands	Document available bands in machine readable metadata	Document in standardized metadata format. Quantify benefits provided by additional bands.
Spectral response curves	Document spectral response curves in public literature	Document spectral response curves in standardized metadata and in CEOS MIM database
Radiometric Accuracy	Document biases and uncertainty in public literature. Acceptable accuracy is application specific.	Document total error budget and temporal consistency for product families in metadata. Continue to improve product accuracy and to understand application requirements.
Revisit time & lifetime	Document revisit time and active lifetime in public literature. Interoperability goal to achieve 7-day cloud free revisit time.	Identify critical time periods and regions. Encourage access to historical archives. Extend interoperable time series globally to the beginning of the Landsat MSS period (1972) or earlier.
Field of View	Document Field of View. High level products need to account for different viewing geometries	Quantify radiometric uncertainty associated with off-nadir viewing angles.
Mean Local Time	Document Mean Solar Time. High level products need to account for different solar geometries.	Quantify uncertainty associated with different solar geometries between missions and through the life of the mission

Coordinate Reference System

Coordinate reference systems are defined for product families. This information should be stored with products and in the CEOS MIM database [4]. Convergence by data production agencies toward a common nested tile system would reduce the need to resample data. It is understood that national requirements may dictate map projections, and cost, performance and latency requirements limit on-demand selection of map projection. The OGC Discrete Global Grid Systems should be investigated as an alternative for common reference grids [32].

Users creating interoperable products need to reproject to either the smaller or larger pixel size, depending upon application requirements and common origin and projection, either through creating a resampled copy of the data or on the fly. The consequences of reprojection/resampling need to be understood.

Reference Grid Accuracy

The absolute geometric accuracy can be no better than the accuracy of the reference database [33-37]. If different reference databases are used, the uncertainty of the reference databases must be added to the geometric accuracy to estimate the geometric accuracy of the multi-sensor data set. Data producers need to coordinate to minimize differences between reference grids.

For example, the reference grid accuracy for Global Land Survey reference used for all Landsat 1-8 product is 17m CE95 and Global Reference Image (GRI), which is under construction in 2017 is 9.5 CE95 [37]. The quality of the GLS reference grid is highly variable with maximum offsets of over 36m.

Date producers need to minimize the absolute error of individual reference grids. When possible reference grids should be shared across sensors.

Geometric Accuracy

Documentation of the geometric accuracy of each image permits selection of the images to meet an accuracy threshold for specific applications [38-40]. Estimates of geometric accuracy permit the identification of images that may not be stackable without further registration. Estimates of per image geometric accuracy are only available for images that are precision registered to a reference grid. Otherwise accuracy estimates are based on systematic models and are not tied to ground references. Newer sensors have much improved ephemeral location data acquired with the images that permit accurate systematic models comparable to precision models.

For example, the geometric accuracy for Landsat OLI is 14m CE95 in relationship to the GLS reference grid. This accuracy estimate is relevant for image to image stacking of Landsat data using the GLS reference grid. For Sentinel-2 the relative accuracy is 10 m 2σ. Predicted Landsat 8 to Sentinel-2 uncertainty is 26m 2σ. Once the Sentinel-2 GRI and Landsat the registration accuracy on the order of 10m 2σ is anticipated.

Data producers need to reduce RMSE to the theoretical minimum per sensor in relation to reference grid.

Spectral Bands

Sensors have different available bands. In some multi-sensor scenarios, unique bands, such as the aerosol, cirrus, red edge and thermal bands, will exist in addition to the core common bands such as VNIR, NIR and SWIR bands. Merged data sets may include unique bands for some sensors or not depending on individual application requirements. Interoperability should never justify the exclusion of information that can improve an application result. However, the application methodology needs to accommodate the differences.

The bands available for analysis will differ among sensors. Users creating interoperable products should, when possible, provide the user community the richest set of alternatives, even when it creates a discontinuity in the time series record for some bands.

Spectral Response Curves

Specific sensor bands, albeit nominally similar, will have unique spectral response curves. The differences between spectral responses may cause significant variability within time series. These differences may be exacerbated in derived products that use ratios such as the Normalized Difference Vegetation Index [41, 42].

Spectral Response Curves should be stored in the CEOS MIM database [4]. Spectral Band Adjustment Factors (SBAF), discussed below in the radiometry subsection, can be used with caution to accommodate spectral response differences.

Radiometric Accuracy

The within-sensor calibration and multi-sensor cross-calibration of at-sensor data using geometric, instrumented and pseudo invariant calibration sites is fundamental to the production of radiometrically and geometrically accurate products. At-sensor uncertainty is a known component of the total error budget of higher level products. The relative accuracy is critical for interoperability. For example, the radiometric differences between Landsat 8 and Sentinel 2 are approximately 2% [43]. Understanding the contribution of atmospheric and bidirectional reflectance corrections to product uncertainty are important to establishing the total uncertainty as high-level products, such as surface reflectance, are more frequently used within user applications.

Data producers coordinate cross calibration of at-sensor products using uniform reference surfaces to minimize overall biases between sensors.

Revisit Time & Lifetime

The rationale for multi-sensor interoperability is to extend the length and density of time series datasets. Longer time series permit the establishment of earlier baselines and the identification of periodic changes. The harnessing of as much data as possible from multiple complementary sensors enables a richer set of data to be used and additionally fill in gaps left by cloud and other data issues allowing denser time series [44]. Denser time series allows the study of changes that may be related to phenology, erosion and other Earth processes allowing a better understanding of natural and anthropogenic impacts.

The creation of multi-sensor time series extends time series and increases the temporal density at the cost of increased variability in the resulting time series.

Multi-sensor time series can consist of streams of measurement data, such as reflectance, or intervals of higher level products, such as classed data. User can select sensors and products as appropriate to meet their analysis goals. Examples include the interoperable use of classed data derived from SAR and optical sensors.

Field of View

A wider swath width reduces the revisit time given that other orbital parameters are the same. However, the greater the swath width, the more importance needs to be placed on illumination and viewing geometry and on the DEM used for corrections. Pixel size is a function of field of view. Off-nadir pixels are inherently larger than nadir pixels. This difference is accommodated in product production, but can result in radiometry variability.

Field of View corrections need to also accommodate point-able sensors, such as ASTER and SPOT, that acquire operational data while pointing off-nadir.

The requirement of solar angle, viewing angle, atmospheric corrections and orthorectification with high resolution DEMs is more critical for larger swath widths with larger off-nadir views particularly with multiple sensors with different nadir lines.

Mean Local Time

Mean solar time is a component of the viewing and solar angle corrections. Mean local time for polar orbiting sun synchronous missions varies from 9:30 to 10:30. Differences in mean local time contribute significantly to data measurement variability. During the 27-year lifetime of the Landsat 5 mission the mean local time varied by over an hour, which caused changes in the solar angle of over 10° [45].

View and solar angle corrections need to accommodate any changes in mean local time

Per-pixel Metadata

The inclusion of per-pixel metadata within data products has increased importance with the distribution of higher level analysis ready data. Cloud, shadow, quality and other information available at a pixel level can be used directly within application models. However, even though much of the per-pixel metadata currently available is not validated, they can provide important information if used with caution. Some per-pixel metadata are derivative products produced from and distributed with the data product; others are external products, such as DEMs and atmospheric model inputs, used in the processing/derivation of the data product. External products have their own uncertainties that must be understood.

General scene-level metadata aggregations of per-pixel metadata, such as cloud cover, data quality, snow/ice, and solar angles are often available in searchable databases. These metadata can be used to reject scenes from inclusion in time series that do not meet application criteria.

Interoperability requirements include documented algorithms and accuracies for cloud cover and shadow, land, water and vegetation, terrain shadow, atmospheric model inputs, including aerosols, and saturation and other data quality. Each of these per-pixel metadata sets is a function of a model that has its own confidence estimates, which will contribute toward the error budget of products. The level of validation and verification of these metadata is highly variable and needs to be documented. Differences in these per-pixel metadata vary between products can add noise to the multi-sensor time series.

Currently there is little standardization of per-pixel metadata by content, structure or implementation within databases including Data Cube methodologies. Interoperable per-pixel metadata provide an opportunity for quickly identifying where clear pixels are not sufficiently available and where more optical or SAR data are needed. The adoption or sharing of a common methodology that can be applied to different sensors would provide consistent metadata for multi-sensor data streams.

Table 4: Per-pixel Metadata

Items	**Threshold Verification**	**Target, Next steps**
Clouds	Document cloud definition and methodology, including treatment of cirrus clouds and cloud edges. Document potential confusion with other classes, such as sand, snow and ice.	Verify and validate cloud masks. Include opacity and probability estimates. Investigate new bands needed to optimize estimates. Quantify confusion with other classes. Adopt common methodology and standards for use on multiple sensors.
Cloud Shadow	Document cloud shadow methodologies. Document potential confusion with other dark objects such as water and terrain shadow.	Verify and validate cloud shadow masks. Quantify confusion with other dark objects. Adopt common methodology and standards for use on multiple sensors.
Land/water mask	Document land/water methodology.	Verify and validate methodologies within context of their use in radiometric corrections. Adopt common methodology and standards for use on multiple sensors.
Snow & Ice masks	Document Snow & Ice detection methodology.	Verified and validated snow & Ice detection methodologies. Adopt common methodology and standards for use on multiple sensors.
DEM	The required accuracy of the DEM is dependent upon the corrections implemented, swath width and pixel size.	Share DEMs when appropriate both among operational agencies and with users. Requirements are highly variable.
Terrain Shadow mask	Terrain shadow masks are needed to estimate radiometric contamination associated with shadows. Known confusion such as with water and cloud shadow needs to be quantified.	Terrain shadows are particularly important for mountainous areas, wide swaths and for SAR sensors. Adopt common methodology and standards for use on multiple sensors.
Illumination and Viewing geometry	Solar angles are needed for reflectance calculations. View angles are needed for BRDF related corrections including terrain illumination corrections	Per pixel versus scene center solar angle corrections. View angle corrections.
Data Quality	No data, saturated, contaminated, terrain occlusion pixels need to be identified.	Establish standardized QA mask for different product levels. Adopt common methodology and standards for use on multiple sensors.

Per-pixel metadata is a combination of mask data derived directly from the data and DEM data. This section will focus on the metadata themselves, whereas the use of these data are discussed in the radiometry and geometry sections.

Cloud Cover

Cloud cover assessments are derived from the available bands and the quality of the assessment will vary depending on which bands are available [46, 47]. Cloud models using both thermal and cirrus bands provide the best results. Research has suggested that the inclusion of additional bands in future missions can increase the quality of the cloud cover estimates [48, 49]. The single most influential band is the cirrus band, closely followed by the thermal band. Cirrus cloud estimates over high elevation land masses may be contaminated by reflectance from the land surface.

The impact of thin clouds on data analysis is application specific. The attenuation of the signal caused by thin clouds must be considered within the overall methodology, total error budget and specific analysis requirements.

The ability to form dense time series of reflectance data also opens the possibility of multi-temporal cloud masking approaches. For example, the CNES MAJA algorithm relies on temporal consistency for identifying cloud [50-53]. These approaches could be extended to multi-sensor data sets.

Cloud algorithms need to be verified and validated. Algorithms to minimize variability need to be shared when appropriate. Different band availability will cause differential results. These differences need to be documented. Known confusion such as with snow/ice needs to be quantified.

Cloud Shadow

Cloud shadow models are geometric models relating cloud objects to related dark objects as a function of solar and viewing angles plus elevation data. Cloud shadows can be confused with terrain shadows, water and very dark surface features. Cloud shadows contain spectral information that can be used within many applications. Adaptive algorithms can use the masks as information within models.

Cloud shadow models need to be verified and validated. Known confusion, such as with water, needs to be quantified.

Land/water mask

Land and water masks generated during the preprocessing of reflectance data are useful as first approximations for atmospheric corrections and higher-level product generation. However, these masks are not appropriate for land cover change or water body detection.

Consistently handle differential corrections over land and water.

Snow and Ice Mask

Snow and ice masks created during the preprocessing of sensor data assists in cloud cover assessment. As in the case of land/water masks, snow and ice masks can only serve as first approximations for monitoring, since there is significant confusion with clouds. However, time series of masks can contribute to the detection of clouds and in the monitoring of snow and ice.

Verified and validated uncertainty estimates improve both applications. Known confusion, such as with clouds, needs to be quantified.

Digital Elevation Models (DEMs)

DEMs are in most cases external input data used in data production by CEOS agencies. DEMs are required for parallax correction and orthorectification of products [54-56]. DEMs are used in many models, including terrain shadow, geolocation, BRDF, and parallax correction. Some sensors, such as SPOT [57], ASTER [58], ALOS [59] and TanDEM-X [60] can be used to produce DEMs. Many of the publically available DEMs are still based on SRTM data [61]. DEMs are also important inputs for many application models.

SAR data production is particularly sensitive to DEM accuracy and resolution. Sigma naught products are not orthorectified providing an opportunity to use locally optimized DEM data. Gamma naught products are orthorectified providing a higher-level analysis ready data product.

Share DEMs as appropriate both among operational agencies and with users. User requirements for DEMs may differ from data producers and need to be selected to meet sensor-specific requirements. Production and use requirements are highly variable.

Terrain Shadow

Terrain shadows are calculated using solar illumination angles and DEMs. Terrain and cloud shadows both significantly affect radiometry and can cause features in shadow to be confused with other dark features. Terrain shadows contain spectral information that can be used within many applications. Adaptive algorithms can use the masks appropriately.

Terrain shadows are particularly important for mountainous areas, wide swaths and for SAR sensors. Known confusion, such as with cloud shadow and water, needs to be quantified.

Illumination and Viewing Geometry

Measurement normalization for solar illumination and viewing angles are critical for BRDF and atmospheric models and become increasingly important for wider swaths. Corrections can include per-pixel solar illumination, viewing angle from sensor and terrain orientation corrections.

Documented, validated and verified corrections are critical for time series analysis using scene overlap regions and multi-sensor data sets.

Data Quality

Data quality metadata needs to be well documented and varies significantly between sensors and between products from the same sensor. Quality issues, such as dropped pixels, dropped lines, and saturation, are more common among older sensors, particularly 8-bit sensors. Quality flags also identify no data areas, such as fill, Landsat 7 scan-gaps, terrain occlusion. If data quality masks are resampled, adjacent pixels can be contaminated and flagged pixels can be lost.

Uncertainty estimates associated with data quality should be provided as possible and appropriate.

The distinction between pixels that are contaminated by the attenuated signal caused by reduced optical transparency or shadow versus pixels that need to be flagged as no-data is application dependent. Quality assessment information for higher level products may be available to help users make this determination.

Define data quality and distinguish between no data and contaminated data. Document how these pixels are handled during resampling.

Data Measurements

Interoperability concerns include compensation for available bands, normalization, atmospheric corrections, and spectral band differences for direct measurements from sensors and numeric derived products such as NDVI. Interoperability of classed data requires knowledge of classification accuracy and confusion among classes within each classification and associations between the product classifications.

Spectral measurements uncertainty will accumulate above and beyond at-sensor noise as the data are resampled and as corrections and application models are applied. Understanding how the uncertainties are distributed for each sensor by processing step helps understand the uncertainties that are inherited by any combined multi-sensor data set.

Perhaps obviously, application models may be sensitive to the existence of specific spectral bands, which may preclude the use of multi-sensor data sets. Spectral band differences need to be accommodated when those differences are a significant proportion of the overall error budget. Spectral band adjustments factors can be used to accommodate band differences, but research is needed to quantify to magnitude of the differences caused by different spectral response curves over different surface types. Indices, such as NDVI [41], are sensitive to band differences.

Reflectance calculations at low solar elevation angles can contribute significant uncertainty to measurement estimates. Reflectance is usually not calculated for low sun elevations threshold (below 15-25 degrees), and the threshold will vary by application.

Resampling and geolocation errors also contribute to measurement uncertainty and will be discussed in more detail within the Geolocation section below.

Table 4. Radiometric measurement corrections

Items	**Threshold Verification**	**Target, Next steps**
Measurements	Documented absolutely calibrated measurement. Feasible goals for current missions is 3% at-sensor accuracy and 5.8% at-surface reflectance[49].	Validated and verified Surface reflectance data. Feasible goals for future missions is 2% absolute accuracy at-sensor reflectance and 3.6% at-surface reflectance[49].
Measurement normalization	Normalize measurements to nadir viewing and temporally constant by spatially varying by latitude solar angle. Use consistent methodology to create multi-sensor data stream	Investigate more complete, but practical BRDF models, which will require prior knowledge of the Earth surface.
Aerosol, water vapor and Ozone corrections	Document atmospheric model corrections. Use consistent methodology to create multi-sensor data stream.	Validate and verify atmospheric models and compare results. If convergence on single model is not possible, document and accommodate differences.
SBAF compensation	Initial estimate is a linear fit between equivalent spectral bands using hyperspectral spectra.	Spectral Band Adjustment Factors (SBAF) need to compensate for different spectral response curves which are surface type dependent.

The radiometric accuracy has an error budget with contributions from at-sensor within sensor calibration, at-sensor multi-sensor cross calibration, spatial misregistration, atmospheric correction, solar angle corrections, and view angle correction [41, 62, 63]. Understanding how each of these contributes to the total uncertainty of the estimates is critical to interoperability.

Measurements

Minimum requirement is at-sensor reflectance calibrated and validated to a known absolute source and trended using pseudo-invariant calibration sites. Atmospheric, solar angle, and viewing angle SBAF corrections are usually needed to minimize variability and uncertainty. For higher level products, uncertainties relevant for those products are needed. The next step reduction in uncertainty requires additional spectral bands for atmospheric characterization. The estimated improvement in accuracy is associated with surface reflectance estimates are from on the order of 5% currently to 3% with additional bands[49].

Minimum requirement is for optical data are reflectance calibrated and validated to a known absolute source. Atmospheric, solar angle, and viewing angle SBAF corrections are usually needed to minimize variability and uncertainty to create an interoperable product.

Measurement Normalization

The view angle of nadir pointing moderate resolution data ranges from +/-7.5° for Landsat, to +/-10.5° for Sentinel-2 to +/-25° for AWiFS. Even within a sensor record the view angle for a point on the Earth will vary widely if side lap regions are included in time series. Off-nadir pointable sensors, such as SPOT and ASTER, can have greater view angles even though their Field of View is small resulting in large potential differences in view angle for any given point on the earth.

For multi-sensor data sets the view angles for a point on the Earth will be highly variable through time if all observations are used. When solar angles through the year are included, the illumination will also be variable. Measurements can be normalized by adjusting the view angle to nadir and the solar illumination angle to a scene constant as a function of latitude [64-67].

At high latitudes, reflectance products may not be available for part of the year. One assumption for solar angle for this framework is to only include AM instruments. As the mean crossing time changes through the life of an instrument, uncertainty can be introduced [45].

As a consequence of viewing angle variability, some observations will be toward the sun and others away from the sun and on terrain with different slopes and orientations further complicating models to require knowledge about the Earth's surface, such as slope, aspect and surface texture, that cannot be directly inferred from the satellite observations. Data can be normalized without introducing full bidirectional reflectance distribution function models; however surface feature specific variability will remain. [41].

Solar and viewing angle corrections compensate for both within- and between-sensor variability. Combining ascending and descending rows adds a further level of complexity. Significant research is needed to establish optimal and achievable level of correction.

Aerosol, Water Vapor, and Ozone Corrections

Different atmospheric models can introduce significant between sensor variability [63, 68]. Atmospheric model must either be shared or validated and verified to a common reference. Available bands and ancillary data will impact corrections; for example, newer generations of sensors capture atmospheric water, these corrections would be better/more reliable than the older generations where estimates are required. Uncertainty of external atmospheric products will contribute to the overall uncertainty associated with the corrections [62, 64].

Atmospheric models continue to improve for moderate resolution satellites. A major challenge is extending the models into the past to include early Landsat and SPOT sensors. Common models should be applied to minimize variability within a single multi-sensor data set.

Spectral Band Adjustment Factor Corrections

Spectral bands can be adjusted using hyperspectral data such as EO-1 Hyperion data [17, 64, 69-76] to determine a regression between similar bands. This mechanism is used to cross-calibrate sensors using spectrally flat pseudo-invariant calibration sites. SBAF becomes a mechanism for homogenization of the similar sensors bands to meet monitoring requirements for specific surface characteristics. Radiometric responses between Sentinel-2 MSI and Landsat 8 OLI can be as high as 17% for different surface types, if SBAFs are not applied [74]. The uncertainty following SBAF correction should approach 5% [77]. If no overlap exists between spectral response curves, no accommodation is possible.

Spectral Band Adjustment Factors (SBAF) compensate for different spectral response curves and may be application and surface type specific. Simple solutions are currently available to support current research and applications.

Geolocation

The analysis of image data through time requires accurate and precise internal geometry and registration to an absolute reference image. Sources of errors lie with the reference database and within each sensor. Within-sensor error components include systematic correction of the data based on ephemeral data acquired with the image and on terrain data. The importance of terrain data is also a function of path width with wider paths being more sensitive to terrain. The systematic and terrain corrected information is convolved with a reference grid accuracy to provide a measure of absolute geometry error and relative error among sensors. Reference grids are created and validated using independent high-resolution data. A shared reference grid and a high-quality DEM are major steps to achieving geometric interoperability between sensors.

The study of geolocation error will be coordinated through the WGCV and at the individual agencies. Several studies of note are addressing geolocation uncertainty from the perspective of uncertainty in relation to ground reference, within sensor and between sensors [34].

Interoperability issues include compensation for different pixel sizes between products, spatial RMSE by image, reference grids with different absolute accuracies, DEMs with different accuracies, and different projection spaces.

Table 6. Geolocation

Items	Threshold Verification	Target, Next steps
Geometric Correction	Image data are precision corrected to a reference data set.	Minimize misregistration through orthorectification and precision registration to a common reference data set. Document methods and uncertainties/error throughout processing chain
Resampling	The number and type of spatial resampling will impact the radiometric signal	Minimize the number of resampling operations. Quantify impact of upsampling or downsampling on time series analysis for different applications. Document resampling type/method applied.

Geometric Correction

Misregistration between images effectively increases variability in the radiometry measurements. Misregistration is minimized through orthorectification and precision registration to a controlled reference grid. Table 7 summarizes variables that contribute to misregistration. The rule of thumb for interoperability is sub-pixel accuracy with acknowledgement that any misregistration adds noise to time series applications and each application will have different tolerances for the increased noise. The geometric accuracy required for time series analysis depends on the application. It is understood that radiometric noise is introduced into the time series as a function of the pixel size, point spread function and misregistration. User guidelines are needed to support application specific decisions. Acceptable accuracy will vary from on the order of 1 pixel to less than 0.1 pixel depending on the sensitivity of the monitored change. These rules of thumb will vary depending on the size and contrast of features plus the point spread function of the sensor. Practical guidelines depend on how well different sensors can be registered combined with available sensors that meet application location and date requirements. Users will accommodate the best available data and adapt analytic methodologies and goals based on what is achievable.

Example measured difference between Landsat 8 and Sentinel-2 before convergence on the Sentinel-2 GRI is 26 meters, which must be corrected. When Landsat changes to using the GRI then the result should approach 10m. Current approaches require an extra resampling until the change is made.

Verify image-to-image registration and remove unacceptable misregistration. Minimize misregistration through orthorectification and precision registration to a controlled and preferably shared reference grid

Table 7. Geolocation Characteristics by Sensor

Platform	Instrument	Reference Grid	DEM	Pixel size	RMSE	References
Landsat	MSS	GLS 2000 (17m)	GLS DEM	79m	134m CE95	[5, 78]
	TM	GLS 2000 (17m)	GLS DEM	30m	10.9m CE95	[78]
	ETM+	GLS 2000 (17m)	GLS DEM	30m	10.7m CE95	[78]
	OLI/TIRS	GLS 2000 (17m)	GLS DEM	30m	15m CE95	[34, 78-80]
Sentinel 2	MSI	GRI (9.5m)	PlanetDEM	20/30 m	12.5m CE95	[34, 36, 37]
TERRA	ASTER	GLS 2000 (17m)				
SPOT	HRV, HRG					
CBERS	MUX, WFI, IRS					
ResourceSat	AWIFS, LISS-III			56m		[81-85]
EO-1	Hyperion, ALI			30 m		[16, 17]
Sentinel 1	C-band					
Radarsat 2	C-band					
ALOS-1/2	PALSAR L-band					
TerraSAR-X TanDEM-X	X-band					

Resampling

To homogenize sensor products to meet RMSE requirements or pixel size using image-to-image registration requires an additional resampling of the data. Upsampling data to smaller pixel size will retain the resolution of the higher resolution sensor at the cost of introducing increased radiometric variability, since upsampled data imputes information for the lower resolution sensor as a function of the resampling mechanism, such as nearest neighbor, bilinear or cubic convolution, used. Downsampling data results in the loss of spatial resolution, but creates a single data set of consistent radiometry. Resampling of classed products can introduce significant new uncertainty in the products.

The identification of a shared reference grid is an important first step for achieving geolocation interoperability. To minimize impact on radiometry, resampling must be minimized particularly if the pixel size is changed. The adoption of a shared mapping grid for high level products, such as the Discrete Global Grid System (DGGS) is an opportunity to reduce resampling. Resampling to a shared projection space should be as early in the production flow as possible, preferably while the data are still path aligned.

Minimize the number of resampling operations and consider impacts such as contaminated pixels, clouds and the resampling method.

Case Studies

The case studies provide the research needed to populate and verify thresholds and to advance the target objectives needed to achieve interoperability. Case studies fall broadly into two categories:

producer determination of product uncertainty estimates; and user determination of application uncertainty requirements. The former determines how good we can make the products within instrument, data and cost constraints. The latter establishes how good the products need to be to meet application needs.

Interoperability research and applications are increasingly common throughout the user community. These serve as a rich source of case studies covering a wide range of lessons learned and good practices for many sensors and thematic areas. A survey was designed and implemented to identify case studies, lessons learned and good practices from throughout the user community.

User application case studies show uses of the data in applications and as technology proof of concept, which complement data case studies designed to test, verify and validate specific characteristics of the products. These are not necessarily mutually exclusive. FDA case studies implement technological solutions to support GEO and other user applications and can help validate interoperable solutions.

The 2017 Landsat-Sentinel-2 interoperability case study provides the initial study advancing the MRI framework. MRI case study summaries will be appended to the MRI framework to provide lessons learned from actual interoperability studies with links to full descriptions of the studies and detailed lessons learned. Generalizations of the results will be incorporated into the core framework document as this living document evolves. The case study summaries should directly respond to framework items for the interoperable solutions evaluated. Which items for which components are in play depend on the sensors and the level of processing. For at-sensor optical products, most items will be relevant. For higher-level classed products, the data measurements and methodologies will need to evolve to quantify uncertainties among classed products.

Conclusions

The USGS 2017 Chair Moderate Resolution Sensor Interoperability Chair initiative bridges the gap between CEOS data products and the user community for the implementation of consistent and complementary multi-sensor data streams. With the current suite of free and open access data products long-term (1972 to the present) and dense (2-4 day revisit) time series are possible, if the products are or can be adapted to be interoperable. These time series can be used to implement a new generation of analysis and monitoring methodologies. The Future Data Architecture Initiative can take advantage of the lessons learned and good practices identified to implement these new methodologies for use by the thematic communities.

Through the continued evolution of the Framework document higher level data products and SAR data can be more completely integrated. New case studies can continue to build the compilation of lessons learned and best practices needed by the user community.

Survey

Moderate Resolution Sensor Interoperability

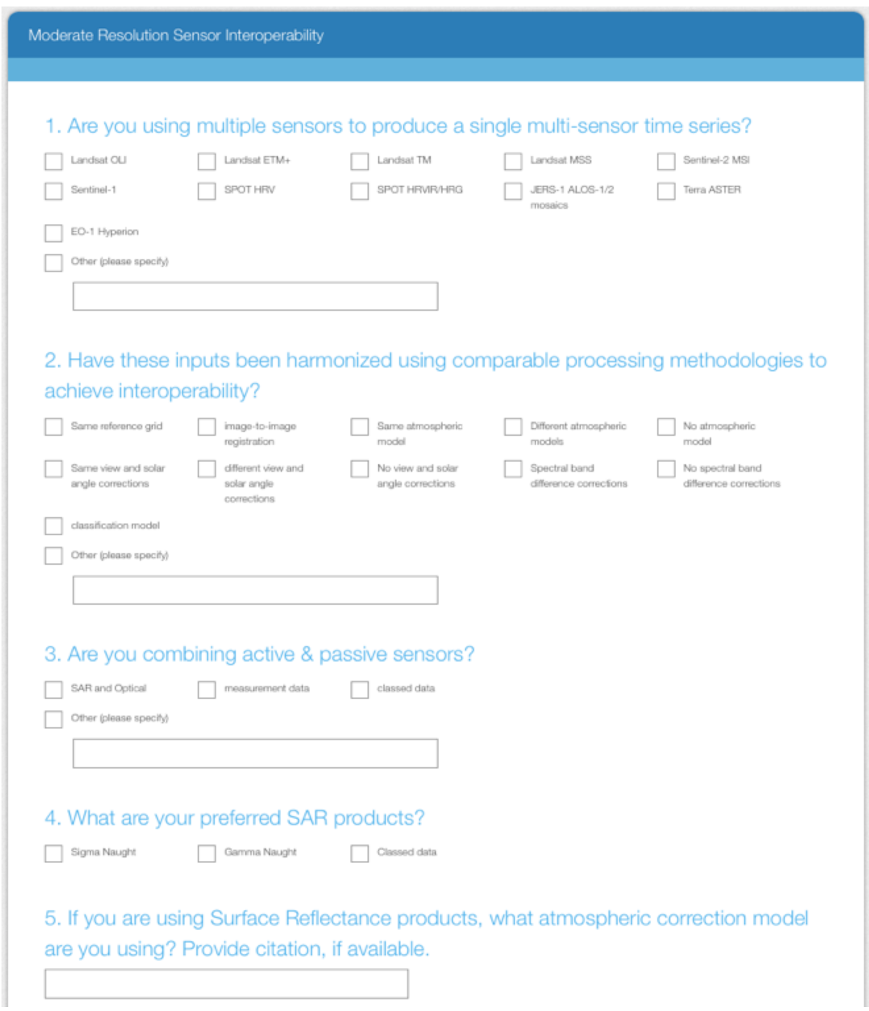
This Moderate Resolution (10-100m) sensor Interoperability (MRI) survey seeks to identify case studies demonstrating the implementation of multi-sensor time series.

The survey supports the work of the CEOS MRI Initiative to improve interoperability among CEOS agencies to support multi-sensor time series analyses and to provide examples of good practices and lessons learned for the user community. Processing level of the products ranges from at-sensor, through at-surface (BRDF, atmospherically and band difference corrected) to indices and classed data. Please use descriptive terminology.

The following questions address some of the multi-sensor interoperability issues.

We would welcome your general feedback in a last open question and would appreciate references to any of your presentations or published papers related to interoperability.

Click the button below to start the survey (https://www.surveymonkey.com/r/QS9YHJF). Thank you for your participation!



Moderate Resolution Sensor Interoperability

1. Are you using multiple sensors to produce a single multi-sensor time series?

- [ ] Landsat OLI
- [ ] Landsat ETM+
- [ ] Landsat TM
- [ ] Landsat MSS
- [ ] Sentinel-2 MSI
- [ ] Sentinel-1
- [ ] SPOT HRV
- [ ] SPOT HRVIR/HRG
- [ ] JERS-1 ALOS-1/2 mosaics
- [ ] Terra ASTER
- [ ] EO-1 Hyperion
- [ ] Other (please specify)

2. Have these inputs been harmonized using comparable processing methodologies to achieve interoperability?

- [ ] Same reference grid
- [ ] image-to-image registration
- [ ] Same atmospheric model
- [ ] Different atmospheric models
- [ ] No atmospheric model
- [ ] Same view and solar angle corrections
- [ ] different view and solar angle corrections
- [ ] No view and solar angle corrections
- [ ] Spectral band difference corrections
- [ ] No spectral band difference corrections
- [ ] classification model
- [ ] Other (please specify)

3. Are you combining active & passive sensors?

- [ ] SAR and Optical
- [ ] measurement data
- [ ] classed data
- [ ] Other (please specify)

4. What are your preferred SAR products?

- [ ] Sigma Naught
- [ ] Gamma Naught
- [ ] Classed data

5. If you are using Surface Reflectance products, what atmospheric correction model are you using? Provide citation, if available.

6. If you are using Surface Reflectance products, what illumination and view angle corrections are you applying? Provide citation, if available.

7. Did you apply spectral band difference corrections to the data? Provide citation, if available

8. What masks are you applying?

- [ ] Terrain shadow mask
- [ ] Cloud masks
- [ ] Cloud Shadow mask
- [ ] Quality mask
- [ ] Water mask
- [ ] Snow/Ice mask
- [ ] None

How are masks created and applied? Citation.

9. Are you using data with different spatial resolutions

- ( ) same resolution
- ( ) resampling to smaller pixel
- ( ) resampling to larger pixel

Other (please specify)

10. Please share any reports or publications on your work that describes your methodology. Additionally, we would appreciate other references by other researches in the field.

Reference

Reference

Reference

Reference

Reference

Done

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Appendix A: Sentinel-2 Landsat HLS Case Study

This case study can serve as an example of the use of the MRI framework for attaining multi-sensor interoperability. The objective of the NASA Harmonized Landsat/Sentinel-2 (HLS) Project is to generate a radiometrically and geometrically (seamless and interchangeable) surface reflectance data set from Landsat-8 and Sentinel-2[64, 77]. Each observation is manipulated to look like it came from a single sensing system with the consistent statistical properties, and the origin of each observation is transparent to end users. HLS performs a series of consistent radiometric and geometric corrections to minimize sensor differences, including a common atmospheric correction, solar/view angle corrections, spectral bandpass adjustments, and gridding to a common UTM projection and tiling system.

Component	Items	Descriptions
General Metadata	Coordinate Reference System	Both products are projected to a UTM/WGS84 map projection. HLS merged products are produced as 30-meter products using the Sentinel-2 tile system. Individual products are available at native resolution prior to resampling Sentinel-2 to 30 meters
	Reference grid accuracy	Landsat data are georegistered to the GLS reference database, which contains errors of up to 36m. In order to provide consistent georeferencing, both Landsat-8 and early (pre-v2.04 processing system) Sentinel-2 data are registered and resampled to the best available Sentinel-2 MSI image. L30 products have absolute geodetic error of <19m (CE90), while S30 products have absolute geodetic error <10.5m (2σ).
	Geometric accuracy and temporal consistency	L30 products have absolute geodetic error of <19m (CE90), while S30 products have absolute geodetic error <10.5m (2σ).
	Spectral bands	The common bands are coastal aerosol, blue, green, red, NIR, SWIR1, and SWIR2. Other bands are available for analysis.
	Spectral response curves	The Sentinel-2 MSI band passes are quite similar to those of Landsat-8 OLI, for those bands in common between both instruments. The near-infrared (MSI Band 8a) and shortwave bands in particular are nearly identical. The MSI green band is slightly broader in comparison to OLI, while the red band is shifted ~15nm to the shorter end of the spectrum. HLS uses a linear regression model (based on training sample from Hyperion hyperspectral data) to derive Spectral Band Adjustment Factors (SBAF's) that convert Sentinel-2 reflectances into "equivalent" Landsat OLI reflectances for the common bands.
	Radiometric Accuracy	Sentinel-2 MSI has a radiometric stability (ie. uniform target over multiple overpasses) requirement of better than 1% (2σ) while Landsat 8 OLI has a requirement of better than 0.5% (2σ). MSI and OLI agree to within 1.5% with the exception of the coastal aerosol and blue bands.
	Revisit time & lifetime	Landsat 8 OLI revisit time is every 16-days and Sentinel-2 A & B revisit every 5 days over Greenland, Europe and Africa and every 10 days over the rest of the world, as of July 2017. Given swath overlap and average cloud cover, a cloud-free HLS observation (either L30 or S30) can be expected every 15-20 days over the humid tropics, and every 5-10 days over mid-latitude agricultural regions.
	Field of View	The Landsat 8 FOV is 15° and the Sentinel-2 FOV is 21°. View angle differences for some ground targets can differ by up to 18.5°
	Mean Local Time	The average mean local time for Landsat 8 is 10:11 and for Sentinel-2 is 10:30. Minimal impact on radiometry.
Per-Pixel	Clouds	The FMask algorithm is used for both Landsat 8 and Sentinel-2 to detect

Component	Items	Descriptions
Metadata		clouds. The lack of a thermal band on Sentinel-2 increases errors of omission and commission.
	Cloud Shadow	The FMask algorithm is used for both Landsat 8 and Sentinel-2 to detect cloud shadows. Adjacent cloud pixels only estimated for Landsat 8.
	Land/water mask	The FMask algorithm is used for both Landsat 8 and Sentinel-2 to detect water.
	Snow & Ice masks	The FMask algorithm is used for both Landsat 8 and Sentinel-2 to detect snow and Ice.
	DEM	Landsat uses the GLS DEM. Sentinel-2 uses the PlanetDEM
	Terrain Shadow mask	Not used in HLS products
	Illumination and Viewing geometry	Solar illumination angles are needed for reflectance calculations. Solar and View angles are needed for BRDF related corrections. View geometry is provided on a per-pixel basis for both Landsat-8 and Sentinel-2 data.
	Data Quality	HLS includes Quality Assessment on a per-tile and per-granule basis, by comparison with contemporary MODIS CMG (Climate Modeling Grid) BRDF-adjusted reflectances. QA summaries are available on the HLS web site.
Data Measurements	Measurements	HLS products record surface reflectance or apparent (TOA, blackbody) temperature.
	Measurement normalization	Reflectance values are normalized to a constant (nadir) view angle and fixed, latitude-dependent solar elevation using the coefficients provided in Roy et al. (2016).
	Aerosol, water vapor and Ozone corrections	Aerosol quality flags are set for Landsat 8. Cirrus per-pixel flags are set for both.
	SBAF corrections	Sentinel-2 reflectance values are adjusted to match those derived from equivalent Landsat-8 bandpasses, using a linear-regression model trained on Hyperion hyperspectral data.
Geolocation	Geometric Corrections	The HLS product uses image-to-image registration to a single reference Sentinel- 2 image for coregistration of each tile.
	Resampling	Sentinel-2 data are resample to 30-meters to preserve the radiometric time series at the cost of lower spatial resolution.

Foundational efforts are already underway to ensure interoperability [64, 86-89], and include pre-flight and on-orbit cross-calibration of Sentinel-2 carried out by NASA, USGS, and ESA. As Sentinel-2's product generation pipelines are fully implemented, a need for higher level coordination exists.

Appendix B: Vegetation dynamics monitoring with harmonized Landsat 8 and Sentinel-2 data

The vegetation dynamics monitoring use case study uses the HLS 30m products at several global locations to determine whether it is possible to detect and monitor vegetation productive dynamics and phenology (i.e. reliable pick the seasonal cycles) based on a relatively small amount of data (dates) and compare those with SPOT/MODIS based observations using the completely reworked Phenolo algorithm (Phenolo#2). This is an important step towards the monitoring of heterogeneous land cover at local and regional scales.

Eight heterogeneous HLS study areas were selected for analysis focusing on main crops, as well as native vegetation. Phenological parameters include among others the onset of green-up, the moment of maximum green vegetation cover, and season length. The identification of phenological parameters from satellite data is made by analyzing the temporal evolution of a remote sensing indicator of vegetation greenness such as the normalized difference vegetation index with various methods [90]. A common requirement to generate robust estimates of phenological parameters is that the evolution of vegetation growth and decay is observed with an adequate frequency [91].

This use case study will continue into 2018.