LANDSAT DATA:
COMMUNITY STANDARD FOR DATA CALIBRATION

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Executive Summary

Landsat has become a widely recognized "gold" reference for Earth observation satellites. Landsat's extensive historical record of highly calibrated data is a public good and exploited by other satellite operators to improve their data and products, and is becoming an open standard. However, the significance, value, and use case description of highly calibrated satellite data are typically not presented in a way that is understandable to general audiences. This paper aims to better communicate the fundamental importance of Landsat in making Earth observation data more accessible and interoperable for global users.

The U.S. Geological Survey (USGS), in early 2020, requested the Landsat Advisory Group (LAG), subcommittee of the National Geospatial Advisory Committee (NGAC) to prepare this paper for a general audience, clearly capturing the essence of Landsat's "gold" standard standing. Terminology, descriptions, and specific examples are presented at a layperson's level. Concepts emphasize radiometric, geometric, spectral, and cross-sensor calibration, without complex algorithms. Referenced applications highlight change detection, time-series analysis, crop type mapping and data fusion/harmonization/integration.

Introduction

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 accurately and coherently describes how Landsat data have become widely recognized as a radiometric and geometric calibration standard or "good-as-gold" reference for other multi-spectral satellite data. Explanations are often technically complex, eluding a layman's understanding[1] and too often impeding appreciation of this as a global good and de facto standard to enable greater Earth observation utility while simultaneously facilitating the commercial Earth observation market to grow. The objective of this paper is to address various aspects of calibration with the goal of expanding the reader's understanding on the importance of Landsat's high calibration standard, the impact it has on other civil and commercial multi-spectral satellite constellations, natural resource applications, commercial application development and integration with other geospatial data sources.

The Landsat program continues to be a spectacular value proposition: it unlocks $3.45B in benefits for its users every year[2], is the foundation upon which commercial missions are

[1] Footnotes include some additional technical explanation for the benefit of readers who wish to learn more.

[2] *Economic Valuation of Landsat Imagery* (https://doi.org/10.3133/ofr20191112).

modelled against[3] and, most importantly, provides humanity our longest continuous high-resolution historical record of the earth's surface since 1972[4].

What is Calibration?

When two people in different parts of the world say that two different things are each exactly one-meter-long, we have confidence that this is true because the unit "meter" is standard and we have many measuring instruments (such as rulers) that are *calibrated* against this standard, meaning that we are confident that "one meter" means the same thing. Contrast that with ancient times, when units such as "one foot" varied from place to place, at times being tied to the size of a king's feet. It's also important that the standard is well known, widely accepted and easily accessible so that it can be universally applied; a standard behind a locked door isn't of much use.

Saying that a satellite image is calibrated[5] means that the earth observing sensor on the satellite gives an accurate and consistent representation of what it is remotely sensing on the ground. It's in the right location (geometric) and the colors (radiometric) are correct. It means that two images of the same scene (from the same sensor or a comparably-qualified sensor) will be the same if the scene hasn't changed. By using some change detection techniques—whether as simple as human visual comparisons or as complex as some sophisticated computer programs—if there has been a change in the images, then you know that the scene has changed as well and in what manner.

Consider the following two images of a scene in Denver, taken six years apart; the image on the left is the most recent. What is most apparent to you as you look at each image? What has changed?

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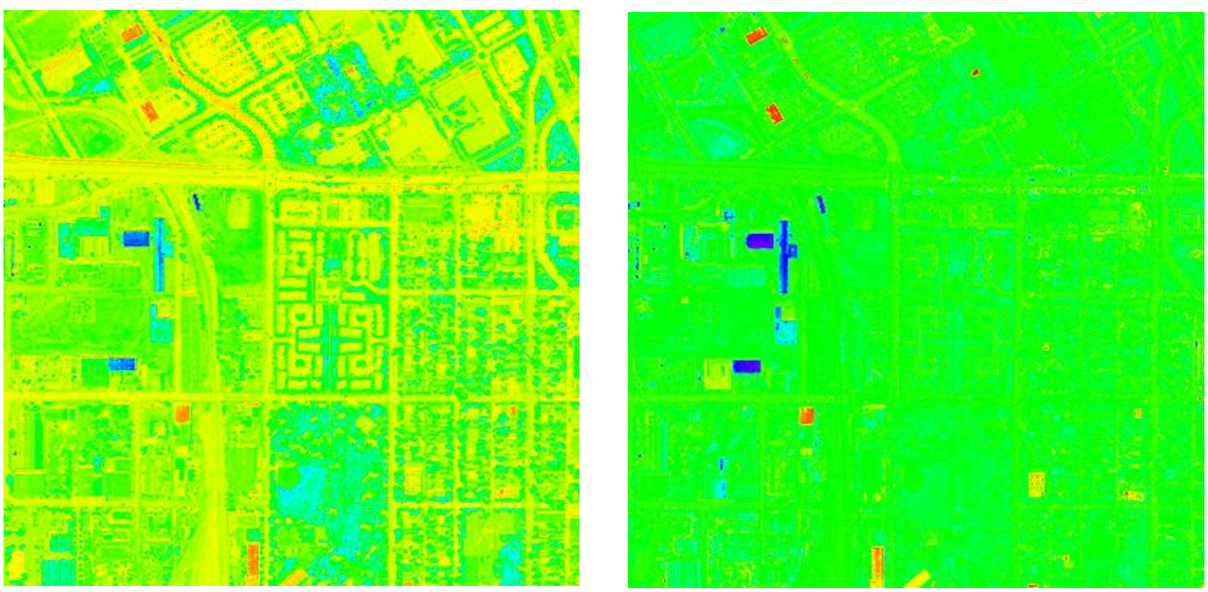
[3] *Observations and Recommendations for Coordinated Calibration Activities of Government and Commercial Optical Satellite Systems* (https://doi.org/10.3390/rs12152468).

[4] *Historical record of Landsat global coverage* (https://doi.org/10.14358/PERS.72.10.1155).

[5] "Landsat satellites are well-designed and calibrated prior to launch, continuous re calibration is required to offset degradation that may be caused by mechanical or electrical effects, or exposure to UV radiation. Calibration requires a comparison between the measuring instrument and an "absolute" reference standard of known accuracy." https://www.usgs.gov/land-resources/nli/landsat/calibration-validation?qt-science_support_page_related_con=2#qt-science_support_page_related_con. "Landsat Calibration Parameter Files (CPFs) provide radiometric and geometric coefficients needed for processing of raw, uncorrected Landsat image data into Level-1 data products. Over 15,000 coefficients are issued to span distinct timeframes and are updated with improved calibration coefficients. CPFs are often updated with improved coefficients. https://www.usgs.gov/faqs/what-are-landsat-calibration-parameter-files?qt-news_science_products=0#qt-news_science_products

Figure 1: Two thumbnail scenes from Denver, CO. Courtesy Maxar.

To illustrate change employing some techniques beyond human vision, we can apply colors to show change where the bluest color indicates “added” and yellow-to-red colors indicate “removed”. If we simply compare images prior to any calibration (and prior to compensation for atmospheric effects due to time change), it appears that there has been significant change (below left). Yet only after calibrations have been applied is the actual—and certainly more limited—extent of the change evident (below right).



Left graphic: Without calibrations applied *Right graphic: With calibrations applied*

Figure 2: Simple pixel-by-pixel change map of the preceding two scenes. Blue represents “added” from the old scene to the newer scene and yellow-to-red represents “removed.” Left graphic is without calibrations applied; right graphic is with calibrations applied. Courtesy Maxar.

There are several different kinds of calibration, all of which are reflected in the above example.

- **Geometric**: satellite images are provided to users with an estimate of where the satellite itself was and in what direction it was looking when it took that image, and thus where that image was located on the ground. ***Geometric calibration is a measure of how close the location, size, and shape that we estimate of each object in the image is to the true location, size, and shape on the ground***. Understanding the expected accuracy of an image's location is important not only when comparing multiple images of the same location but also when combining with GPS data and other data sets such as road networks, environmental data, geologic maps, political boundaries, etc. Landsat geometric calibration is generally good to about 7.5 meters, or 1/2 the width of a Landsat panchromatic pixel, when projected to the ground.[6] Landsat Collection 2, due to be released around the time this paper is published, will provide dramatically improved geometric accuracy over the current Collection 1, due to enhanced processing techniques and improved ground control points.[7] As an example, "The Australian block's horizontal accuracy improved from 15.4 m to 3.6 m with the use of AGRI (Australian Global Reference Image) controls and from 15.4 m to 8.8 m without the use of those AGRI controls."[8] [9]

- **Spectral:** are the colors in the image accurately represented? If a red roof appears red in one image and orange in the next, but it's the same roof and it hasn't been changed during the interval between images, that is an example of bad spectral calibration. We've had a related experience in our daily lives when the same photo appears to have different colors on our laptop and desktop monitors; this is a case where the displays aren't properly calibrated. (Remember how disappointed you were when the shirt you ordered online was not quite the color you expected?) ***Good spectral calibration for an image taken from a satellite takes into account a variety of factors, including compensation for things like haze in the atmosphere, sun position in the sky, as well as the consistency of the sensor itself***. Not only must colors be consistent if there has not been a change between subsequent images, but they must be accurate to the true color

[6] https://www.usgs.gov/land-resources/nli/landsat/landsat-geometry
RMSE goal has been 12 m or just over 1/3 a pixel after processing using the ground control points. Every scene is released with metadata including the spatial RMSE. In requesting imagery through EarthExplorer, a user can request images with accuracy boundary. "Cartographic accuracy of 12 m or better (including compensation for terrain effects) is required of Landsat 8 data products." https://landsat.gsfc.nasa.gov/landsat-data-continuity-mission/. When discussing the panchromatic images, the Landsat 8 (L8) Data Users Handbook (p.46) says: "Geodetic accuracy of one-half of a panchromatic pixel (7.5 m) should be sufficient, although higher accuracy is desirable."

[7] https://www.usgs.gov/media/files/landsat-collection-1-vs-collection-2-summary

[8] **Storey, J., Rengarajan, R., Choate, M.** *Bundle Adjustment Using Space-Based Triangulation Method for Improving the Landsat Global Ground Reference Remote Sens.* **2019**, *11*(14), 1640; https://doi.org/10.3390/rs11141640

[9] According to the Landsat 8 (L8) Data Users Handbook, without the calibration processing "Data from the two sensors, the "Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS), are calibrated to better than 5 percent uncertainty in terms of Top of Atmosphere (TOA) reflectance or absolute spectral radiance and have an absolute geodetic accuracy better than 65 meters (m) circular error at 90 percent confidence (CE 90). "

of the object. This is important for some of the applications we will discuss subsequently.

When we refer to “colors” here, we are referring to slices of the electromagnetic spectrum, known as “spectral bands,” that correspond both to the colors that we see (e.g., red, green, blue) and also colors that lie outside of the visible range. Landsat-8 collects a total of 10 distinct spectral bands, plus a “panchromatic” band (think of this as grayscale) as illustrated in the graphic below.[10] Each spectral band must be precisely calibrated.

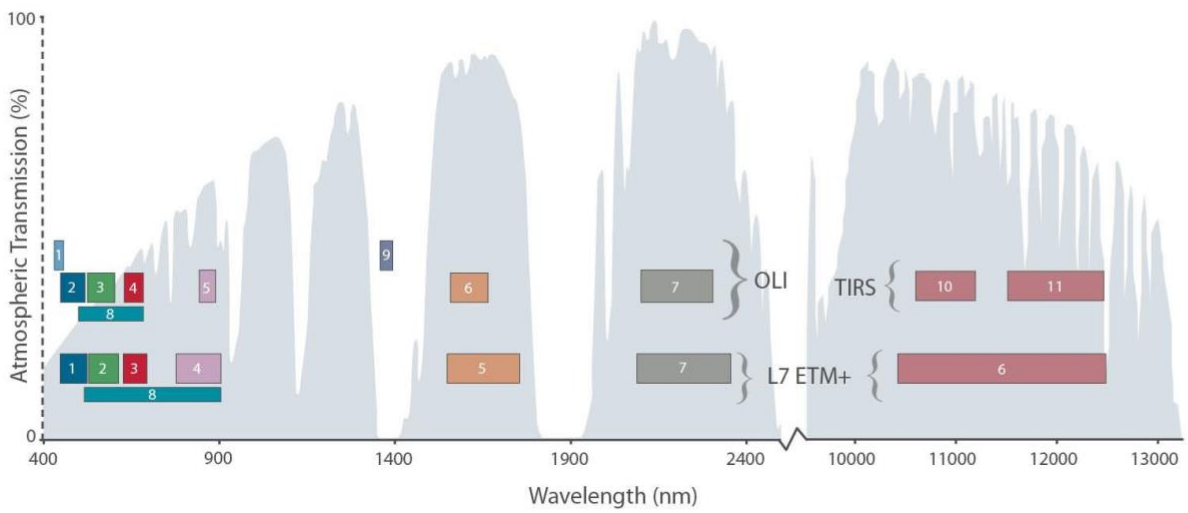


Figure 3: Landsat-8 bands are listed in the top row, and those of Landsat-7, its predecessor, in the bottom row. Landsat-8’s visible bands include #2 (blue), #3 (green), #4 (red), and #8 (panchromatic). Band #5 is the near-infrared band used in the creation of the NDVI vegetation index, described below. Courtesy NASA GSFC.

- **Radiometric**: is the intensity or brightness of each color in the image accurate? This goes hand in hand with spectral calibration, and takes into account different lighting conditions (such as the differences between summer and winter), again ensuring consistency in a time series of data. Just because the red roof appears dimmer in winter (assuming it’s not snow covered!) when the sun is lower in the sky than it does in the bright summer sun, it’s the same red roof. Likewise, atmospheric conditions, e.g., aerosols and humidity, can influence feature’s appearance in an image. ***Radiometric calibration adjusts the effects from sensors, solar factors, and atmospheric influences to enable us to use Landsat data to draw that conclusion with confidence***. In addition, the Landsat program requires that currently collected data is radiometrically consistent with previous Landsat sensors, which is sometimes referred to as “cross-calibration.” Sensors are calibrated before launch and subsequently through the life of the mission to ensure consistency.

[10] https://landsat.gsfc.nasa.gov/landsat-9/landsat-9-spectral-bands/.

Illustrative Examples

Since a picture is so often worth a thousand words, let's look at some images. In our daily experience, we see the effects of haze in the atmosphere that soften or obscure colors in the distance. Comparably, when looking down from a satellite, you can see differences in the original images in the top row below, which were taken of the same location at different times when what might have been in the atmosphere between the satellite sensor and the ground differed. An important part of the calibration of Landsat images is effective removal or mitigation of these atmospheric effects[11], as shown in the bottom row of surface reflectance images - provided for this paper through the courtesy of Maxar (The clouds do remain, however.).

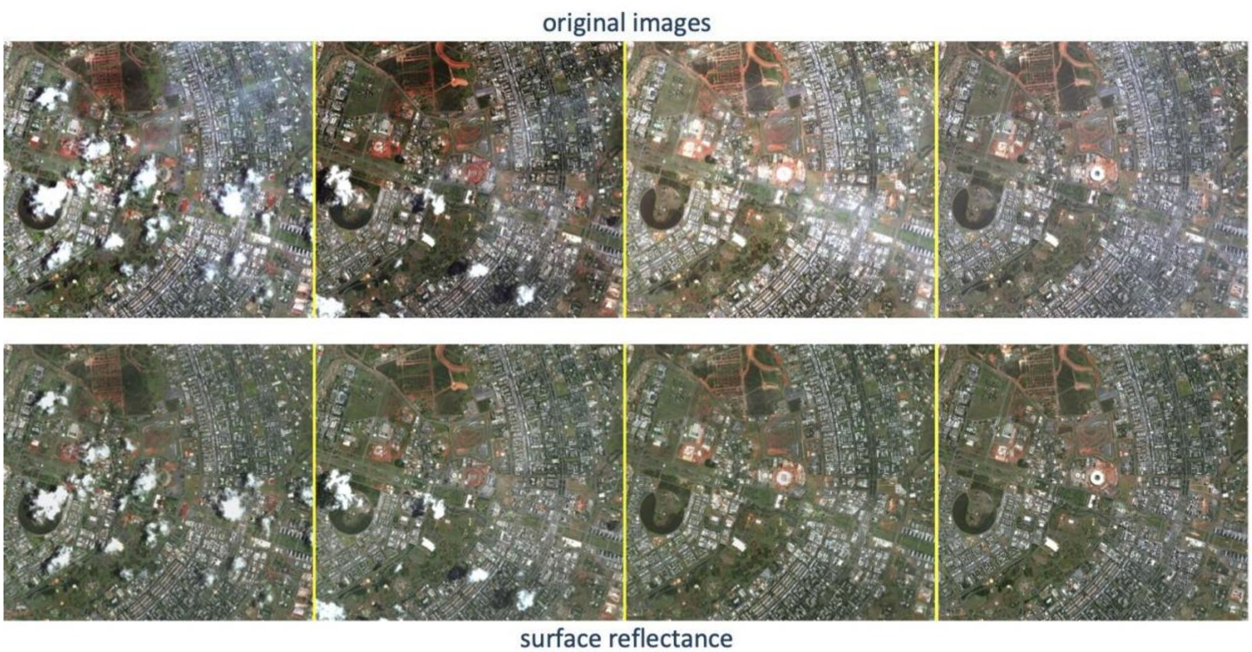


Figure 4: Thumbnail images of Brazil taken on different dates. Courtesy Maxar. Top row are without calibrations applied, bottom row are calibrated to produce surface reflectance, resulting in the cloud free areas being much more consistent from scene to scene.

The excellent calibration of Landsat data has enabled products that analyze time series data to highlight areas that have changed. Removal of perceived but not actual change by applying appropriate atmospheric calibration in a consistent and coherent process, accomplished by USGS, results in the Analysis Ready Data (ARD) cube stack, providing both "top of the atmosphere" and surface reflectance values. That product, available on request from the Earth Resources Observation and Science (EROS) Center, allows custom use of a specific time series,

[11] See https://www.usgs.gov/land-resources/nli/landsat/landsat-collection-2-surface-reflectance for a discussion of the approaches used to compensate for atmospheric effects in Landsat data, creating products known as "surface reflectance."

permitting analysis of the past, determining some changes over time, and enabling some predictive insights.[12]

Another example, depicting change-over-time, is the National Geospatial-Intelligence Agency's Persistent Change Monitoring product, which identifies both when and where change has taken place, such as this example showing construction over Dubai.

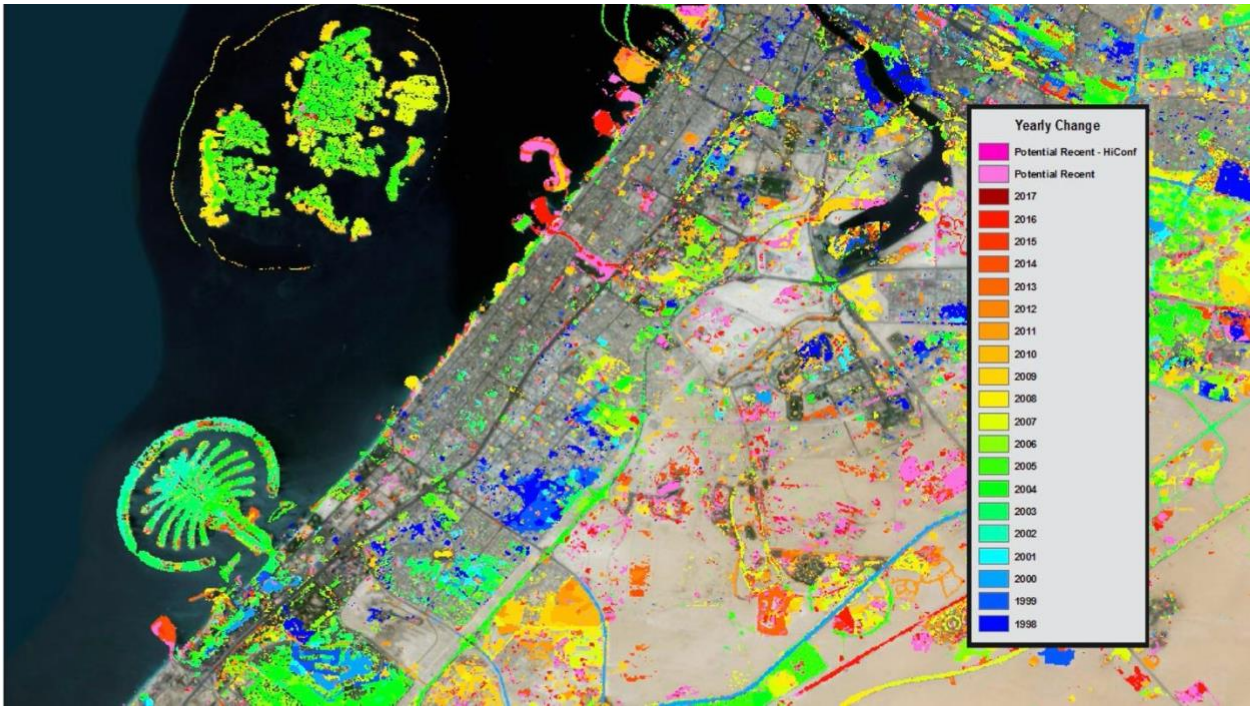


Figure 5: NGA Persistent Change Monitoring product, which leverages Landsat data to show change in land cover by year. Courtesy Maxar.

Beyond simply identifying whether something has changed or not, Landsat imagery over time intervals can be interpretively used to draw important conclusions such as the health of vegetation. If you intend to monitor vegetation change over time, you must apply atmospheric correction before any subsequent processing, such as an index, called the Normalized Difference Vegetation Index (NDVI), that is used to indicate status of plant health since healthy vegetation reflects light in certain colors and absorbs it in others. In agriculture, farmers use NDVI to enable precision farming. In forestry, NDVI helps quantify forest stands and leaf area. As a derivative use, then, NDVI can also indicate drought since restricted vegetation growth would have lower relative NDVI than desired.

The example below shows NDVI of an agricultural region in Australia taken at the same time of year in different years showing variability in crop health.

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[12] https://www.usgs.gov/land-resources/nli/landsat/us-landsat-analysis-ready-data?qt-science_support_page_related_con=0#qt-science_support_page_related_con

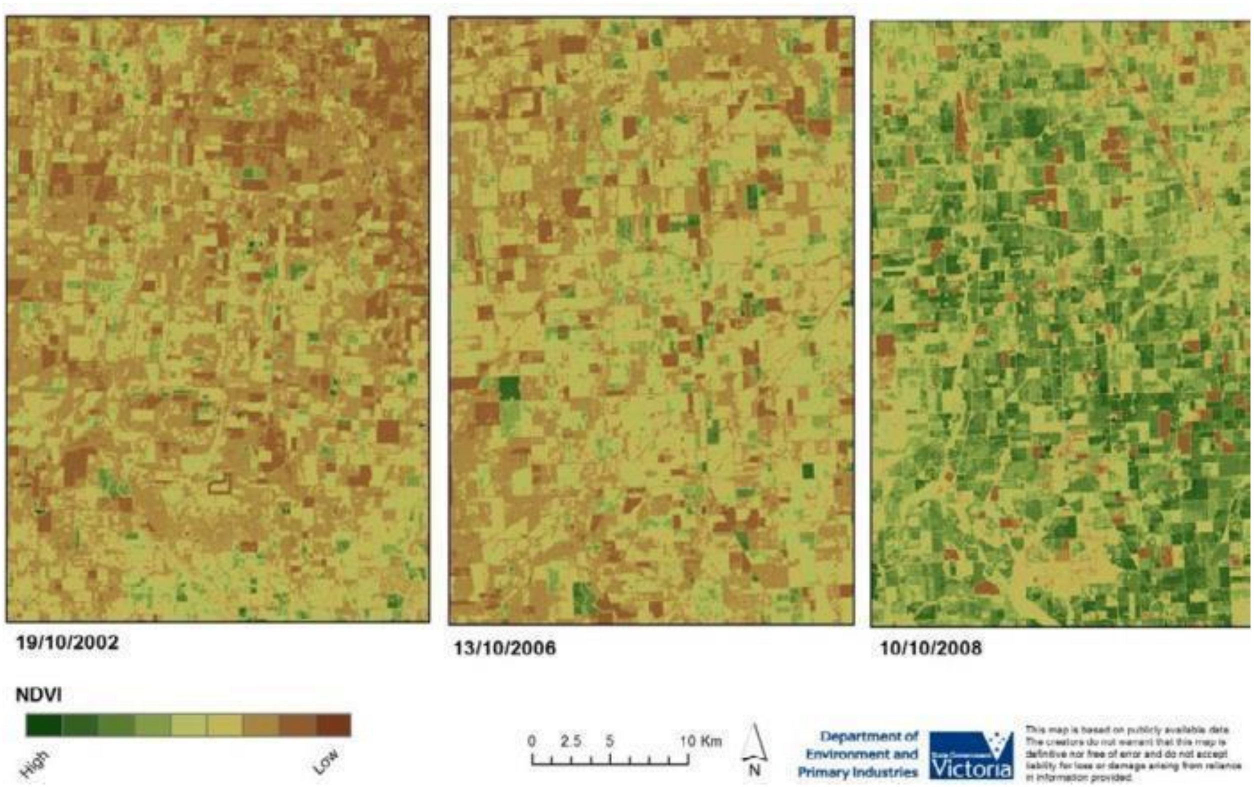

Figure 6: Normalized Difference Vegetation Index (NDVI) computed from Landsat data on three different years over the same agricultural area in Australia. Red indicates little to no vegetation (e.g., man-made objects or fallow fields) and green indicates vigorous vegetation (forested areas or agricultural croplands).

Landsat data have been extensively used in monitoring agriculture, mapping crop productivity and food security globally, which is critical in feeding the growing population and improving quality of life. USDA's National Agricultural Statistics Service (NASS) uses Landsat data to produce maps of crop types and acreage in the lower 48 states, which is known as cropland data layer (CDL) program. The cropland data layer published annually identifies what is growing where. The CDL collections are widely used by policy makers and managers to understand the global food supply, evaluate crop damage from floods and extreme weather events, direct crop rotation, and study water availability/consumption for agriculture.

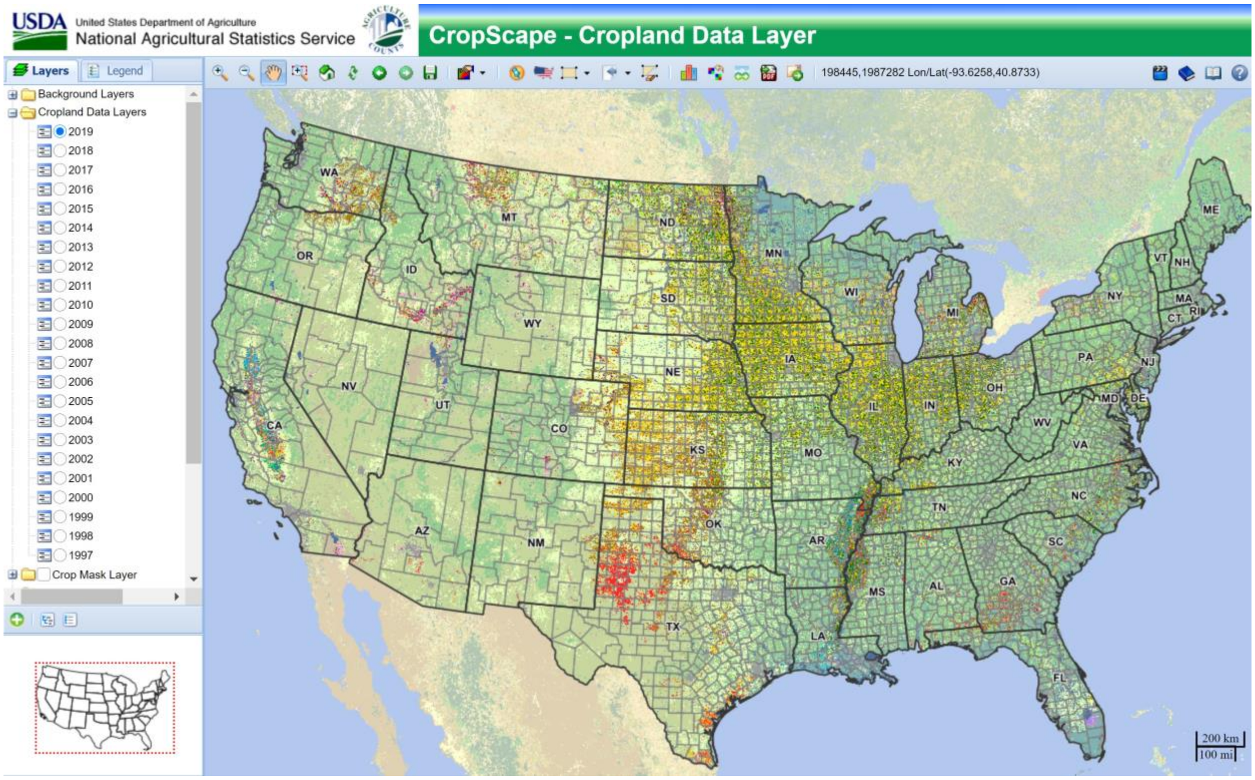

Figure 7: Historical cropland data produced and maintained by NASS, publicly available through the CropScape website (https://nassgeodata.gmu.edu/CropScape/).

Leveraging the Calibration Efforts and Sharing the Benefits

The well calibrated nature of Landsat products also lends itself to enhancing data from other satellites, which is sometimes referred to as cross-sensor calibration or registration. Writing in 2005, Dr. Joanne Grabynowicz, when commenting on the Land Remote Sensing Policy Act of 1992, noted the impact of Landsat program's commitment to its reliable calibration quality.[13] As Larisa Serbina and Colin Leslie from the USGS Fort Collins Science commented in 2015, "The products and processes developed by the Landsat program provide tools for data accuracy and visual communication improvement of other satellite imagery."[14] In that same article are several references to a Mapbox blog, written by Charlie Loyd, an imagery specialist at that company. He noted the spatial correction assistance that Landsat provided for DMCii, Planet Labs, and BlackBridge (now part of Planet Labs).

[13] "The importance of Landsat for calibration purposes was demonstrated with the emergence of Mission to Planet Earth (MPE). MPE was envisioned as a long-term, integrated monitoring system comprised of satellites and other on-orbit platforms. To prepare for MPE, NASA and NOAA needed a global data set to calibrate the mission's new sensors. The then existing law required them to purchase the data from EOSAT who quoted a price of $50 million. This became a major reason the law was changed." J.I. Gabrynowicz, The Perils of Landsat from Grassroots to Globalization: A Comprehensive Review of US Remote Sensing Law with a Few Thoughts for the Future, Chicago Journal of International Law: Vol 6: No.1, Article 6.

[14] https://landsat.gsfc.nasa.gov/landsat-and-the-private-tech-sector-direct-and-complementary-uses-of-imagery/

The scientific legacy of Landsat is also enabling the next generation of commercial constellation missions. For example, Planet Labs' disaggregated Dove land monitoring constellation of over 100 small satellites collect imagery at higher spatial resolution (3-5 meters) and revisit rates (as frequently as daily) than Landsat. Dove imagery that is collected near-simultaneously with trusted reference missions like Landsat is then automatically and continuously leveraged to bring all the Dove images to geometric and radiometric alignment with the Landsat calibration standard.[15] This enables Planet to leverage the Landsat historical record and scientific models to enable "new science" at higher spatial resolution and at a higher daily frequency going forward. Through a system-of-systems approach the public missions are already the calibration cornerstone for commercial land monitoring today.

Landsat data have also been used to improve both the spectral and radiometric calibrations and the aesthetics of other sources of satellite imagery by color-matching other satellite images against a Landsat-derived base layer. This is particularly useful when combining satellite images from multiple sources with varying degrees of their own calibration as well as varying color sensitivity, since Landsat provides a trusted reference layer that can be viewed as a "gold standard." This enables turning the left-hand mosaic (which resembles a pasted-up ransom note) into the seamless mosaic on the right.

Left: patchy assemblage *Right: seamless mosaic*

Figure 8: Left image: mosaic produced from individual scenes without calibration. Right image: seamless mosaic produced from individual, calibrated scenes. Courtesy Maxar.

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[15] Huang, Haiyan, Michigan State University, "Validation of a 30 m combined Landsat 8 and Sentinel 2A/B burned area product using high resolution PLANET Dove-Classic and Dove-R constellation data," American Geophysical Union, December 2019 (link).

The work done to establish Landsat as a calibration gold standard has other downstream benefits. Companies such as Maxar perform calibration of their own satellites[16], leveraging NASA calibration resources such as the Goddard Aeronet Network and many of the methods developed for Landsat, as well as comparing their calibration results to those of Landsat to ensure that they are consistent.

Landsat Calibration and Derived Societal Benefits

The continuous collection history of the Landsat program, as a record of land observations since 1972, is in itself a remarkable accomplishment. More significantly, however, is why that continuity has been so critical to societal advancement. The persistent and consistent cross-calibration and updated recalibration of the satellite sensors within the federally-funded program empowers trusted monitoring of both promising and threatening change-over-time. The Landsat archive is not just any collection of Earth imagery; Landsat is dynamically recording history. The Landsat mission unlocks the historical and tactical quantitative value of the commercial missions that are calibrated against it. It provides these capabilities for the public and commercial good in the most economical fashion in terms of taxpayer expense. Moreover, use of this historical archive reliably documents change, enables dependable Earth science research and analysis, and facilitates development of both commercial and government applications to address societal challenges.

Frequently, the Landsat benefits have been analyzed from an economic-benefits perspective, as mentioned in our introduction. This paper points to multiple comparably valuable quality-of life uses resulting in profound benefits because the Landsat continuity—for nearly five decades—permits a better understanding of our global ecosystem, improves practitioners' wisdom dealing with daily challenges, and relieves some of the tension in our daily lives.

In September 2019, the USGS Earth Resources Observation and Science (EROS) Center, launched an ongoing series of short podcast episodes entitled "Eyes on Earth."[17] A recent topic this past July was "Remapping LANDFIRE" which provides fire scientists with vegetation and fuels data needed to map the path of fires, to keep firefighters safe, and to model fire recovery. Such a presentation reflects the dependency upon remote sensing for monitoring Earth and giving global decision makers valued information. Other topics in this series include but are not limited to: *Wildfire Risk to Communities, EcoSystem Monitoring, Forests of Ghana, Mapping Alaska Permafrost, Evapotranspiration, Land Use, Plant Health (NDVI), Landsat and Water Quality, Famine Early Warning*.

[16] https://blog.maxar.com/earth-intelligence/2020/absolute-radiometric-calibration-is-an-essential-tool-to-imagery-science-but-what-is-it

[17] https://www.usgs.gov/centers/eros/science/eyes-earth?qt-science_center_objects=0#qt-science_center_objects

NASA also sponsors an excellent website "How Landsat Helps"[18] with interesting current case studies, including images, graphics, and traditional maps. The general topic tabs (Agriculture, Carbon and Climate, Disasters, Ecosystems and Biodiversity, Energy, Fire, Forest Management, Human Health, and Water) lead the reader to recent presentations and articles, underscoring the wide range of Landsat influence. In April 2020 there was an article on "Raising a Glass in Wine Country to Better Water Management." In March 2020, there was a review of a conversation with Dr. Donal Bisanzio "about the intersection of epidemiology and remote sensing." This was not specific to the COVID-19 pandemic but an explanation of the statement that "Most diseases are linked with particular characteristics of the environment." Dr. Bisanzio comments: "Many researchers working in public health institutions produce maps using Landsat images. These maps can be used to plan surveillance and interventions. For example, Landsat images are used to plan intervention targeting mosquitoes by identifying rice fields which are perfect breeding sites." In December 2019, there was an AGU presentation preview "Smokey the Beaver? Beaver Dams and Wildfire."

In 2020, remote sensing aficionados celebrated the fiftieth Earth Day. Landsat images proliferated as part of that celebration. Not only do those images reflect the beauty of Earth from space but they remind us of our responsibility to use the imaged resources providently for all society's benefit.

Landsat: The "Gold Standard"

The continuing investment by DOI/USGS and NASA to sustain the Landsat program of platforms and sensors calibrated to high accuracy creates confidence within the diversified and international user community. All expect that Landsat data is spectrally well-characterized, geometrically and radiometrically accurate, and that as techniques are developed and applied to improve that reliable accuracy, those data will continue to be used as the standard against which other sensors are compared.[19] Landsat is also the longest running, multi-decadal record of calibrated observations of the earth's surface. Because of this, it's possible not only to evaluate change over time but also to register other data sources to Landsat data that was collected in the same timeframe.

Acknowledgments

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[18] https://landsat.gsfc.nasa.gov/how_landsat_helps/

[19] Minsu Kim, KBR, "Radiometric & Geometric evaluation of Dove Classic, Dove Landsat, and Dove-R" Session 11, JACIE 2019 Thurs, Sep 26, 2019.