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Landsat 8–9 Geometric and Radiometric Calibration and Characterization

The U.S. Geological Survey (USGS) Earth Resources Observation and Science Cal/Val (Calibration and Validation) Center of Excellence (ECCOE) is a global leader in improving the accuracy, precision, and quality of remote-sensing data. Calibration is the process of quantitatively defining a system's response to known and controlled signal inputs. Validation is the process of assessing, by independent means, the quality of the calibrated data products derived from system outputs (Committee on Earth Observation Satellites, 2025).

The Landsat Cal/Val team, comanaged by ECCOE and the National Aeronautics and Space Administration (NASA) Landsat Science Project, continually monitors the geometric and radiometric performance of active Landsat missions and makes calibration adjustments, as needed, to maintain data quality at the highest level (Haque and others, 2024), ensuring its reliability for scientific research (Hemati and others, 2021). Landsat data quality is often referred to as the "gold standard" (National Geospatial Advisory Committee, 2020; NASA, 2025) and gives other civil and commercial satellite programs a trusted reference point for measuring their own data quality (Wulder and others, 2019).

The Landsat program started more than 50 years ago. Since then, Landsat missions have gone through multiple technological advances, which, together with improved calibration and validation techniques, have led to higher data quality over time (Mishra and others, 2016). The Cal/Val team also maintains consistency in data calibration across the multiple generations of sensors, which is vital to many scientists for time-series analysis (Bullock and others, 2020; Zhu and others, 2020).

Overview of Landsat 8–9 Sensors

Landsats 8 and 9 carry two sensors: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). Both sensors image the Earth with a 185-kilometer swath in the east-west across-track direction. An example of a Landsat 9 OLI Level 0 three-band color composite shows the staggered sensor chip assembly (SCA), detector, and band misalignment between OLI spectral bands (fig. 1). The OLI focal plane

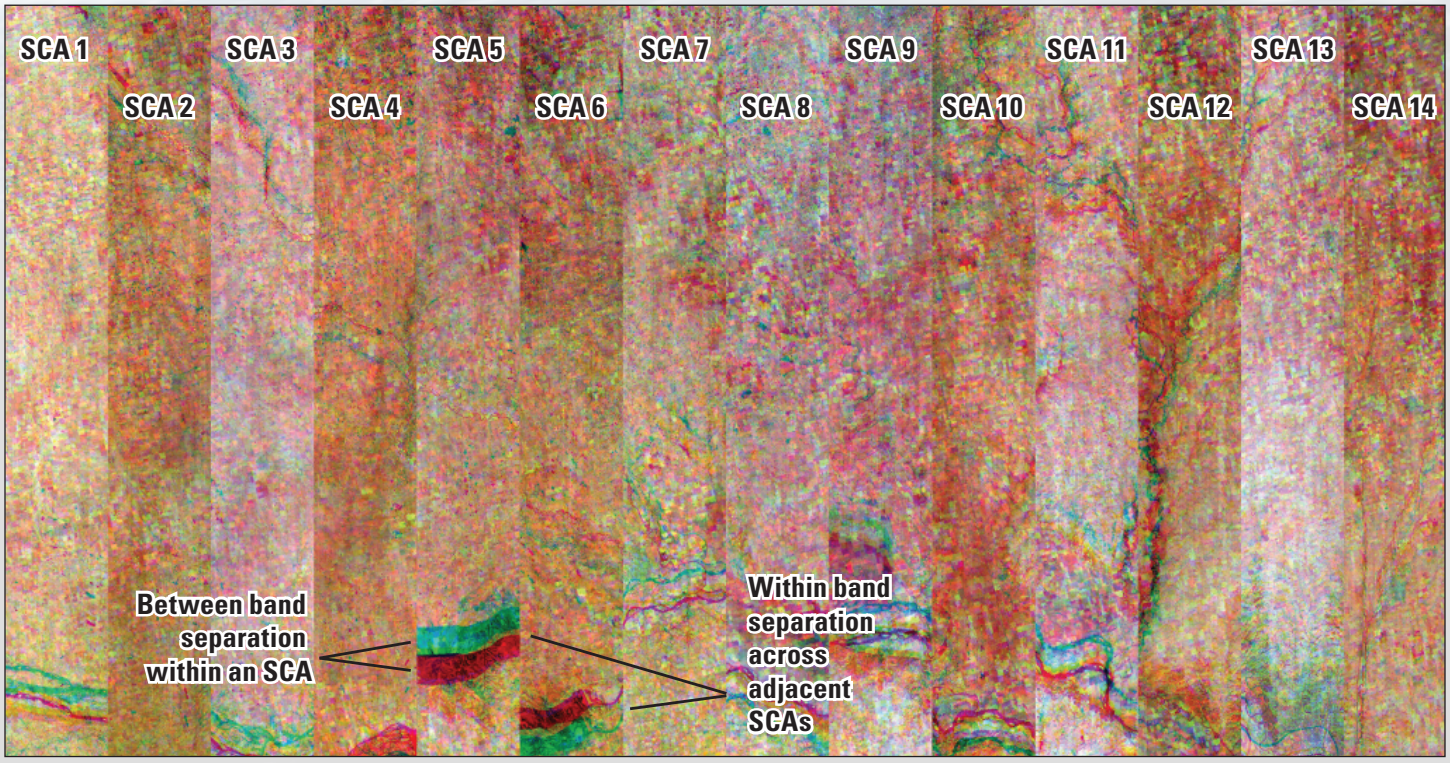

Figure 1. Landsat 9 Operational Land Imager shortwave infrared 1, near-infrared, and red bands (bands 6, 5, and 4) in Level 0 image (from Shaw and others [2024]). [SCA, sensor chip assembly]

is made up of 14 SCAs with 9 spectral bands that cover the visible, near-infrared, and shortwave infrared reflective regions of the electromagnetic spectrum (fig. 2). All OLI bands have a 30-meter spatial resolution, with the exception of a 15-meter panchromatic band.

The TIRS focal plane is made up of 3 staggered SCAs (A, B, and C) with 2 spectral bands in the thermal emissive region of the electromagnetic spectrum (fig. 3). Both bands have a spatial resolution of 100 meters.

Geometric and Radiometric Characterization and Calibration

Many factors affect the pixels in a final Landsat image product. Sensor artifacts, viewing and illumination angles, atmospheric conditions, terrain, stray light, spectral variation, and spacecraft attitude (that is, its orientation in space) all affect the accuracy and quality of the data. To ensure that Landsat data meet the highest standards, the Landsat Cal/Val team regularly monitors and characterizes the performance of each sensor, the spacecraft, and the overall image. Calibration and validation processes work together to correct and verify performance, ensuring accurate and reliable images that deliver the best "gold standard" product to end users (National Geospatial Advisory Committee, 2020).

Geometric characterization assesses how sensor and spacecraft performance affect the placement of pixels within an image. Geometric calibration corrects these effects so that pixels appear in the correct geographic locations. Geometric validation independently assesses and reports the accuracy of pixel locations in the final product.

Radiometric characterization assesses sensor performance and its effects on pixel brightness within an image. Radiometric calibration removes sensor effects from image pixels and ties the image pixel values to an accepted reference to ensure the brightness values are scientifically correct. Radiometric validation independently assesses and reports the accuracy of those values in the final product.

Figure 2. Operational Land Imager focal plane. [SCA, sensor chip assembly]

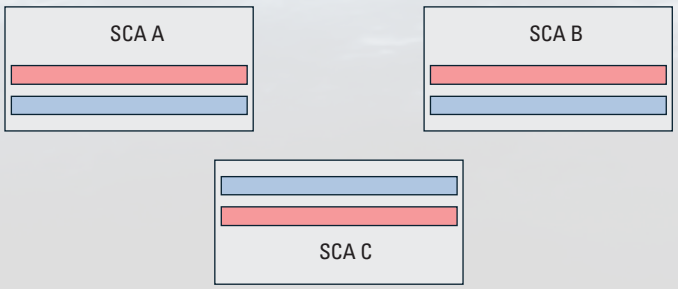

Figure 3. Thermal Infrared Sensor focal plane. [SCA, sensor chip assembly]

Landsat 8–9 Data Correction

Raw Landsat data (Level 0) consist of uncorrected digital numbers captured by the sensors with geometric misalignment between odd and even detectors, SCAs, and spectral bands. An example of a Landsat 9 OLI Level 0 single-band image is shown in figure 4. Throughout the image, misalignment in the SCAs is visible. Discontinuities between two adjacent SCAs are shown in the inset image. The zoomed-in image shows odd and even detector staggering.

Radiometrically corrected and geometrically raw Landsat data (Level 1R) contain the same geometric offsets present in Level 0 data, but the raw sensor values have been corrected and are represented as calibrated and scaled digital numbers. An example of a single-band grayscale Level 1R Landsat 9 OLI image is shown in figure 5. Within the image, geometric detector and SCA offsets are still visible, but radiometric distortions are corrected.

Radiometrically and geometrically corrected Landsat (Level 1) data consist of the radiometric correction applied in the Level 1R processing plus geometric correction. For Level 1 Terrain Precision (L1TP) products, the leading and trailing SCA imagery is removed, and data are geolocated and transformed to a map projection coordinate grid. Products are geometrically corrected and registered to the Landsat ground control library, which also accounts for terrain effects. The completion of these steps produces precise radiometric and geometric products that are well registered to each other. A single-band grayscale L1TP Landsat 9 OLI image is shown in figure 6. An L1TP three-band OLI color composite is shown in figure 7.

The Landsat Cal/Val team continually monitors the geometric and radiometric performance of active Landsat missions and makes calibration adjustments as needed to maintain data quality at the highest level. Results of these analyses are summarized in quarterly USGS Open-File Reports (for example, U.S. Geological Survey [2025]).

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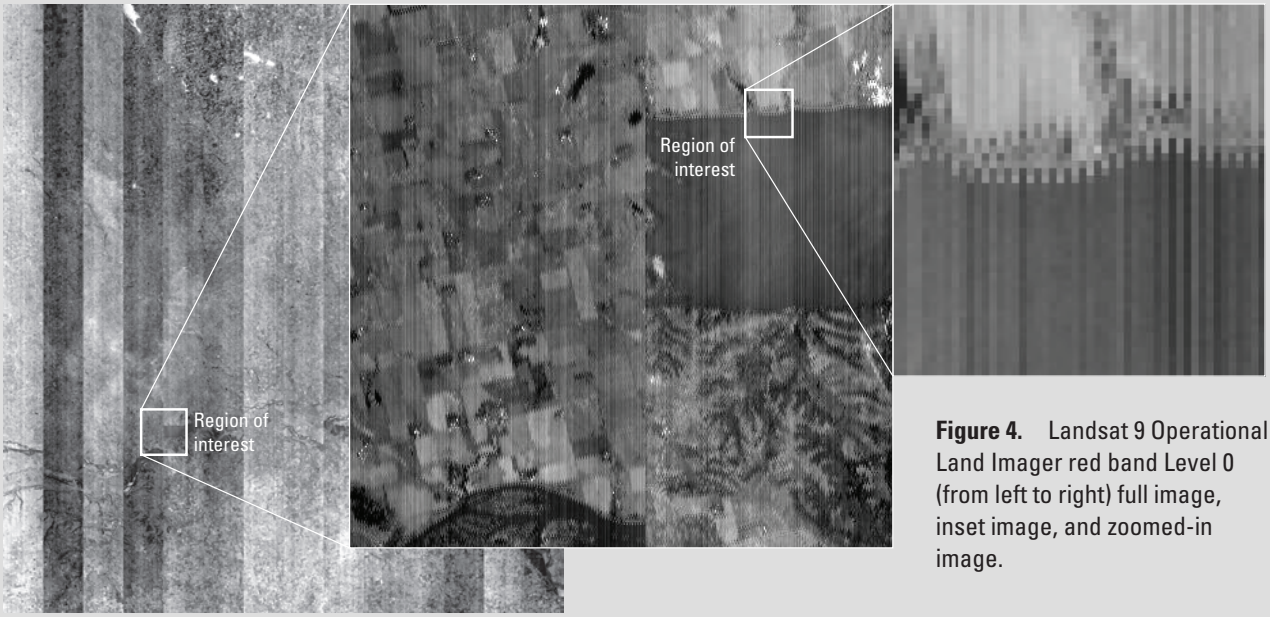

Figure 4. Landsat 9 Operational Land Imager red band Level 0 (from left to right) full image, inset image, and zoomed-in image.

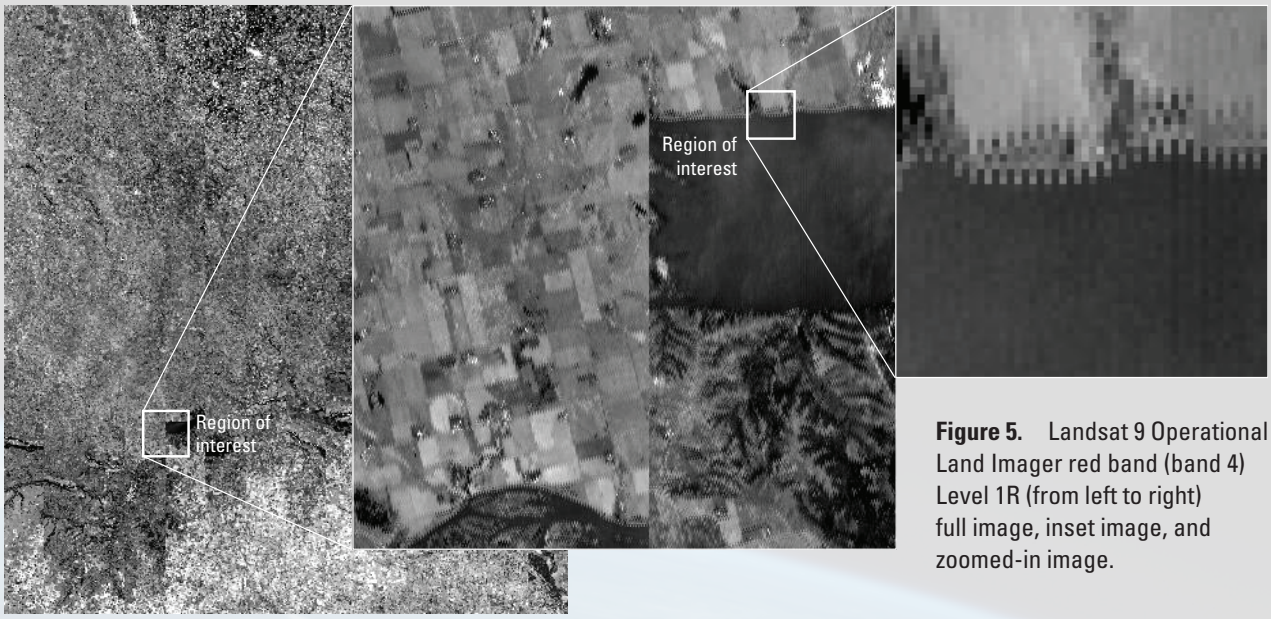

Figure 5. Landsat 9 Operational Land Imager red band (band 4) Level 1R (from left to right) full image, inset image, and zoomed-in image.

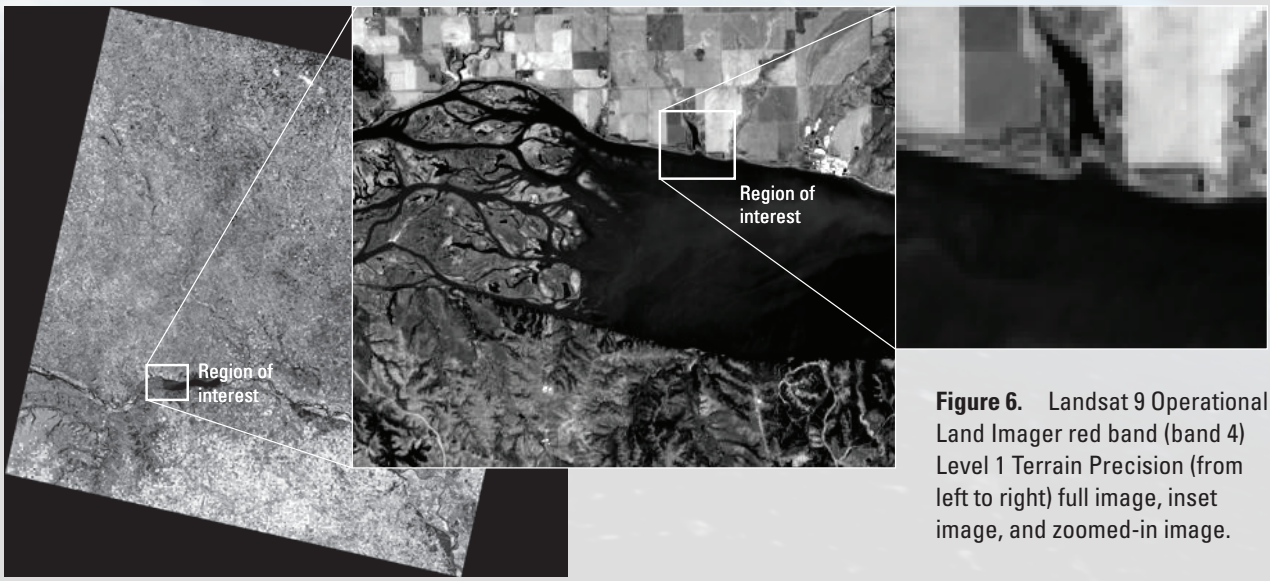

Figure 6. Landsat 9 Operational Land Imager red band (band 4) Level 1 Terrain Precision (from left to right) full image, inset image, and zoomed-in image.

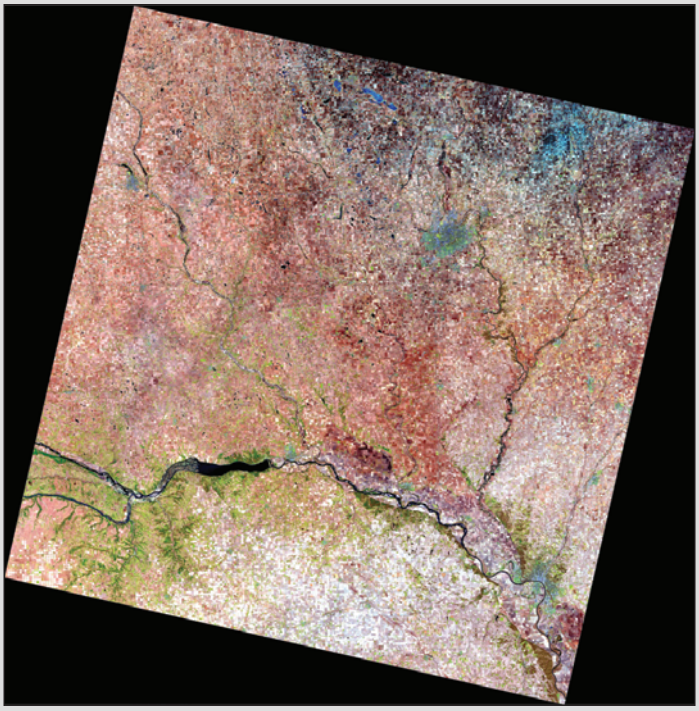

Figure 7. Landsat 9 Operational Land Imager Level 1 Terrain Precision true-color image consisting of shortwave infrared 1, near-infrared, and red bands (bands 6, 5, and 4).

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