LOOKING AHEAD:
THE WATER'S EDGE OF THE USGS NATIONAL LAND IMAGING PROGRAM

Building the Global Commons of Earth Observation Data

A Report of the National Geospatial Advisory Committee
Landsat Advisory Group
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1.0 Executive Summary

USGS asked the Landsat Advisory Group (LAG), subcommittee of the National Geospatial Advisory Committee (NGAC), to prepare a paper that explores what earth observation products, in forms of data, algorithms or workflows, the federal government should appropriately provide to optimize benefit to the public, particularly in light of the industry transformations. As such, this paper prospects the scope to which USGS can maximize its productivity and optimize its leadership role in this transforming environment of evolving technology and expanded providers and users. This report examines the current state of earth observation collection, distribution, and use, reflects on the quality and content needs of the global community, and highlights the following findings and recommendations:

Finding #1*:* The earth observation landscape is being fundamentally transformed by two major trends. The first is an explosion in the accessibility of earth observation data, both from new sensors coming online and its availability on cloud platforms. The second is the rise of 'Analysis Ready Data (ARD) Harmonization' products that promise to enable the scientific community and non-expert data users to spend more time conducting research into urgent issues in earth system science, such as climate change, food-energy-water nexus, and other priorities, rather than data cleaning and standardization procedures.

Finding #2: These two trends open the possibility for a completely harmonized 'Global Land Imaging Analysis Ready Data commons'. This would mean that diverse disaggregated sensors from different countries and companies can all contribute to a coherent, consistent record of change on earth. Such data commons allow integrated digital representations of the physical, ecological, and human environments to facilitate shared views and solutions to local, regional, and global challenges.

Finding #3*:* Harmonized ARD baseline can provide a foundation for many higher level data products like biophysical measurements, land classifications and change monitoring. The USGS science community is uniquely positioned to be able to supply these measurements of the state of the earth's health, and the need for such measurements is greater than ever before. The massive longitudinal observations of the earth and the ever innovative machine learning algorithms synergize the advances in pattern mining and knowledge discovery of the Earth's past, present, and future.

Recommendation #1*:* USGS should work with NIST, OGC and ISO to create the standards that would underpin harmonized analysis ready data. This will likely require CEOS agencies' resourcing, as well as targeted work on Cal/Val and WGISS to support international standards.

Recommendation #2*:* Standards must account for sensors of differing quality than Landsat and Sentinel 2, incorporating them into the global commons with clear communication of quality.

Recommendation #3: USGS should continue to produce higher level science products built on the harmonized data baseline provided to other users, and the USGS should seek out international government, likely in participation in CEOS, and public-private-partnerships to encourage a wide range of valuable measurements of our planet's health. USGS should maintain open communication with the commercial remote sensing industry – both those that collect data and those that focus on data analytics – to ensure synergy between government developments, academic research, and trends in the commercial sector.

2.0 Introduction

In recent years there has been a remarkable change in the volume of data, ease of access, and processing power for Earth Observation data. This has expanded the diversity of applications, products, and services to quite non-homogeneous user groups. While the amount and types of remotely sensed data now available from a growing number of providers overwhelm most users, some difficulty addressing the variety has been mitigated by harmonization efforts like Harmonized-Landsat-Sentinel (HLS) and Sen2Like. These products abstract out the more challenging parts of remote sensing to create cross-sensor Analysis Ready Data, facilitating work with the volume of data being generated. Collectively (along with other data fusion efforts driven by the research and commercial landscapes), these efforts point to the near term realization of harmonized/standardized earth information based on the collective inputs of Landsat, Sentinel, and other Earth observation platforms.

The National Land Imaging Program leadership from the U.S. Geological Survey (USGS) requested that the Landsat Advisory Group (LAG), a subcommittee of the National Geospatial Advisory Committee (NGAC), prepare a paper that explores what earth observation products, in forms of data, algorithms or workflows, the federal government should appropriately provide to optimize benefit to the public, particularly in light of the industry transformations. With increasing capability and capacity of national, academic, and commercial actors in the Earth observation community, the roles and responsibilities will evolve amongst actors. This shifting boundary between the federal government's responsibility and those of new operational actors will be continuous, and here we introduce the analogy of the "Water's Edge" in recognition of a growing, dynamic community and how each actor interfaces with one another. We encourage every actor to embrace the changing landscape and adapt programs and plans over the years to increase public benefit and create a more efficient Earth Observation Enterprise.

These trends shift USGS from being the primary source of global monitoring imagery to a key leader within the global 'virtual constellation'. This builds upon Landsat's unprecedented record of collecting and distributing, multi-decadal calibrated observations of the earth's land surface. The Landsat program has improved the spatial and thematic accuracy of its imagery over the fifty years of operation as well as increased the spatial and temporal resolution. It has further enhanced the quality of those resolutions by increasing the spatial and temporal resolution of this record by combining Landsat's data with other open global monitoring missions. The NLI's core mission is to provide Federal and public access to a collection of authoritative remote sensing datasets that best enable their exploitation. Among those datasets are USGS products such as Level-1 satellite quantized image data, Level 2 geophysical parameter products (e.g., Surface Temperature, Surface Reflectance, and Aquatic Reflectance), and the other derivative Level 3 sciences products.[1] With Landsat Collection 2, these products have been spatially aligned to enable improved time-series analysis in support of applications such as climate change studies. As the referenced website clearly illustrates, the "Water's Edge" of data content, product development, and application focus cannot remain static. Questions necessarily emerge. Should users anticipate major changes in the total scope of the remote sensing and GIS community's work with the inclusion of newer sensor systems? Will any change in focus to the more complex Level "X" products require different expertise than what USGS already has? This paper examines those issues, offering insights and recommendations as well suggesting further study.

3.0 The Earth Observation Landscape

There are two transformative trends occurring in the Earth Observation (EO) domain. The first is a phase shift in the volume of data, ease of access, and processing power for EO data. More earth observation satellites and collection platforms are being engineered, launched and/or flown than generally anticipated only two decades ago. Each of them can have far more capable and diverse sensors, acquiring much more complex data than previously. Petabytes of new data arrive every single week. The promising use of both onboard processing and cloud computing has enabled some initial editing or fusion. Remote sensing workflows are increasingly shifting to the cloud, with use of Google Earth Engine, Microsoft Planetary Computer and government systems being developed on AWS that enable global scale computations. In turn, this revolutionizes access to EO data, as but one example, with copies of Landsat and Sentinel missions available on every cloud. Users no longer need to select which images they want and then wait for the download to their desktop computer. Instead, cloud-native geospatial approaches enabled by standards like Cloud-Optimized GeoTIFF (COG) and SpatioTemporal Asset Catalogs (STAC) enable users to process the data in place, with far more computing horsepower than they ever imagined for their desktop systems. Furthermore, the cloud-computing platform also facilitates standardization and community commons for innovations by algorithm sharing and social coding. The copies of the missions on different clouds and diverse machine learning models, however, raise the concerns about data provenance, data authenticity and integrity, as well as confidence and trust in algorithms and models. In its leadership role, USGS could greatly influence the establishment of standards to assure authoritative data and cloud-computing workflows as it asserts responsibility there at that water's edge. The process for developing and sharing open source algorithms, models, and

[1] https://www.usgs.gov/core-science-systems/nli/landsat/landsat-science-products?qt-science_support_page_related_con=2#qt-science_support_page_related_con

code should ascribe to international standards and best practices with process improvement for establishing emerging standards in the Earth Observation ecosystem.

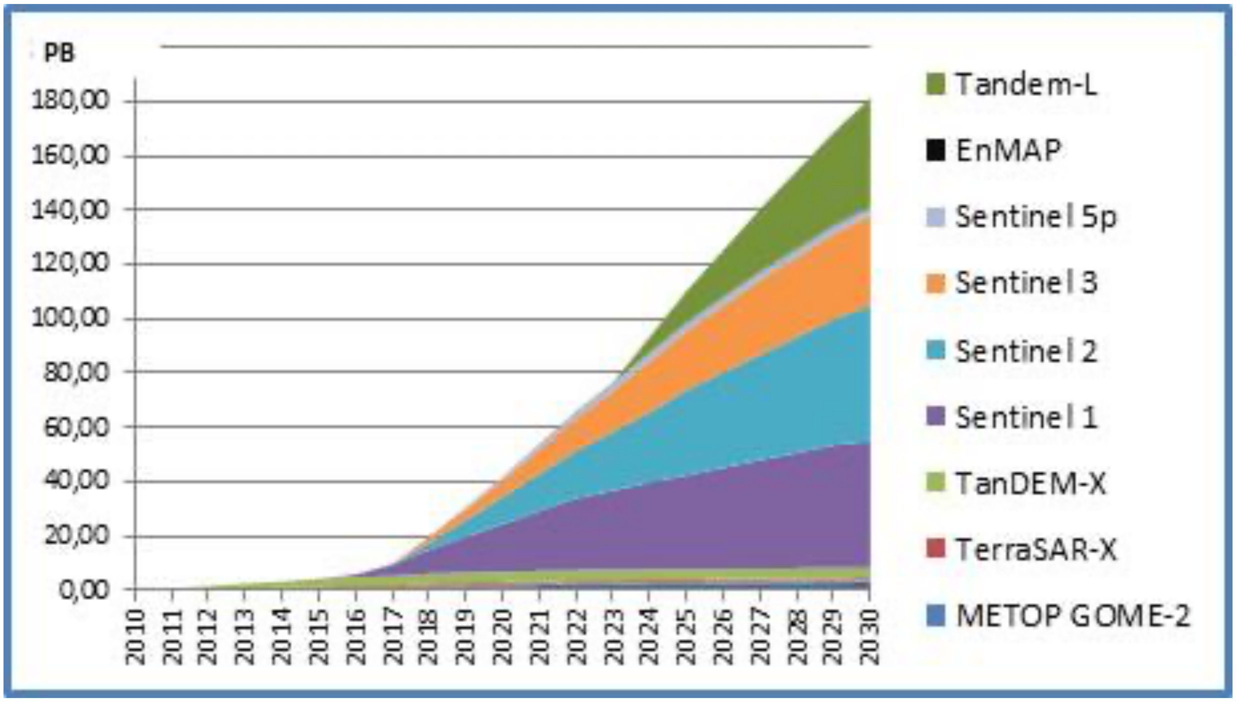

Figure 1: *The petabytes (PB) of Earth Observation (EO) data being collected have grown significantly and are projected to continue growing.*

The second transformative trend includes huge strides in making imagery easier to work with. Traditional remote sensing workflows would require a user to perform atmospheric correction, align each image in a time series so the pixels match, mask out clouds, etc. Landsat has established a community leading model with 'Analysis Ready Data', which takes the pre-processing steps everyone used to do on their own and puts them in a deliverable product ready to be confidently used to address myriad needs and issues. Analysis Ready Data broadens societal applications and expands the value of remote sensing imagery, which would otherwise have limited use outside environmental or biological sciences. A subsequent phase of this initial pre-processing aims to 'harmonize' multiple sensors so their radiometry becomes compatible, enabling the same algorithms to work on any data gathered from any of the input sensors. The two leading efforts on this ARD Harmonization (ARD-H) front have been Harmonized-Landsat-Sentinel (HLS) and Sen2Like, both bringing together Landsat and Sentinel 2 into a single stack of Analysis Ready Data. The Sen2Like product takes the best of Landsat and Sentinel 2 data and fuses it into a data product that is at the Sentinel 2 spatial resolution (10m) and higher cadence with the combination of both missions. The potential of harmonization and fusion, to transform the expanding remote sensing landscape, cannot be overstated, as it enables any satellite with similar capabilities to participate in the shared mission of global monitoring combining the best qualities of each sensor. This will establish the foundation for an even greater revolution in making remotely sensed information accessible to a wider group of users, since the harmonized

ARD layer can enable fusing key biophysical and land classification measurements to synthesize information products as well as monitoring changes of our planet. These processes can extract from all the complexities of remote sensing the needed and valued data products that provide answers and drive decisions.

4.0 Landsat and the 'Global Virtual Constellation'

Landsat has provided the longest continuous scientific record of global earth observations, with its sensors providing a 'gold-standard' reference that many other missions rely upon.[2] The latest developments of harmonization see new missions like the Copernicus program's Sentinel satellites not 'competing' with Landsat, but instead enhancing the global earth observation scientific record with sub-weekly 10-meter observations. The software advances that power this harmonized Analysis Ready Data (ARD-H) enable us to use diverse spectral and spatial resolutions to get a more complete picture of what is happening on earth. As a matter of scientific practice, the resulting multi-sensor ARD-H data products hold the promise of enabling the scientific community and Landsat data users to spend more time conducting research into climate change and other scientific priorities, rather than data cleaning and standardization procedures. Both Landsat OLI and Sentinel MSI sensors have unique spectral bands that add to the diversity of any product derived from the harmonized and/or fused sources that include Landsat.

This enables a true "commons", where any new public dataset can add to the overall measurement of what is happening on earth. This portends a future where any satellite can contribute to Landsat's mission - providing the longest continuous record of earth observation data - as long as its data meet certain calibration standards to enable them to be harmonized. In addition, two ARD products that are not harmonized, but are interoperable (e.g., can be corrected to the same ground geometry) can be conjoined to add value. This could result in a 'data cube' that increases in spatial, temporal, and spectral resolution as more sensors come online, strengthening the time series and heightening the reliability of any predictive assessment.[3] As the number of launches increase because the costs of building spacecraft and launching them decreases, diverse nations, research organizations and companies will find it easier to contribute to the anticipated and desired Global Land Imaging Analysis Ready Data "commons." That concept opens the possibility of disaggregated sensors, where thermal, multi-spectral, hyperspectral or RADAR sensors are flown on government or commercial satellites, with software able to combine all readings of the earth into a coherent, consistent record of change. It could even be possible to incorporate higher resolution imagery from planes, high-flying drones, and balloons into this harmonized global data commons.

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[2] https://www.fgdc.gov/ngac/meetings/october-2020/ngac-paper-landsat-data-community-standard-for.pdf

[3] See recommendations made by the Landsat Advisory Group in 2018.
https://www.fgdc.gov/ngac/meetings/april-2018/ngac-landsat-data-cube-feasibility-for-forecasting.pdf

5.0 Evolving the Role of the National Land Imaging Program

In this future where many are contributing raw pixels to the Global Land Imaging Analysis Ready Data record, the role of the National Land Imaging Program should evolve to better leverage its unique strengths in service of the needs of its community of users. The two pillars of the USGS Landsat operations program have been serving as the 'gold' reference for calibration, and stewarding the longest record of earth observation. These should remain the pillars of what the USGS does, but that agency must continue to transform from being the sole 'source' of medium-resolution earth-observing data and must effectively advance into a trusted developer of quality methods and standards and an advocate for the global commons of monitoring sensors, in service of all its direct and indirect users. The core product focus should be the 'gold' reference implementation of interoperable earth information ARD products. As a matter of scientific practice, this direction holds the promise of enabling the scientific community and Landsat data users to spend more resources and cultivate expertise conducting research into climate change and other environmental, social, and public good priorities. Rather than being beset by data provenance concerns, data quality checking and cleaning, and seeking standardization procedures from an expanding array of sensors, USGS should strategically emerge from the avalanching pixels of data as an active leader and advocate in the creation and adoption of needed standards to harness the plethora of new sensors and platforms.

USGS should also encourage delivery of cloud-based, deep-learning processing software tools that openly enable operating within the expanse of the highest quality global virtual constellation. An open source policy that shares algorithms, models, and codes for data productions and analytical workflows on Landsat projects by USGS scientists and sponsored researchers can enhance USGS productivity in two ways. First, open algorithms and codes allow users to produce customized data products. Second, users can contribute to algorithm improvements and novel modeling techniques for new Landsat and multi-sourced products and analytics. The resulting data output will upgrade and enhance the Global Land Imaging Analysis Ready Data to ever improving spatial, temporal, and spectral resolutions as more sensors come online.

These standards development and instantiation efforts should be actively supported by government agencies, which can promulgate them and then embed their required use in procurement decisions. This approach would follow in the path of initiatives like IETF and ICANN where the government funds an appropriate neutral mission-driven organization to facilitate the global standards-creation process, while serving as a key leader and stakeholder in the effort. The resulting effort enabled a growing, dynamic community of government, academic and commercial actors to build the foundation for the internet to become a public utility and a new domain for commerce. In the geospatial community, the Open Geospatial Consortium is a likely choice for a forum to build consensus on critical science and technological infrastructure issues. Bringing actors together to create candidate standards through ISO will allow the global and national standards bodies to set the fundamental standards to ensure full global compliance. Instantiation of a successful suite of earth observation standards demands ensuring a robust ecosystem of software tools that support the standards. The US Government is already leading in these domains, such as with NOAA's/NLI's involvement in the US Group on Earth Observations (USGEO) and NASA's role in the Open Data Cube[4] internationally. NOAA may also consider taking on an increased diplomatic role to develop synergies between Landsat (and other U.S. Earth Observation assets), the European Sentinel program, and EO datasets from other programs including JAXA and ISRO at the Committee on Earth Observation Satellites (CEOS). These flagship efforts are increasingly utilized in combination by the global EO user community, and NOAA is uniquely positioned to broker conversations around standards and user experience and help guide the roadmap of global sensors in service of a coherent record of earth information to be used by all.

6.0 Leading Global Land Imaging Analysis Ready Data

The following products and initiatives demonstrate how this shift would further USGS's leadership role in a Global Land Imaging ARD effort.

6.1 Calibration Standards, Tools, and Leadership

A key component of making Landsat the 'gold' standard is an array of ground calibration sites that enable precise measurements against established and well-defined targets to enable continued correction of sensors in space. Many diverse commercial and governmental organizations already leverage NASA calibration resources such as the Goddard Aeronet Network and many of the methods developed for Landsat to do their own calibration. The instantiation of EROS Calibration Center of Excellence (ECCOE) is largely providing these services today. Improved calibration methodologies, working with university and international cal/val sites and with participation/leadership in community-of-interest organizations. The leadership role in setting standards and building tools for ground calibration should extend in the future, to enable any country or university to contribute more high-quality calibration sites to help any sensor reach the quality required to be part of the Global Land Imaging Virtual Constellation. One could imagine a 'radcal site in a box', that brings the tools, processes, and training to enable anyone to create a radcal site that becomes part of the global sensor calibration commons. These calibration sites are critical to enable interoperable data collections and calibrate biophysical properties and measurements needed for the various levels of data products. Consider the impact to the global community for various opportunities to collaborate by new actors and the timely impact to the science missions of organizations like USGS and the issues associated with the global climate environment.

USGS should aim to set the 'gold' reference implementation of a sensor that meets the NLI standard of excellence. With the proliferation of new earth observation satellites in space, USGS could certify these sensors and data products, or explore the best way to help the virtual constellation with a 'reference satellite'. This could be a smaller instrument with lower resolution that focuses on providing crossovers for others to validate against, perhaps using a hyperspectral sensor. Crossovers for calibration and data continuity is not a novel concept. The

[4] https://www.opendatacube.org

most recently launched Landsat 9 included crossovers with Landsat 8 to confirm quality in positional and spectral accuracies.

6.2 Global Land Imaging Analysis Ready Data

As mentioned above, the primary product focus should be on the 'gold' reference development and implementation of a standardized product suite which enables cross-sensor/observation exploitation by regular end-users and not only highly-skilled remote sensing scientists. With the introduction of Collection 2, USGS has made Landsat data across missions consistent and analysis-ready, enabling end users to exploit with ease. With this leadership, USGS shall encourage other earth observation data collection, storage, and exploitation users across the US government to be interoperable and analysis-ready. Leaning further into a standard-setting mode would require collaboration with NASA and ESA to seek a framework that can sustain robust HLS products, leading cross-sensor harmonization and standardization, and ensuring the entire Landsat data archive is compatible with global analysis-ready data standards to enable multi-sensor harmonization for an end user. This should serve as the global reference implementation that meets the quality requirements of the Landsat constellation users. This should ideally be able to harmonize the entire Landsat historical record with the modern analysis-ready data spectral targets, like those of HLS. Though the data product from any remote sensing collection itself is important, even more important will be the standards defining the quality standards that a 'gold' harmonized Global Land Imaging ARD data set must meet, including metadata tracing for scientists to understand the 'error bars' of diverse source data. The future of virtual constellations should not rely on every new sensor being able to meet the high standards set by Landsat and Sentinel 2, but there must be comprehensive metadata with provenance tracking to all source data so that users can understand exactly what appropriate use of the data entails. What are the reproducible and/or repeatable scientifically credible processes, anyone can expect from data use? The CEOS CARD4L specification (with 'target' metadata implementation) is an effort to define the metadata content which improves source interoperability and provenance.

Successful development of Global Land Imaging Analysis Ready Data can empower diverse commercial operators, academic programs, and nation states to credibly contribute to the global commons of earth observation data. A clear target will be to establish standards for data holders to clean and harmonize their data to the 'gold' standard, and ideally there are also standards that set lower quality levels to provide a path forward for any sensor to work towards the 'gold' target. The CEOS ARD certification process provides an appropriate baseline to build upon here, but more resources or a "lighter" and/or more automated approach is needed for lower-level certification. It is important that the standards are sensor agnostic, working at a high enough level that any new sensor meeting the appropriate calibration targets will be easily incorporated into the global commons of analysis-ready earth observation data. For example, the original Planet Labs' Dove sensor red channel was different from the Planet Labs' Super Dove and Sentinel 2's red channels, which cover a wider spectral range. This doesn't mean that it should be excluded from the global land imaging record - any measurement in the passive optical EM spectrum is relevant to earth's changes over time. So, an Ideal standard would be able to accommodate any spectral information, and appropriately leverage its unique spectral characteristics. Thus, HLS should become HLS + X, where X is virtually any other sensor that shares the same mission, easily incorporating diverse spectral characteristics into a harmonized output. Achieving this clearly requires a non-trivial amount of work, but the benefit to the world is immense, enabling more users to get insight from remote sensing than do today.

An expanded role for USGS to lead the global commons of earth observation harmonized data, here at the "water's edge" of so many emerging technologies and global environmental needs, USGS can lead the global community with multi-national and public-private-partnerships. Those innovative partnerships will enable the purchase of data and services from commercial providers for government, academic, commercial, and public use to form the Global Land Imaging ARD commons. This could even include higher spatial resolution (and likely lower temporal resolution) aerial, drone, and tasked high resolution satellites. It should be possible to include national aerial programs like NAIP in the overall harmonized dataset, even serving as a target for upsampling images, as long as the processing error potential is clearly communicated to users.

Beyond just setting the standards for the data itself, leadership on data accessibility must be a component of this USGS expanding role. The Open Geospatial Consortium has committed itself to the FAIR principles for data: Findable, Accessible, Interoperable, and Reusable. The user community commends the Landsat program for the accomplishments in making its collections incredibly accessible, embracing cloud-native geospatial approaches like COG and STAC, and enabling copies of its archive on every major cloud and in higher level tools like Google Earth Engine and Microsoft Planetary Computer. Continuing leadership and standard setting in this area cannot become lax.

6.3 ARD Harmonization Software Tools

One of the most important parts of making a standard usable and widely accepted is to ensure that the software that enables its creation and use is flexible, robust, and well-maintained. There are numerous algorithms used to create HLS, including atmospheric correction, cloud masking, spatial co-registration, BRDF[5] normalization, band pass adjustment and more. Each algorithm should continue to be refined, upgraded, documented, and released in readily-accessible libraries. These composable, trusted algorithms can be usable in a wide variety of open or proprietary tools, so it's easy for anyone to create a new harmonized product or workflow. The software should also evolve to make it possible to incorporate other data sources into the harmonized analysis-ready data output. This ideally is a nice plug-in system, where every new data source can be coded as a 'plugin' after the addition of a couple of data sources past the core Landsat and Sentinel. Then an open source ecosystem can be encouraged to build up the harmonization transforms for diverse data sources.

[5] Bidirectional Reflectance Distribution Function

This software should be the same as that used in production environments to create the 'gold' standard reference product, so it is not just the libraries available to the global community but scientifically accurate and composable building blocks of a processing pipeline. Taking a leadership role in this means not just releasing the libraries but building up the open source ecosystem of diverse contributors, so the software becomes a part of the global commons, to allow new sensors to easily join the Global Land Imaging Analysis-Ready data cube.

7.0 Going Beyond Analysis Ready Data

The 'users' of the National Land Imaging program have always been experts in remote sensing and geospatial sciences who are able to work with imagery and extract insights from it. USGS has the potential to greatly expand its user base and tap into a broader community of experts to build consistent, reliable, trusted 'variables' (e.g., Level 4 data products) of the state of the earth's health. The requirement for such measurements is greater than ever before, as governments need to certify 'green' bonds; companies want to prove that their corporate social responsibility programs are having a measurable impact; financial institutions seek more reliable ways to provide climate risk ratings to analyze companies against ESG targets; and civil governments install community planning tools (such as community resilience, star community, climate adaptation planning, or other planning templates) and environmental planning tools (drought analysis, water management, etc.). These organizations don't necessarily have – or need to have - remote sensing experts, but with guidance, they could describe, help design, and employ decision-support tools, that they are assured have been enabled by trusted data sources. USGS must address head-on the question of authenticity in satellite imagery by incorporating measures that can assure a downstream user of Landsat data that it has been unadulterated. Tools and procedures that expose manipulation must be readily available. Making the USGS and the NLI the trusted actor for how to set up trustable measurements, with accepted methodology, will give a clear seal of approval to reliable scientific measurements facilitating trust in the indicators that power novel decision support tools. The resulting metrics would enable a hugely expanded economic benefit for the Global Land Imaging ARD, as it would make the record of the earth's changes directly available to a much wider range of users.

USGS and NASA already have substantial experience providing these types of data product 'variable extensions.' As an example, MODIS data products go beyond delivering only the calibrated imagery. Products like snow cover, burned area, chlorophyll-a and others have enabled earth science MODIS data users to focus more time and expertise completing scientific research and to avoid time in data preparation. Just consider how a wise and selective public or private investment in quality-consistent and standards-compliant Level 4 products, based on Harmonized Sentinel Landsat and its future evolutions, could advance a significant step-change in Earth observation science. Building the measurements on harmonized, multi-sensor analysis-ready data would enable each user to confidently start with a standard credentialed input for resulting products, tailored to a specific – perhaps quite complex – need. As the global virtual constellation improves in resolution (spatial, temporal and spectral), so too would the measurements. Ideally users, whether earth scientists, economists, environmentalists, sociologists, community planners, and so forth, would also be able to access summaries of change over time in key measurements for key geographies (for example: countries, states, counties, municipalities) so that the data easily import into spreadsheets, business intelligence tools and cloud data warehouses for analysis by a wider group of users.

Beyond just biophysical measurements, like the type that MODIS provides, there is the opportunity for USGS and other FGDC geospatial data providers to assert a leadership role in land cover classification and change detection and in refining the theme classification accuracy standards. For instance, the definition or semantic use of 'forest' may vary depending on the country and culture, thus making data interoperability more difficult when trying to accurately and consistently deliver a trusted data source. Acknowledging and handling language connotation is fundamental to accelerate the development of new decision-making applications for a wide range of national and international issues that range from environmental guidelines to law enforcement to emergency response. Analysts need to know things like 'how much deforestation has happened in X country in the past decade' or 'what's the urban growth rate and change in urban heat index for Y city' or 'what activity inhibits potable water'. The USGS need not enter the deeper societal or political debates that build on differing interpretations of the core variables. By assuming a respected, collaborative, and collegial leadership role within the standards community, the USGS can set – and be the strongest advocate for – the standards for categorization codes and analytical procedures that characterize the report of how and why the observed status of things in place change over time, following certain taxonomies and methods. USGS in its expanded global commons leadership role can help the community certify analytics as properly following a scientifically valid protocol (USGS's recognition, providing film camera calibration certification in the past, is a noteworthy parallel). Such validated analytics would be valued immediately for financial and regulatory compliance, as but one example. USGS need not be the compliance authority, but instead should lead a public-private partnership to develop, test, and establish a certified process and then encourage other agencies, like FWS or FDA, to build out compliance applications powered by scientifically valid and reproducible indicators.

This paper has mentioned the possibility of embracing public-private-partnerships, as part of understanding how the "Water's Edge" might adjust in the future with cooperative, collaborative relationships. Public-private-partnerships (P3) are not all alike since they must adapt to the details of the specific partnering to address key objectives. Understanding both successful and flawed cases would be beneficial to the other recommendations of this paper. More understanding, gained by continuing to examine case studies of such partnerships, is necessary to meet both the public need for reliable information and the private benefit of delivering innovation as an on-going operational service. Previous NGAC efforts reviewing such partnerships for best practices should continue[6] to add case studies to the 2020 work.

[6] Advancing the NSDI through P3s and Innovative Partnerships December 2020
https://www.fgdc.gov/ngac/meetings/december-2020/ngac-paper-advancing-the-nsdi-through-public.pdf

8.0 LAG Findings and Recommendations

As identified in the Executive Summary above, this paper provides the dialogue for the following findings:

1. The earth observation landscape is being fundamentally transformed by two major trends. The first is an explosion in the accessibility of earth observation data, both from new sensors coming online and its availability on cloud platforms. The second is the rise of 'Analysis Ready Data (ARD) Harmonization' products that promise to enable the scientific community and non-expert data users to spend more time conducting research into urgent issues in earth system science, such as climate change, food-energy-water nexus, and other priorities, rather than data cleaning and standardization procedures.

2. These two trends open the possibility for a completely harmonized 'Global Land Imaging Analysis Ready Data commons'. This would mean that diverse disaggregated sensors from different countries and companies can all contribute to a coherent, consistent record of change on earth. Such data commons allow integrated digital representations of the physical, ecological, and human environments to facilitate shared views and solutions to local, regional, and global challenges.

3. Harmonized ARD baseline can provide a foundation for many higher level data products like biophysical measurements, land classifications and change monitoring. The USGS science community is uniquely positioned to be able to supply these measurements of the state of the earth's health, and the need for such measurements is greater than ever before. The massive longitudinal observations of the earth and the ever innovative machine learning algorithms synergize the advances in pattern mining and knowledge discovery of the Earth's past, present, and future.

The paper examines those findings and makes the following recommendations to move the community ahead, recognizing that the "water's edge" of requirements and technology improvements will not remain static over time but that the leadership role must be a steadfast commitment to service users as data proliferate, new sensor systems emerge, and needs expand:

1. USGS should work with NIST, OGC, and ISO to create the standards that would underpin harmonized analysis ready data. This will likely require CEOS agencies' resourcing, as well as targeted work on Cal/Val and WGISS to support international standards.

2. Standards must account for sensors of differing quality than Landsat and Sentinel 2, incorporating them into the global commons with clear communication of quality.

3. USGS should continue to produce higher level science products built on the harmonized data baseline provided to other users, and the USGS should seek out international

government, likely in participation in CEOS, and public-private-partnerships to encourage a wide range of valuable measurements of our planet's health. USGS should maintain open communication with the commercial remote sensing industry – both those that collect data and those that focus on data analytics – to ensure synergy between government developments, academic research, and trends in the commercial sector.

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