### Title: Landsat Program

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# 3.1. Abstract

Landsat initiated the revolution in moderate resolution Earth remote sensing in the 1970's. With seven successful missions over 40+ years, Landsat has documented - and continues to document - the global Earth land surface and its evolution. The Landsat missions and sensors have evolved along with the technology from a demonstration project in the analog world of visual interpretation to an operational mission in the digital world, with incremental improvements along the way in terms of spectral, spatial, radiometric and geometric performance as well as acquisition strategy, data availability, and products.

# 3.2. Introduction

The Landsat program is rapidly converging on a half-century of global land monitoring, our longest continuous satellite record of the land environment. The changes in the world environment during that span have been tremendous and the overarching trends of increased population and economic growth have accelerated the human transformation of the land surface. In some cases, such as agriculture and urbanization, the human imprint is direct; in other cases (climate impacts) the forcing is indirect.

The architects of the Landsat program anticipated this increasing human impact in the mid-1960s. Although global climate change was a distant concern, U.S. Geological Survey (USGS) Director William T. Pecora discussed in very direct terms the anticipated difficulty in sourcing natural resources for an increasing global population: "Since we must take from the Earth to provide for ourselves we must employ value judgment and trade-off concepts in deciding how much to take...If the Earth is to provide the materials for the survival of man's society, then a prudent society must provide for an intimate understanding of the Earth." (1) Thus was born the idea of using the new vantage point of space to routinely assess Earth's natural resources against anticipated needs.

Since the launch of Landsat-1 in 1972, the seven successful Landsat missions have provided some 6 million multispectral images of Earth's land areas (2). While the technical quality of those images has steadily improved with the addition of new spectral bands, better radiometry, and improved spatial resolution, the core "visible and near-infrared" record stretches back to the start of the program. This record has allowed researchers and resource managers to track global deforestation, urban growth, changes in agricultural management and extent, water quality, glacier dynamics, and a host of other Earth processes. The rapid increase in the number of moderate-resolution imaging systems worldwide is tribute to Landsat's success. Systems such as Système Pour l'Observation de la Terre (SPOT), China-Brazil Earth Resources Satellite (CBERS), ResourceSat, Sentinel-2, and the Surrey Disaster Monitoring Constellation (DMC) now provide "Landsat-like" data on a near-daily basis for the entire globe. As noted by Robinson Meyer in *The Atlantic* : "If that sounds like an unremarkable idea, it's only because—just as you might read Shakespeare and find it full of clichés—the assumptions of the Landsat program have so soaked into society that we hardly notice them." (*3*)

Despite the proliferation of moderate-resolution satellite imagers, Landsat still provides a unique value proposition for users. Five aspects make Landsat the "gold standard" for land remote sensing:

1) Spatial resolution is sufficiently fine to monitor human land use and environmental changes but sufficiently coarse to permit routine seasonal coverage of the globe.

- Spectral coverage is across the visible and infrared parts of the electromagnetic spectrum, including coverage in the shortwave-infrared (1.55-1.75 μm, 2.08-2.35 μm) and thermalinfrared (10.4-12.5 μm) regions.
- 3) Science-quality data is calibrated to at-sensor radiance and reflectance, so that long-term trends in land properties can be distinguished from changes in instrument performance.
- 4) A true global acquisition strategy ensures seasonal acquisitions for all land masses.
- 5) Distribution of data is free and open.

While the increasing numbers of international and commercial imaging systems provide a tremendous augmentation to the core Landsat capability, no other system has yet satisfied all of these criteria.

Applications of the Landsat data set have evolved over the program life. Early applications required only a limited number of satellite images (almost entirely photographic products at that point) and represented a direct extension of traditional aerial photography practice. Very quickly, however, the opportunity to use Landsat imagery to track both inter- and intra-annual change in land vegetation properties became obvious (*4*). For the early U.S. Department of Agriculture (USDA)/National Aeronautics and Space Administration (NASA) joint projects such as Large-Area Crop Inventory Experiment (LACIE) and Agriculture and Resources Inventory Survey Through Aerospace Remote Sensing (AgRISTARS), mapping crop type, condition, and yield was predicated on establishing the seasonal evolution of vegetation spectra rather than simply classifying single date images. Today, parallel computing combined with rapid access to large volumes of free data have revolutionized the multi-temporal use of the Landsat archive. Applications involving thousands (and sometimes millions) of scenes are now common and the

science community is pushing toward daily temporal resolution by combining Landsat data with other satellite sources (5, 6).

The evolution from visual interpretation to automated processing of daily imagery could only come about because of the high radiometric and geometric consistency of the Landsat products. The job of ensuring this quality has rested with the mission managers and calibration experts within NASA, USGS, and academia. Each Landsat sensor has a unique personality, with particular technical capabilities and limitations. The sensors degrade with age and the calibration teams develop workarounds to mitigate the worst effects. The sensors must in turn be cross-calibrated across the entire data record back to 1972.

This chapter provides an opportunity to explore the technical side of the Landsat data record. We wish to document the design characteristics and performance issues that govern the Landsat data record, and also document the operational changes to the system over its lifetime.

# 3.3. History

# 3.3.1. Program History

As the origins of the Landsat program have been covered in detail elsewhere (4, 7, 8), this discussion will provide only a short summary of the main developments. In particular, the reader is directed to the forthcoming Landsat legacy book, currently titled "Landsat's Enduring Legacy: Pioneering Global Land Observations from Space", to be published by the American Society for Photogrammetry and Remote Sensing (ASPRS) (9), which provides a comprehensive history of the technology and political context based on project documents as well as interviews with the surviving participants.

## 3.3.1.1. Background

Two threads of technology came together in the late 1960s to spur the development of Landsat: (1) the development of in situ and airborne multispectral (infrared) imaging and (2) early civilian space-based imaging. Aerial photography had been used for cartographic and geologic mapping since the early 20<sup>th</sup> century and the USDA began systematic air surveys of croplands in the 1930s. By the 1940s, advances in both infrared film and electronic detectors provided an opportunity to fly multispectral instruments that provided separate measurements of the visible and infrared portions of the electromagnetic spectrum. In the postwar years, researchers such as Robert Colwell (University of California, Berkeley) and Ralph Shay (Purdue University) publicized applications of multispectral observations for forestry and agriculture. By the 1960s Purdue University's Laboratory for Agricultural Remote Sensing (LARS) began building alldigital multispectral airborne instruments, marking the inevitable migration away from filmbased aerial photography and providing an important prototype for the Landsat spaceborne instruments.

The 1960s also marked the beginnings of space-based Earth observation. The Television Infrared Observation Satellite (TIROS-1), launched in 1960 by NASA, provided the first television images of Earth from orbit. Although crude, these images showed that the atmosphere of Earth (unlike Venus) was sufficiently transparent to allow surface features to be observed from space. This capability was further explored via astronaut photography experiments conducted during the manned Gemini and Apollo projects. These surveys used 70 mm color and color-infrared film, and provided numerous examples of land features that could be discerned from orbit. Because these images were publicly available, they became important in "selling" the subsequent Landsat program to the public and Congress (*10*). A parallel development was military reconnaissance photography, particularly the orbital Corona program which began in 1959. The Corona satellites used 70 mm black and white film (subsequently color infrared) to image targets of opportunity deemed strategically important (*11*). The film canisters would then be ejected from the spacecraft, reenter the atmosphere, and be retrieved in midair by airplanes. Unlike the astronaut photography programs, the emphasis in Corona was on operational reliability and maximizing spatial resolution, the latter achieved by specially engineered films and optical systems. However, despite the parallelism between civilian Earth observation and the military reconnaissance, there does not appear to have been significant collaboration between these domains during formulation of the Landsat program (*7*). Taken together, these technology threads lay the groundwork for a civilian satellite program for monitoring Earth resources. Specifically, by the late 1960s it had been demonstrated that:

- Orbital imagery could provide synoptic views of land features, with sufficient spatial detail to support management objectives.
- Multi-spectral images, with separate coverage for visible and infrared channels, yielded unique information critical for geologic and vegetation mapping.
- Weather and intelligence satellites could provide imagery on an operational basis, day in and day out.

## 3.3.1.2 Programmatic Origins of ERTS

The concept of an Earth-orbiting resources satellite was first advocated within the Department of Interior (DOI) and USGS. As early as 1962, plans were formulated for a small orbital observatory for vegetated land cover. However, these concepts gained little traction with NASA, which was primarily concerned with manned spaceflight and the upcoming Apollo program.

Instead, in September 1966 Interior Secretary Stewart Udall unilaterally announced plans for an Earth Resources satellite project to be managed by the DOI. The announcement, issued without consultation within the Johnson Administration, angered both NASA and the Department of Defense (DOD). On the civilian side, NASA did not want competition as the nation's single space agency, while the defense establishment was wary of any public dissemination satellite imagery for fear of compromising strategic advantage.

Nevertheless, facing a need to demonstrate practical applications of the space race, NASA initiated its own Earth Resources Technology Satellite (ERTS) program in 1967. A National Academy of Sciences panel endorsed the concept and issued recommendations for a satellite observatory that included three polar-orbiting imagers focused on land use applications. NASA made plans for a two-satellite ERTS program and in early 1969 issued contracts for the implementation of an ERTS-A (later Landsat-1) satellite and ground processing system. Although the recent emphasis in the Landsat program has been to secure continuity of observations across sequential missions, it should be remembered that the original National Academy vision was three satellites operating simultaneously, in order to obtain near real-time information to support land management. The launch of ERTS-A / Landsat-1 took place a mere three years later, on July 23, 1972, quickly followed by its clone in 1975. From here on, NASA decided the satellites would officially be named Landsat-1 and Landsat-2.

The primary sensor on ERTS was the Return Beam Vidicon (RBV) from the Radio Corporation of America, essentially an analog video camera with three visible and near-infrared (VNIR) bands based on instruments flown for the TIROS meteorological program. Since the RBV used cathode ray technology it was susceptible to within-image distortions that made the data challenging for use in cartographic applications. A second, experimental instrument – the

Multispectral Scanner System (MSS) - was provided by Hughes Santa Barbara. The MSS was a digital, across-track scanner with four VNIR spectral bands. Since the scanning system did not image an entire "frame" at once, it was further removed from traditional concepts of aerial photography. However, the fact that the image could be precisely reconstructed via ground processing meant that the image geometric quality was superior to that of the RBV. In any case, the RBV instrument stopped working only 15 days after launch, and the MSS became the primary instrument for the early Landsat missions.

#### 3.3.1.3. Early Operations and Commercialization

Early results from ERTS/Landsat-1 were presented at national workshops, including the first NASA/USGS Pecora Conferences, the ERTS Principal Investigator Program symposia, and the Environmental Research Institute of Michigan (ERIM) Machine Processing Workshops. It was clear from the outset that MSS data provided a host of new applications for agriculture, forestry, water resources, and geology. In the middle to late 1970s, after the launch of Landsat-2, the focus of the Landsat program switched specifically to agricultural remote sensing with the LACIE and AgRISTARS programs, both joint programs between NASA and the USDA. These were major data analysis efforts designed to build the capability to predict wheat production across the Soviet Union (LACIE) and later expanded to other crops on a global scale (AgRISTARS). Although the technical aspects of these programs were largely successful, limitations to timely data delivery as well as the subsequent privatization of the Landsat program and resultant high data costs hindered the operational adoption of Landsat within the USDA. To justify building and launching Landsat-3 in 1978, NASA added a thermal infrared band to the MSS and redesigned the RBV sensor. By the end of the 1970s, however, NASA's role as a

research agency was coming into conflict with the perception of Landsat as an operational satellite system. Accordingly, the Carter administration transferred operations of the existing Landsat program to the National Oceanic and Atmospheric Administration (NOAA), the home of the nation's operational weather satellites, in 1979. The administration also recommended an eventual transfer of the program to commercial operation over the 1980s.

At the same time, NASA began investing in new technology for the Landsat satellite series with Landsats-4 and -5 (referred to as Landsat-D and -D Prime while under development). Following recommendations of a user's working group and the National Research Council (NRC), the Thematic Mapper (TM) instrument was conceived primarily to support land cover and vegetation mapping (12). The TM instrument was designed to acquire imagery in the shortwave infrared and thermal infrared as well as the visible-near infrared portions of the spectrum. In addition, the spatial resolution of the VNIR-SWIR (reflective) bands was improved to 30 m. In order to allow the satellite platform to be serviced by the Space Shuttle, the orbit was lowered from 910 to 705 km, and the imaging repeat cycle decreased from 18 to 16 days. The combination of higher spatial resolution, improved radiometry, and expanded spectral coverage proved extremely challenging for the instrument builder (Hughes Santa Barbara Remote Sensing). Due to difficulties with both the instrument and spacecraft, the project ran over schedule and over budget. Although Landsat-4 suffered several technical glitches after launch in 1982 that limited its use, these were resolved in its twin, Landsat-5, prior to its accelerated launch date in 1984. Landsat-5 proved to be the workhorse of the fleet, acquiring imagery for some 27 years after its launch in 1984.

The transition to the Reagan administration in 1981 began a drive to reduce government spending and commercialize government activities. An initial push was for greater cost recovery

from the Landsat program. NOAA began to set product prices to cover the entire operating budget of the Landsat program, not just the marginal cost of producing the products. As a result, the cost of data products to end users jumped up by an order of magnitude and Landsat usage stagnated or declined, especially among the research and academic communities. Subsequently the land satellite program as a whole was targeted for privatization. This effort was driven by the belief that if Landsat data had widespread utility for land management, then a commercial company should be able to sell the data and use that revenue stream to future spacecraft development. The existing operational Landsat system was transferred to the winning (and only) bidder, the EOSAT Corporation, in 1985. EOSAT also declared plans for building and launching two more satellites (Landsat-6 and Landsat-7) by the early 1990's with minimal government subsidies.

As has been documented extensively, commercialization of Landsat by EOSAT failed on both scientific and economic terms. From the science perspective, Pecora's original vision of a global observatory was pushed aside in order to maximize acquisitions from paying customers, relatively few of whom had direct interest in Africa, Antarctica, the Amazon, and other environmentally critical (but less developed) parts of the globe (*8*). From an economic perspective, although EOSAT was able to slowly grow revenue from sales of Landsat products, the revenue was never sufficient to comfortably fund construction of a new spacecraft without significant government subsidies and cutting corners on engineering. With increasing data costs generating complaints within the user community and the continued need for government support, it was clear by the late 1980s that the commercialization effort was not succeeding. When the EOSAT-managed Landsat-6 failed to achieve orbit after launch in 1993, EOSAT

quickly withdrew from the Landsat arena and (under the new name Space Imaging) turned its attention to the more lucrative market in high-resolution imagery.

The 1992 Landsat Remote Sensing Policy Act reaffirmed the importance of the Landsat record for global change science and returned operation of future missions to the U.S. government (8). Of particular importance, the Act directed implementation of a Landsat-7 mission as well as study of options for a follow-on. A subsequent period of management turmoil saw both NOAA and DOD exiting the program management structure and by 1997 Landsat again became a joint partnership between NASA (responsible for building and launching the space hardware) and USGS (responsible for the ground system and operations). With some degree of program clarity restored, the Landsat-7 mission, with an Enhanced Thematic Mapper Plus (ETM+) instrument, was launched in 1999. Technically the ETM+ was similar to the earlier TM instrument but with improvements in radiometric quality, onboard calibration, and the addition of a 15 m panchromatic band. Landsat-7 was incorporated into the NASA Earth Observing System (EOS), which aligned the mission with long-term global studies of land cover and the terrestrial carbon cycle. As a result, Landsat-7 adopted the first true global acquisition plan since the early days of Landsat-1. At the same time, USGS dropped the cost of data products to users, thus spurring use of the data set.

## 3.3.1.4. Landsat-8 and Sustainable Land Imaging

To provide continuity with Landsat-7, the 1992 law directed NASA and USGS to examine a set of options for procuring the next mission. In order of priority these were: (1) a privately (commercially) operated system; (2) an international consortium; (3) a government-run system; and (4) a private-government partnership. After failing to find support for either the purely commercial "data buy" or an international partnership, attention turned to establishing a commercial-government partnership during 2000-2003 (*13*). In this arrangement, a commercial partner would build and launch the Landsat Data Continuity Mission (LDCM), and retain rights to sell higher spatial resolution data derived from the sensors. A reduced (30 m) resolution data set would then be provided to the government for free and open distribution. Although the concept appeared promising at first, the tightening of credit markets following the "dot com" crash of 2001 precluded any bidder from securing enough capital investment to offset the government contribution. As a result the commercial-government procurement was cancelled in October 2003. An additional two years was then spent looking at the options for placing a Landsat sensor on the NOAA/DOD polar-orbiting meteorological satellites (now called the Joint Polar Satellite System – JPSS). This option was eventually discarded due to the cost and complexity of adapting the Landsat instruments to the satellite platform. Finally, in December 2005 the Office of Science and Technology Policy (OSTP) directed NASA to pursue LDCM as a free-flyer, government-owned system.

Landsat-8 (as LDCM was renamed after launch) includes two sensors – the Operational Land Imager (OLI) covering the VNIR-SWIR bands and built by Ball Aerospace and the Thermal Infrared Sensor (TIRS) covering the long-wave infrared and built by NASA Goddard Space Flight Center (GSFC) (*13*). Both sensors use across-track linear arrays of detectors ("pushbroom" scanners) for the first time in the Landsat program (although the concept had been advanced originally for Landsat-D in the 1970s). The pushbroom architecture gives OLI and TIRS relatively long dwell time compared to the earlier "whiskbroom" across-track scanners, providing improved signal-to-noise performance. Landsat-8 OLI also provided two extra spectral bands in the VSWIR: a 440 nm coastal/aerosol band, and a 1370 nm band for detecting cirrus clouds. TIRS split the broad thermal band of the Thematic Mappers into two separate bands to support split-window approaches for atmospheric correction.

Landsat-8 was successfully launched in February 2013 onboard a United Launch Alliance Atlas-V rocket. As of this writing, Landsat-8 continues to be the backbone of the Landsat program. Although originally specified to acquire 400 scenes per day, the system is now operated to acquire over 700 scenes per day, essentially all of the Earth's land areas. Unfortunately, a stray light issue with the TIRS design has led to significant radiometric error in the longest wavelength thermal band (band 11), but the shorter wavelength thermal band (band 10) provides comparable radiometric accuracy to Landsat-7 ETM+.

Probably the most significant programmatic change in the last ten years was the decision by USGS to stop charging for data products. In 2008, Secretary of Interior Dirk Kempthorne announced the new policy based on internal recommendation as well as the example of the Brazilian Space Agency (INPE), which had begun distributing satellite products at no cost in the mid-2000s. The availability of "free data" from the USGS archive led to a dramatic surge in the downloading of Landsat data from the USGS archive, with 1.1 million scenes in fiscal year (FY) 2009 to 8.8 million scenes in FY 2015 (2). The availability of unlimited free data has revolutionized the application of Landsat data to continental- and global-scale mapping, and to understanding land dynamics via analysis of dense spectral time series (5, 6, 14, 15). Despite the evident importance of Landsat data, the program has never had a stable footing. With the exception of Landsats-1/-2 and Landsats-4/-5, each mission has essentially been formulated and funded individually, frequently leading to long gaps between launches. In 2014, the administration announced the Sustainable Land Imaging (SLI) program to ensure continuity of Landsat-type data over the next three decades. SLI is intended to be a long-term solution to

securing continuity of moderate-resolution observations and consists of both operational missions (Landsat-9 and Landsat-10) as well as technology investments to advance capabilities and reduce costs of future missions. Development of the first SLI mission, Landsat-9, was initiated by NASA GSFC in March 2015. Landsat-9 will be a rebuild of Landsat-8 (with upgraded TIRS instrument) and is slated for launch in 2020/2021.

### 3.3.2. Satellite Capabilities

All Landsat satellites have been launched into polar, sun-synchronous orbits in order to provide consistent viewing illumination (Table 1). Landsat-1 through -3 orbited at an altitude of 917 km, providing an 18-day repeat cycle. For Landsat-4 the orbital altitude was lowered to 705 km, providing a 16-day repeat cycle. Although the original justification for the lower orbit was to permit the Space Shuttle to service Landsat satellites (a plan abandoned after the abandonment of a West Coast Space Shuttle launch capability in 1986), the lower orbit was preserved for subsequent Landsat missions. The daylight portion of the orbit corresponds to the north-to-south ("descending") node. Midmorning equatorial crossing times have been preferred to minimize cloud cover and (at least early in the mission history) provide some sense of topographic relief for visual interpretation. The midmorning vantage was also used by some NOAA polar satellites and by the NASA EOS Terra platform, facilitating data fusion opportunities. However, beginning with the Suomi National Polar-orbiting Partnership (NPP) mission, future planned NASA/NOAA polar orbiting missions will have afternoon/night crossing times, limiting the possibilities for synergy between Landsat and coarse-resolution sensors.

*<note: insert Table 1 near here with the following title and footnote (also found in Table document)>* 

 Table 1: Orbital parameters for Landsat spacecraft.

\* Landsat-5 crossing time drifted to as early as 9:12am in 1995 due to the failure to maintain orbit inclination during EOSAT operations. (Sheffner Landsat Program chronology online: <u>http://geo.arc.nasa.gov/sge/landsat/lpchron.html</u>)

Landsat images are organized according to an orbit-based Worldwide Reference System (WRS) grid (*16*). WRS "paths" are defined by the orbital swath of the sensors, while WRS "rows" segment the paths by lines of latitude. The result is a grid of "path/row" combinations that define the geographic extent of each Landsat scene. Since the orbital parameters of the Landsat system changed between Landsat-3 and Landsat-4, there are two separate WRS systems in use: WRS-1 for Landsats-1 through -3, and WRS-2 for Landsats-4 through -9.

Spacecraft characteristics for the Landsat missions are given in Table 2. The first series of Landsat platforms were based on the Nimbus-4 weather satellite and built by General Electric. Landsat-1 through -3 included a Wideband Video Tape Recorder for storing imagery and subsequently downlinking to ground stations. Landsat-4 and -5 were designed to use the NASA Tracking and Data Relay Satellite (TDRS) system, such that image data would be relayed to TDRS in real time and then directly to ground stations. Accordingly, neither Landsat-4 nor -5 included an onboard recorder. Unfortunately, Landsat-5 lost its TDRS transmitting capability in 1992 and Landat-4 in 1993. After those dates, each satellite could only provide imagery in real time via direct downlink to ground stations. Since the ground station network had limited or no coverage in many parts of the globe, including Africa, northern Eurasia, and Antarctica, the density of global acquisitions suffered during the 1990s until the launch of Landsat-7.

<Insert Table 2 near here with the following title and footnote>

Table 2: Landsat spacecraft characteristics.<insert table>

Note: mass is given as dry (d) or wet (w). Sources: USGS Landsat Mission History: <u>http://landsat.usgs.gov/about\_mission\_history.php;</u> EO Portal Satellite Database: <u>https://eoportal.org/web/eoportal/satellite-missions;</u> WMP Oscar Tool:

<u>https://www.wmo.int/pages/prog/www/wigos/wir/oscar.html;</u> Landsat legacy book (9); NASA LDCM Launch Press Kit: https://www.wmo.int/pages/prog/www/wigos/wir/oscar.html.

# 3.3.3 Sensors

### 3.3.3.1 Basic Design

Over the course of the Landsat program there were 5 basic instrument designs: the Return Beam Vidicon (RBV), the Multi-Spectral Scanner (MSS), the Thematic Mapper (TM) and its derivatives, the Operational Land Imager (OLI), and the Thermal Infrared Sensor (TIRS). The early RBV's on Landsat-1 and -2 were three co-aligned television-like cameras, each with one spectral band, spanning visible to near-infrared (VNIR) wavelengths. Earth images were recorded on the imager's photosensitive surface and scanned by an electron beam to generate an analog video signal. While conceived as the primary instrument over its MSS counterpart, hardware malfunctions limited its utility. There were two higher resolution single band RBV's on Landsat-3 mission. Only limited RBV film products can be readily obtained from the USGS archive, so these instruments will not be discussed further. Additional information on the RBV can be found in the USGS Long Term Archive and SBRC RPT41741 (References 17 and 18).

Unlike the RBV, the MSS was a whiskbroom scanning system that generated digital multispectral data. Five instruments were flown. The first two MSS instruments had four VNIR bands and were flown on Landsat-1 and -2. The MSS on Landsat-3 included a thermal band. However, due to poor noise characteristics and an early failure of one of the detectors, the thermal band was shut off after a year of operations (19). The MSSs on Landsats-4 and -5 returned to the four-band design. Additional design changes were made to account for the lower Landsat-4/-5 altitude.

The original two TM instruments flew on Landsat-4 and -5 and provided improved radiometric, spatial, and spectral performance over the MSS. The Enhanced Thematic Mapper (ETM) added a panchromatic band at higher resolution, but it was lost in the launch failure of Landsat-6. The Landsat-7 Enhanced Thematic Mapper+ (ETM+) improved upon the ETM design by providing higher resolution thermal data while adding several calibration devices.

For Landsat-8, the whiskbroom scanner design was replaced with two pushbroom instruments; the Operational Land Imager (OLI), which covered the visible, NIR, and SWIR bands and the Thermal Imaging Sensor (TIRS), which acquired two thermal infrared bands. In addition to both instruments providing greater signal-to-noise characteristics, the OLI provided broader spectral coverage with the addition of a 440 nm coastal/aerosol (CA) band and a 1375 nm Cirrus band.

The instrument design characteristics and specifications for the Landsat instruments are summarized in Tables 3 and 4.

#### <insert Table 3 near here with the following title/caption>

**Table 3. Sensor Per Band Specifications – Spectral Band Pass, Precision, Resolution.** From Lansing and Cline, 1975 (*20*), Engel and Weinstein, 1983 (*21*), Mika, 1997 (*22*), Knight and Kvaran, 2014 (*23*), Reuter et al., 2015 (*24*), Tarde et al., 2012 (*25*).

<Insert Table 4 near here with the following title/caption>

**Table 4. Sensor Specification – Sensor, Telescope, Detectors, Calibrators.** (Lansing and Cline, 1975 (20), Engel and Weinstein, 1983 (21), Mika, 1997 (22); Knight and Kvaran, 2014 (23); Reuter et al., 2015 (24).

### 3.3.3.1.1 Telescopes and Optics

From Landsat-1 through Landsat-7, all telescopes for the MSS, TM, and ETM+ instruments

were reflective Cassegrain (Ritchey-Chretien) systems. The relatively narrow field of view of

the telescope was scanned across the Earth with a scan mirror. For Landsat-8, wide field of view telescopes were used (~15° across-track). OLI is a Four Mirror Anastigmatic (FMA) all reflective design; TIRS is a four element refractive design.

## 3.3.3.1.1.1 MSS

In addition to the telescope mirrors, the MSS optical path included a scan mirror, rotating shutter, and fiber optics that transmitted the light from the focal plane to the detectors (Figure1). The primary and secondary mirrors were made of fused silica. For the scan mirror, a beryllium (Be) substrate was selected for its stiffness and low metallic density and flex pivots were used to minimize rotational wear. While the scan mirror provided wide-field spatial coverage across its detector array, active imaging only occurred while scanning in one across-track direction (i.e., "west to east" with respect to the spacecraft's orbital direction). The Landsat-3 MSS thermal band required relay optics to get the signal to the separate thermal focal plane. The relay optics for the Landsat-3 MSS thermal band consisted of three lenses for collimation and correction and two flat mirrors.

#### *<insert Figure 1 near here, with the following caption>*

**Figure 1. Optical Path of the MSS instruments.** The scan mirror sweeps across the Earth view and while turning around, the shutter wheel rotates the on-board calibration source onto the optical axis. The band 5 Relay Optics were only included on Landsat-3 MSS. Lansing and Cline, 1975 (20).

#### *3.3.3.1.1.2 TM and ETM+*

A major improvement in the TM design and its derivatives was the addition of the Scan Line Corrector (SLC) mirror system (Figure 2). This provided for active bidirectional imaging, (i.e., on both forward and reverse scans). By compensating for the spacecraft motion, the SLC effectively aligned the scans in a parallel manner. The SLC was comprised of a pair of beryllium (Be) substrate flat mirrors oscillating on flex pivots to minimize rotational wear. Ultimately this improved design provided ~2x greater "scanning efficiency" (i.e., % of total scan period devoted to active imaging) over the MSS, allowing for longer detector dwell times and increased detector

signal and spatial resolution.

The separate cold focal plane for the SWIR and thermal infrared detectors required relay optics.

The additional folding and spherical mirrors allowed for thermal isolation between the cold and

warm portions of the optical path.

# <insert Figure 2 and the following caption near here>

**Figure 2. ETM+ Optical Path with a photo of the calibration shutter detail.** The oscillating scan mirror sweeps across the Earth view and while it is reversing direction the shutter flag sweeps across the optical axis. Fiber optics and lenses in the shutter flag pipe the light from the off-axis on-board lamps to the focal plane. The mirror on the shutter flag reflects the energy from the off-axis blackbody onto the focal plane. The shutter itself serves as the dark target for all bands. The TM optical design is similar Arvidson et al., 2013 (*19*).

# 3.3.3.1.1.4 OLI

An off-axis, four-mirror anastigmatic design was chosen for the wide field of view needed for a pushbroom instrument. The system was designed with a front aperture stop to reduce the size of the solar diffuser and to be nearly telecentric to reduce angle of incidence effects on the spectral filters across the focal plane. The four telescope mirrors were all manufactured from a Zerodur® substrate (Figure 3). A tilted, anti-reflective coated zinc selenide (ZnSe) focal plane window sits in front of the OLI focal plane. A focus mechanism is available for on-orbit focus adjustments, if necessary, though it has not been used to date.

<insert Figure 3 near here with the following title/caption>

**Figure 3. OLI Telescope Assembly Diagram**. This shows the four-mirror anastigmatic design. Also shown are the location of the internal calibration lamp assemblies and the focal plane. Modified drawing from Ball Aerospace (26).

# 3.3.3.1.1.4 TIRS

The TIRS telescope is a four lens refractive system (Figure 4) with one ZnSe and three

germanium lenses. Heating elements and a passive radiator control the temperature of telescope

optics to approximately 186 K to provide a low thermal background. The Scene Select

Mechanism (SSM), a flat rotatable mirror, sits in front of the telescope. The SSM mirror rotates

to one of three positions: 1) Earth view, via its nadir port; 2) on-board blackbody view; or 3)

deep space view, via its deep space port.

## <insert Figure 4 near here with the following caption>

**Figure 4. TIRS Telescope Design.** The cut-away diagram of the telescope shows the four lenses, the location of the spectral filters, and the focal plane. At the top of the telescope, the Scene Select Mechanism (SSM) mirror rotates between three positions to view deep space, the internal blackbody, and the nadir Earth view. Barsi et al. 2014 (*27*).

# 3.3.3.1.2 Detectors

# 3.3.3.1.2.1 MSS

At the time of MSS development, limited detector technology and cost led to the use of relatively large photomultiplier tubes (six per band) for three bands and six silicon photodiodes for the second NIR band. The size of the detectors precluded their direct location at the focal plane and relay fiber optics with their terminations at the instrument focal plane were used. For Landsat-3 MSS, two mercury cadmium telluride (HgCdTe) detectors were used for the thermal band. The detector outputs were digitized to 6-bits on board for all bands. The photomultiplier tube outputs were typically non-linearly compressed prior to digitization.

# 3.3.3.1.2.2 TM

With the advances in solid-state technology in the 1970s, the TM band detectors were arrayed in 16 element (4 for the thermal band) monolithic designs that were physically located at the focal planes. Bands 1-4 used silicon photodiodes; bands 5 and 7 indium antimonide (InSb) photodiodes, and band 6 HgCdTe photodiodes. Each band consisted of two staggered rows of eight detectors, except for band 6 which consisted of two staggered rows of two detectors. The SWIR and thermal detectors require cooling to increase sensitivity so the arrays were mounted on a separate focal plane from the VNIR bands. A radiative cooler maintained the cold focal plane arrays to ~ 90 K. The cooler could be set to other operational set point temperatures, specifically, 95 and 105 K. TM data were digitized to 8 bits.

### 3.3.3.1.2.3 ETM+

The primary focal plane was redesigned from TM to accommodate a single, monolithic detector array across all the VNIR bands. The single array construct provided better geometric band-band registration stability. The number of thermal band detectors was doubled to increase the spatial resolution of the band. With the electronics modified to accommodate two selectable gain states per detector, along with a number of refinements to improve the offset stability and A/D convertor uniformity, the ETM+ also achieved better radiometric performance over its predecessor sensors.

### 3.3.3.1.2.4 OLI

The change to a pushbroom design results in many more detectors and a physically much larger focal plane. The OLI focal plane consists of 14 Focal Plane Modules (FPM's) (Figure 5). Each module hosts ten rows of detectors, each with its own spectral filter (including a masked band

mask for determining SWIR detector offsets). The modules are staggered with overlap across the focal plane and span the 185 km FOV. The focal plane is passively cooled to ~ 205 K. Every band has 494 detectors per module, except the Pan band with 988. Silicon PIN detector arrays are used for the visible and NIR bands, and HgCdTe arrays for the SWIR bands. In addition, detector redundancy is provided with multiple rows of detecting elements: 2 rows for the visible and NIR bands, and 3 rows for the SWIR bands. This redundancy allows for problem detectors to be removed from use prior to launch; also, the detector selection can be changed on-orbit if any one detector is deemed inoperable. OLI data are digitized to 14 bits, though only 12 are transmitted to the ground.

*<insert Figure 5 here with the following title/caption)* 

**Figure 5.** Photograph of the 14 Focal Plane Modules on the OLI Focal Plane Assembly (left) and a close up of the module spectral filter (right). The order of the bands in the filter is Cirrus, SWIR1, SWIR2, Green, Red, NIR, CA, Blue, and Pan (top to bottom) though on the assembly, the top modules are inverted from the bottom modules, so the spectral band order is reversed. Courtesy of Ball Aerospace (26).

### 3.3.3.1.2.5 TIRS

The TIRS focal plane hosts three Sensor Chip Assemblies (SCA's), each an array of 512 x 640 gallium arsenide (GaAs) Quantum Well Infrared Photon (QWIP) detectors, two spectral filters (10 and 12  $\mu$ m), a masked band, and associated electronics (Figure 6). The arrays are staggered on the focal plane and span the 185 km FOV. While each SCA hosts 512 rows of detectors, only six are selected for imaging within each SCA: two rows under each filter and two from the masked region. The focal plane is cooled to approximately 40 K with a two-stage cryocooler in order to eliminate excess dark current. 12 bit TIRS data are transmitted to the ground.

<insert Figure 6 near here with the following title/caption>

**Figure 6. The TIRS focal plane with three QWIP arrays exposed (left) and the focal plane with the filter assembly installed (right).** The six filter segments are visible on the filter assembly, which is tinted a green color due to the anti-reflective coating. Reuter et al. 2015 (24).

## 3.3.3.1.3 Calibration Systems

All Landsat instruments with reflective bands had some type of lamp and shutter based system, often called an Internal Calibrator (IC), for calibration of the reflective bands. Those instruments with thermal bands had various combinations of blackbodies, shutters, and deep space views for radiometric calibration. For the MSS, TM, and ETM+ instruments the IC calibrators were designed to operate in synchronization with their scanning mirror systems. This provided perscan calibration values (i.e., gains and offsets). For the Landsat-8 OLI sensor, the continuous pushbroom scanning did not allow for per-line lamp signals, so the lamps were powered on before or after acquisition intervals when the shutter was closed. Similarly for Landsat-8 TIRS, the blackbody and deep space calibrations occurred in a special calibration operation preceding and following each acquisition interval. A solar calibrator was first introduced with the Landsat-1 MSS. No solar calibration was available on Landsat-4 and -5 MSS or TM. Solar calibration was reintroduced on Landsat-7 ETM+ and included a deployable solar diffuser. Table 5 lists the calibration devices and the frequency of use for each instrument.

<insert Table 5 near here, with following title/caption>

**Table 5. On-board calibration devices and their frequency of use**. The TIRS calibration intervals changed in 2015 due to an electronics failure which required that the SSM be used less frequently. The ETM+ included two types of solar calibrators though only one proved useful.

# 3.3.3.1.3.1 MSS

The MSS shutter was a rotating wheel that included a mirror and variable Neutral Density Filter (NDF) that varied in transmittance with rotation angle *(28)* (Figure 7). The lamp assembly included two lamps - a primary and a redundant. A lamp illuminated the shutter wheel and as

the shutter wheel rotated, the light was attenuated through different regions of the NDF producing a wedge-shaped detector response, known as the calibration wedge, during every other scan retrace interval. Six samples of this calibration wedge provided six intensity levels that were used for calibration.

#### <insert Figure 7 near here with the following title/caption>

**Figure 7. Expanded view of the MSS shutter wheel.** At two points on the wheel, the shutter wheel obstructs the view of the Earth. At one closure, the detectors see the internal calibration source (lamps) through the NDF. The other closure served as the dark target for the NIR-2 silicon band. Lansing and Cline, 1975 (20).

Solar calibrations were also performed for bands 1-4 using the Sun Calibrator. This passive device was comprised of four adjoining mirror facets with each mirror positioned at an offset angle to accommodate a solar acquisition in any given facet. The sun was acquired approximately 18 degrees prior to terminator crossing to allow an independent verification of the lamp calibration. The solar calibrator on Landsat-1 MSS became contaminated (*20*) and although the later MSS Sun Calibrators were not contaminated, the data were not used in calibration processing. The Landsat-4 and -5 MSS sensors did not have the sun calibrator.

#### 3.3.3.1.3.2 TM

For the Landsat-4 and -5 TM, the Internal Calibrator (IC) system was changed from a rotating shutter wheel to a calibrator flag assembly. The assembly included a mechanical arm (or "flag") extending from a rotation motor at its base. Fiber optics ran from the base to the top of the flag. The top of the flag included a black painted region for use as dark target for the reflective bands and a near-ambient temperature target for the thermal band, a toroidal mirror, and miniature optical elements (see detail in Figure 2) The flag oscillated in synchronization with the Scan

Lane Corrector such that signals from both the shutter and lamp could be detected while the scan mirror was turning around between each scan of the Earth.

"Stationary illuminators" near the base of the arm provided light for bands 1-5 and 7 (Figure 8). The illuminators were comprised of three lamps, three lenses, and three fold prisms. A field lens directed light from these illuminators to fiber optics in the flag, through the miniature optical elements in the top of the flag, and onto the focal planes. During calibration, all three lamps were continuously cycled through eight lamp states so there were eight distinct signal levels for calibration. The dark region on the flag provided bias values for the reflective bands. For the thermal band, the calibration source was a temperature-controlled cavity blackbody whose energy was reflected from the toroidal mirror on the calibrator flag onto the detector array. The flag dark region had an imbedded thermistor and provided the second near-ambient temperature reference.

#### <insert Figure 8 near here, with the following title/caption>

**Figure 8. The optical path of the TM Internal Calibrator.** The energy from the lamps in the stationary illuminators is piped to the focal plane via two sets of fiber optics for calibration of the reflective bands. The energy from the off-axis blackbody is reflected onto the thermal band detectors by a toroidal mirror. SBRC internal report (29).

#### 3.3.3.1.3.3 ETM+

The ETM+ IC was similar in design and operations to the TM calibration flag providing per-scan calibrations (Figure 9). Key design differences included two lamps (primary and backup), which operated at a single illumination level, and relay optics in the arm of the calibration flag using sapphire rods in lieu of fiber optics. The primary lamp was used in most of ETM+ imaging since launch. The use of the backup lamp was limited to prevent degradation due to usage. The backup lamp was used sparingly during the on-orbit checkout period (the first 90 days after launch),

during every other monthly solar calibration, and after the third year of mission operations,

during one interval every 16 days.

<insert Figure 9 near here with the following title/caption>

**Figure 9. The ETM+ Internal Calibrator Flag Assembly.** (a) is the optical drawing of the flag, (b) is the mechanical drawing. A detail of the shutter flag is also shown in Figure 2. SBRS, internal report (*30*).

Two calibration devices were used for solar calibrations: one passive and one deployable. The passive device, the Partial Aperture Solar Calibrator (PASC), was similar to the sun calibrator on the early MSSs (Figure 10). It consisted of four mirrors in the sunshade of the ETM+ that reflected solar energy onto the optical axis without need for maneuvering the satellite (28). The PASC data were acquired once per day while the satellite was exiting eclipse but before the northern hemisphere terminator was crossed. Large increases in the response of the ETM+ to the PASC solar signal were observed and are likely the result of contamination (31). In the end the

PASC results were not used for ETM+ calibration.

<insert Figure 10 near here with the following title/caption>

**Figure 10. The ETM+ Partial Aperture Solar Calibrator Design.** The uncoated silica plates and the apertures were intended to reduce the signal below the ETM+ saturation level, though a contaminant likely built up on the silica plates making the data of little use. Markham et al., 2003 (31).

The Full Aperture Solar Calibrator (FASC) was a deployable diffuser panel mounted outside the entrance aperture of the ETM+ (Figure 11). The panel was deployed shortly before exiting the eclipse portion of the orbit. The sun would illuminate the panel at solar zenith angles of  $90^{\circ}$  to about  $65^{\circ}$ . The panel was stowed shortly after the satellite crossed the terminator.

The ETM+ thermal calibration system was very similar to the TM design.

<insert Figure 11 near here with the following title/caption>

**Figure 11.** The ETM+ Full Aperture Solar Calibrator Design. Upon deployment, the panel moved from its stow location to in front of the instrument entrance aperture. Markham et al., 2003 (*31*) and SBRS (*30*).

### 3.3.3.1.3.4 OLI

The Landsat-8 OLI on-board calibration system consists of two lamp assemblies, a shutter, and two solar diffusers. The shutter and diffuser wheel are mounted in front of the telescope in the calibration assembly. Each of the OLI lamp assemblies contains two sets (a primary and a redundant) of three tungsten halogen bulbs. Each set contains a working, back up, and pristine bulb (Figure 12). Each lamp in one assembly is wired in series with one lamp in the other assembly. The lamp assemblies are located on opposite sides of the telescope at the entrance aperture (see Figure 3). When turned on, a given lamp pair illuminates the full focal plane. The lamps operate in constant current mode and are monitored for stability with a silicon photodiode. The lamp pairs are used at different frequencies to aid in detecting lamp degradation. The working pair are used once a day, the backup pair once every 16 days, and the pristine pair once every six months.

#### <insert Figure 12 near here with the following title/caption>

**Figure 12. OLI Lamp Assemblies showing illuminated bulbs in the aperture baffle (left) and a schematic drawing of the lamp assemblies showing the six bulbs and the monitoring diode (right).** Knight and Kvaran, 2014 (23).

The OLI shutter consists of a wheel and housing on the calibration assembly (Figure 13). An open slot in the wheel and housing are aligned during nominal Earth imaging. The shutter wheel is rotated to block the Earth view for acquisition of a dark image at the top and bottom of each orbit. The shutter is also closed during maneuvers or to maintain the health and safety of the instrument. A fail-safe actuator ensures against the shutter wheel remaining stuck with the shutter in the closed position.

The Solar Diffuser Assembly consists of diffuser wheel with three slots; the working and pristine panels occupy one slot each and the third remains open. A stepper motor is used to control the deployment of the diffuser wheel and a fail-safe actuator ensures that the diffuser wheel can be restored to its open-aperture position. During calibration, a diffuser is rotated into position in front of the instrument aperture, overfilling the FOV and the calibration port is pointed at the sun via a spacecraft maneuver. Like the lamps, the diffusers are used at different frequencies to aid in detection of their degradation: approximately weekly for the working diffuser and twice yearly for the pristine diffuser. Along with the lamps and lunar calibration data, both diffusers provide for calibration stability monitoring.

#### <insert Figure 13 near here with the following title/caption>

**Figure 13. The OLI Solar Diffuser and Shutter Assemblies**. The diffuser wheel is shown in its open position. The Earth is viewed through the Entrance Light Shade, the sun is viewed through the Solar Light Shade, and the entrance aperture to the OLI is at the Aft Light Shade. Knight and Kvaran, 2014 (23).

### 3.3.3.1.3.5 TIRS

The Scene Select Mechanism (SSM) on the front of the TIRS telescope assembly provides views to nadir (Earth), deep space, and the on-board blackbody (see Figure 4). The deep space view and the blackbody provide the cold and warm signals required for calibration. The blackbody is a v-grooved flat plate with high emissivity. It can be set to any temperature between 270 K and 330 K. Although it is regularly set at the nominal temperature of 294 K, there are semiannual campaigns to sweep through the range of blackbody temperatures to monitor linearity and noise level stability.

In 2015, the encoder that detects the position of the SSM mirror began behaving erratically. In order to maintain the life of the SSM, the operational concept had to be modified to use the SSM

less. This involved reducing the calibration acquisitions of deep space and the blackbody from twice an orbit to once every two weeks.

# 3.3.4 Operations Concept/Acquisition Plan

From its inception, a continually refreshed global archive has been a primary goal of the Landsat program. Many obstacles arose through the years to prevent a consistent achievement of this goal: onboard tape recorder problems in the 1970s, communications and cost issues in the 1980s and 1990s, and instrument duty cycle limitations in the 2000s. Not until Landsat-8, launched in 2013, has this primary goal been consistently achieved. This section addresses these obstacles in more detail, as well as the evolution of both the operations concept and acquisition plan to the point of enabling this global archive.

## 3.3.4.1 The MSS Era – Landsats-1 through-3

The MSS instrument operations concept in the 1970s was to send science data in real-time, using S-band narrowband links, to U.S. stations (Alaska, California, and Maryland) and place data acquired outside their view circles on the onboard recorder for later downlink to these stations. This worked for the first few years of each mission, but was problematic once the recorders began their inevitable on-orbit deterioration. A saving grace in this era was the involvement of ground stations sponsored by other countries, though these data were not as easily accessible. These stations collected data in real time every time the satellite passed overhead during the day. Some night passes were acquired from Landsat-3, which had a thermal band added to its MSS. In 2006, USGS started an archive consolidation initiative to repatriate these internationally-

acquired data back to the U.S. archive, thus filling in some of the large gaps in global coverage resulting from the recorder issues.

Given the recorder problems in the later years of the first three Landsats, the original acquisition goal of global coverage was quickly revised to full U.S. coverage plus locations required to support ongoing science investigations. The latter included a vigorous Principal Investigator program with over 300 projects scattered globally. Additionally, two agriculture-centric programs—LACIE and AgRISTARS—drove acquisitions over farming regions of South America, northern Europe, and Africa. In their best year, Landsats-1 through -3 acquired an average of 147, 122, and 70 scenes/day, respectively. In contrast, Landsat-8 acquisitions are a sustained 740 scenes/day.

### 3.3.4.2 The TM Era – Landsats-4 and -5

The Landsat -4/-5 communications architecture incorporated lessons learned from dealing with the cumbersome, unreliable tape recorders of the earlier missions. Landsats -4/-5 had direct downlink capability using the higher speed X-band. But instead of recording data onboard when out of view of the U.S. downlink stations, Landsats -4/-5 would relay the science data to the ground via a geostationary tracking and data relay satellite (TDRS). The initial configuration was two TDRSs, one stationed off the coast of Brazil and one over the Pacific Ocean, each in constant view of the White Sands Complex in New Mexico. White Sands would then relay the science data, via the commercial Domestic Satellite (DOMSAT) link, to the Landsat processing centers at NASA Goddard and USGS Earth Resources and Observation and Science Center (EROS).

Unfortunately, Landsat-4 was on orbit over a year before the first TDRS was launched in 1983 and in its intended position. In that first year, the primary science downlink failed two months after launch, the redundant link failed five months later, and solar array problems resulted in a loss of half the onboard power. There were no science downlink options after this until the first TDRS was ready. Even then, coverage was restricted to the U.S. in 1983 and essentially turned off after March 1984, with acquisitions assigned to the newly launched Landsat-5. The second TDRS was manifested on the Challenger shuttle in 1986, lost in the launch failure, and was not replaced until late 1988. Landsat-5 continued to carry most of the load until it too started having communication link failures.

In addition to being the TM and TDRS era, this was also the full-cost-accounting era at NASA and the commercialization era for Landsat. The commercial operator of Landsats -4/-5, Earth Satellite Company (EOSAT—later bought by Space Imaging), was charged dearly by NASA for the use of TDRS and, given irregular release of negotiated funds from Congress, chose to employ an acquire-on-request approach to acquisition planning after a few years of good faith global coverage with Landsat-5. Also, TDRS availability during human spaceflight missions was restricted.

Landsat-4 acquisition levels were very erratic—they were essentially dormant from 1984-1986 then were revived to offload Landsat-5 as its communication links started to fail, leaving Landsat-5 to cover the U.S. while Landsat-4 acquired global data through TDRS. In the late 1980s, EOSAT/Space Imaging revised their acquisition plan and started increasing global coverage as well as supporting specific campaigns, such as bathymetric collections over the ocean and forest acquisitions for the Forest Resources Assessment project. In early 1993, Landsat-4 acquisitions for the U.S. archive were terminated but some international stations continued to receive MSS data on a limited basis.

Landsat-5 acquisition levels dropped in the late 1980s as one of two Ku-band TDRS links and one of two X-band direct downlink links failed. In 1992, the second Ku-band link failed, terminating all science data relay links with TDRS. From this point, international coverage was achieved using the established international stations and transportable ground stations that were strategically placed where EOSAT/Space Imaging thought they could sell data (e.g., Dubai station that provided coverage of Somalia, Afghanistan, as well as Iran/Iraq) or in underserved areas such as Antarctica and the northwest corner of South America.

Landsat-5 operational responsibility was ceded by EOSAT/Space Imaging in 2001 and USGS assumed operations. Coverage in the 2000s spiked in support of the 2000, 2005, and 2010 global land survey (GLS) acquisition campaigns, with negotiated support from international stations who returned data to the U.S. for inclusion in the survey data sets.

In its lifetime, the peak Landsat-4 daily acquisition average was 50 scenes/day in 1999. Landsat-5 acquisitions peaked at 147 scenes/day in 1986 and averaged 50–140 scenes/day from 1993 onward.

### 3.3.4.3 The LTAP Era – Landsat-7

Once again, lessons learned were applied to the next Landsat mission. By this time, technology had evolved such that space-qualified solid-state recorders were available and promised to be much more reliable than the tape-based mechanical recorders of the 1970s. As a result of design trades, the TDRS science data downlinks were removed from the configuration and solid-state recorders added. X-band wideband links to ground stations were used to get science data to the

ground. Use of some stations would be free, while others would carry a price, but the overall costs would be lower than with TDRS.

With the optimism engendered by the large-capacity onboard recorders that were capable of holding over 100 scenes, the Landsat program set out to formulate a plan for achieving that elusive goal of consistently refreshing a global archive. Developers, planners, scientists, and managers collaborated to create the long-term acquisition plan (LTAP) that would work in concert with the acquisition scheduling software to "stock" the archive with relatively cloud-free, sunlit, global land scenes and refresh that archive on a seasonal basis. In addition to the basic global archive refresh goal, attention was paid to niche science communities with specific coverage needs, such as reefs just after the annual bleaching event and six months later, glaciers at the end of summer and before the first snowfall, tropical rainforests at every opportunity to defeat near-constant cloud cover conditions, and volcanoes at night if recent or imminent activity is observed. These were added to the LTAP as niche campaigns.

The LTAP also specified the default gain setting to be used across the year for each scene (each ETM+ band can be acquired in either high gain or low gain mode). The final leg of the LTAP was the climatological history of each scene, in terms of average cloud cover for each month of the year as computed from an eight-year cloud data set (*32*).

Implementation of the LTAP was primarily via database queries, allowing a lot of flexibility in setting up and tuning parameters to maximize use of available onboard resources (i.e., recorder capacity and ETM+ duty cycle) and scheduling of the "best" 250 scenes. With the three major factors defined—seasonality, gain setting, and cloud climatology—the database queries determined the most optimal scenes to schedule each day based on acquisition history (are there recently acquired clear scenes?), cloud cover predictions (better than average or worse?), missed

opportunities (how many times have we tried and failed to schedule it?), and nearness to end of the request (is time running out?). Completed prior to launch, the LTAP became operational after the 90-day on-orbit commissioning period and very quickly proved its worth by filling the archive with global, relatively clear imagery.

It became clear early in operations that the onboard recorder was filling up with acquisitions over Asia and could not be emptied at existing downlink sites before we overflew Europe, Africa, and South America, thus skewing our acquisition coverage. Contacts were added at Svalbard, Norway and Alice Springs, Australia to download data recorded over Asia and make room for western Hemisphere acquisitions.

Evolution of the LTAP included:

- Adding a few buffer "land" scenes around selected coastal areas to accommodate some of the international ground stations whose software needed additional data ahead of the first target scene.
- Tailoring the annual Antarctic campaign to increase the acquisition timespan but restrict overall coverage to those areas with a high change rate, active studies, and persistent cloud cover.
- Removing niche campaigns that were no longer useful or had been subsumed into the primary LTAP seasonality.
- Changing the sun angle threshold for daytime acquisitions from 5 degrees of elevation, the at-launch value, to 15 degrees of elevation in the northern hemisphere to reduce winter imaging of persistently snow-covered regions.
- Reworking the gain settings, in coordination with the calibration team, to change gains based on sun angle and land cover, thus avoiding saturation observed by users in the early data products. Included was the classification of desert and snow/ice scenes.
- Dithering the location of gain changes to avoid repeatedly impacting the same scene with a gain change.

LTAP validation efforts confirmed that annual coverage was achieved for most land locations and seasonal coverage of most global land was achieved quarterly, but not yet monthly (*33*). Biases in the acquisitions included:

- Too many desert scenes due to very few clouds to degrade the acquisition priority.
- Too few boreal scenes due to the frequent cloud cover and poor cloud predictions.
- Undue influence of western continental offshore morning fog banks on the whole-scene cloud cover assessment, resulting in repeat acquisitions of scenes with foggy ocean and clear land.

Adjustments were made to priorities and seasonality for desert and boreal scenes. The need for land-only cloud cover assessment was identified and an algorithm was delivered to USGS to implement, but it wasn't incorporated into the Landsat-7 baseline until 2015. The validation also confirmed that cloud predictions between 0–10% and 80–100% were reasonably accurate, while the remaining values were not well correlated with cloud truth, especially in the tropics. This knowledge was incorporated into the LTAP by setting an upper threshold of 80% predicted cloud cover when assessing candidates for scheduling. If the predict was greater than 80%, it was removed from consideration with a high level of confidence that the resulting image would indeed have been highly cloud covered. In general, the cloud avoidance scheme of comparing predictions against climatology resulted in a much clearer archive than any previous Landsats or other Earth imaging missions such as SPOT.

The 2003 scan-line corrector failure led to a major change in the scene acquisition philosophy. To maximize the likelihood of a second scene being acquired within a few cycles to facilitate gap filling, the scheduling queries were modified to make use of the gap phase statistic denoting the gap locations to consider the likelihood of successfully filling the gaps, to aim for 315 scenes daily instead of 250, and to prioritize the pairing of scenes.

Operations were reasonably steady through 2011. At that point, work was in progress on Landsat-8 and thought was being given to the new mission's acquisition requirements and user products. A pilot program to explore standard Level 1 terrain-corrected products was started and, as part of that, Landsat-7 raised its acquisition levels to 345 scenes/day in July 2011 and eventually to 450 scenes/day by August. To accommodate this, tweaks were made to the acquisition priorities and an additional recorder unloading opportunity was added. In 2013 a deliberate effort was made to maximize the acquisitions of Landsat-7 data prior to its eventual demise. It was already a 14-year mission, well beyond its 5-year design life. The new approach, the continental land strategy, restricted acquisitions to continental land masses, some selected large islands, and any special requests submitted to and approved by the USGS. This was the end of the annual Antarctic campaign, as well as acquisitions of reefs, atolls, coastal waters, and scattered island groups. The new strategy also served to raise the cloudiness of the global archive as we were in effect acquiring all available land, within the given parameters. Some updates were required to assure sufficient coverage of western Africa and Southeast Asia, where ETM+ duty cycle constraints and recorder capacity were persistently causing scenes to be rejected during scheduling. The pilot test was such a success that in March 2014 the daily quota

was raised to 500 scenes and in September 2015 it was set at 550 scenes. In effect, there was no daily quota. The sole constraints during scheduling were instrument duty cycle and recorder capacity. Because the rejections in Africa and Asia were still occurring, a further experiment was performed in 2015 in which the ETM+ duty cycles were allowed to be exceeded by as much as five percent. After several months of testing and confirmation that the sensor was not at risk, the new duty cycles were made operational.

Thanks to the flexibility of the LTAP, and its rigor in scheduling only the best and clearest scenes, the Landsat archive in the Landsat-7 era grew tremendously and has achieved the annual global coverage dreamed of by the early Landsat pioneers.

## 3.3.4.4 Relatively Unconstrained Scheduling Era – Landsat-8

Most of the constraints imposed upon ETM+ scheduling fell away with the advances achieved by the Landsat-8 program in instrument design, onboard recorder capacity, and LTAP fine tuning. Both the OLI and TIRS instruments were designed to remain on, eliminating the need for duty cycle constraints. It would be possible (but not practical) to acquire imaging data around the clock, excluding time required for calibrations. However, the latter is not insignificant. Both the OLI and TIRS are new technology for Landsat and include new types of calibration, such as lunar observations, dark collects, and integration sweeps. While duty cycle concerns no longer impose on the scheduler, allotting time for calibrations does. The system capacity for imaging is still much greater than previous Landsats. The initial requirement was at least 400 scenes daily, but this soon grew to 550 scenes daily average eight months after launch and settled at 740 scenes daily average in July 2014 (this number includes an average of 15 daily flywheel scenes that close one-scene gaps between scheduled scene intervals).

The high acquisition rate is facilitated by the increased onboard recorder capacity, an upgrade from Landsat-7's ~100 scenes to Landsat-8's ~400 scenes. There is still a need for sufficient station contacts to empty the recorder several times each day, but the system has demonstrated an ability to "catch up" when one or two of these contacts are missed for some reason. A huge advance with the new recorder is the ability to track data receipt at the EROS archive and only overwrite the data on the onboard recorder after such acknowledgement is received. Files not successfully received can be scheduled for retransmission, a luxury not available to Landsat-7. The Landsat-8 LTAP is based on the plan developed for Landsat-7, with fine tuning to take advantage of Landsat-8's higher acquisition capacity as well as lessons learned on Landsat-7. Some of the more notable differences are:

- Selective areas of open water have been incorporated—the China Sea, Mediterranean Sea, Caribbean Sea, and Yellow Sea, among others—as well as water scenes around continental shores and occasional single water scenes between existing land scenes.
- The sun elevation constraint in the northern hemisphere was lowered from 15 degrees to 5 degrees to facilitate monitoring of northern snow and ice regions.
- Night imaging has been increased beyond the Landsat-7 15-minute constraint, with up to 90 scenes/day permitted by special request. Nighttime cloud predicts are now ingested to use in assessing night scenes for inclusion in the schedule.
- Base priorities have been exploited by creating polar ramps (decreasing priority toward the poles) to shift acquisitions from areas of high overlap near the poles to the midlatitudes and relying on the polar overlap to fill in.

 Antarctica is included in the baseline LTAP, with selected areas identified as "acquire once" as well as other areas designated for acquisition every opportunity. Ascending Antarctic scenes are still handled via special requests.

The parameters guiding the decisions made during scheduling, such as adjacent scene boost, missed opportunities boost, and cloud cover boost, are very similar to those used for Landsat-7 and have been tuned to the specifics of the Landsat-8 paradigm.

## 3.4 Understanding and Using Landsat Sensor Data

Four fundamental aspects of the Landsat sensors describe what is being measured and consequently how to interpret Landsat image data. These are: (1) the spectral response, which is the part of the electromagnetic spectrum that the sensor is measuring; (2) the spatial response, which is size and shape of the area being measured by the sensor; (3) the geometry, which is the location on the surface of the Earth that the sensor is measuring, and (4) the radiometry, or the amount of signal the sensor is measuring. Each of these topics will be discussed in sequence. Specifically included is where to find information on each sensor and the uncertainty in the characterizations.

### 3.4.1 Spectral Characteristics of Landsat Sensor Data

Basic sensor description tables provide a list of the spectral bands (Table 3). Often these tables provide the nominal spectral bands in terms of band edges, or band centers and bandwidths. The nominal data are typically based on the requirements or specifications as opposed to actual measured performance. More useful tables provide the measured average band edges (Table 6). The measured band edges still provide only part of the picture of where in the electromagnetic spectrum the energy in a given image is coming from; the sensor response as a function of wavelength provides the full picture. Typically this spectral response is separated from the radiometric response and expressed in terms of a relative spectral response, meaning that it is normalized to the maximum response. Complicating the process is that all the Landsat sensors have multiple detecting elements per band and each detector combined with the spectral filter has a slightly different spectral response.

A sample of the Landsat typical relative spectral response curves is shown in (Figure 14). The response is divided into "in-band" response, (i.e., response in the desired spectral region), nominally between the 1% relative spectral response points, and "out-of-band" response, (i.e., response outside of the desired spectral region), typically beyond the 1% response points. Often in-band response is shown on a linear scale and out-of-band response is shown on a logarithmic

scale.

## <insert Table 6 near here with the following title/caption>

**Table 6. Landsat Sensor Spectral Bandpasses**. These bandpasses (except Landsat-8 OLI and TIRS) are based on ambient pressure measurements and some, particularly the Landsat-5 sensors and earlier, can be expected to shift with the vacuum conditions on orbit. The upper edges of some bands, particularly MSS NIR-2 and Landsat-4 TM band 6 will shift with operating temperature. See Table 8 for source of RSR data for these calculations. Palmer et al., 1980 (*39*) and Markham and Barker, 1983 (*40*).

# <insert Figure 14 near here with the following title/caption. Note: the parts of the figure should be labeled as follows: A – upper left, B- upper right, C-lower left, D-lower right>

**Figure 14.** (A) In-band average spectral response for Landsat-8 OLI band 4, based on integrated instrument level measurements. (B) Full band average spectral response including out-of-band regions, based on component level measurements. Barsi et al. 2014 (*37*) (C) In-band average spectral response for Landsat-8 TIRS band 10, based on component level measurements. (D) Full band average spectral response for Landsat-8 TIRS band 10, based on component level measurements. Montanaro et al. 2014 (*38*).

## 3.4.1.1 Factors determining relative spectral response

All of the Landsat sensors to date have been multi-band radiometers, which means the spectral

separation is primarily determined by spectral filters as opposed to a dispersing mechanism as

used in a spectrometer. Although the filter is the dominant spectral determination device in these instruments, the full optical and detection system also contributes to the spectral response, particularly in the out-of-band spectral region. It is therefore important to understand the contribution of all the elements of the system: optics, filters (technically optics, but will be treated separately), and detectors. The components used by each Landsat sensor are listed in Table 7.

<insert Table 7 near here with the following title/caption>

**Table 7. Optics, Filters and Detector effects contributing to the Landsat sensors spectral responses.** Note that the interference filters were manufactured using electron-beam deposition for Landsats-1 through -5 and ion-assisted deposition techniques for the Landsat-7 and later sensors.

## 3.4.1.1.1 Optics

Landsat sensors have used a number of different kinds of optics: mirrors, lenses, windows and fiber optics. Most of the Landsat sensors have been reflective optic systems, which means mirrors are the primary telescope optics. Broadband coatings are used on these sensors' mirrors. As such, these mirrors generally have very little impact on the in-band spectral response, except perhaps a shallow slope contribution (Figure 15). The coated mirrors also rarely have much impact on the out-of-band response, except below 400 nm. The Landsat-8 TIRS sensor is the exception from the reflective instrument design, TIRS being a refractive, (i.e., a lens-based) system. For TIRS, the lenses material is either germanium (three elements) or zinc selenide (one element). As can be seen in (Figure 16), germanium cuts off fairly sharply around 2 µm on the shortwave length side and zinc selenide cuts off around 20 µm on the long wavelength side, significantly contributing to out-of-band suppression beyond these wavelengths.

Most of the Landsat sensors have non-powered transmissive elements in their optical path, often to control contamination. The MSS sensors used fiber optics to transmit the signal from the focal plane to the detectors, while the TM and ETM+ sensors had multiple windows in front of the cold focal plane to aid in contamination control, and the OLI sensor had a tilted window in front of the focal plane, also for contamination control reasons. These optics generally have very little impact on the spectral in-band response, but can contribute to out-of-band blocking, particularly if coated. The anti-reflection coating on the ETM+ windows (zinc selenide), for example, has a transmittance of about 5% in the 850 to 950 nm spectral range, which helps reduce the impact of some interference filter leaks of about 4% transmittance in this spectral range. Likewise the OLI focal plane window anti-reflection coating contributes modestly to the out-of-band blocking (Figure 15).

<insert Figure 15 near here with the following caption>

**Figure 15. Landsat-8 OLI optical component transmissions on linear scale (above) and log scale (below)**. Barsi et al., 2014 (*37*).

#### <insert Figure 16 near here with following caption>

Figure 16. Germanium and zinc selenide transmission at normal incidence on linear scale (left) and log scale (right). Data provided by Thorlabs, <u>www.thorlabs.com</u>.

#### 3.4.1.1.2 Spectral Filters

The spectral filters are the principal component of the sensor system determining the in-band response as well as much of the out-of-band blocking. The designs and manufacturing techniques used for filters have changed and improved over the years and this is reflected in their usage in the Landsat sensors. Both absorption (a.k.a. colored glass) and interference filters have been used alone and in combination in the designs. The interference filter manufacturing

technique has evolved from using electron beam deposition alone to various techniques to add energy to the deposition process, for example, ion-assisted deposition (IAD). These developments, which occurred largely in the 1990s, resulted in filters that were considerably denser and less prone to the absorption of water between the layers (*34*). The absorption, which normally occurred in ambient conditions, tended to shift the related band edge to longer wavelengths (*35*). The absorbed water tended to be released under vacuum conditions causing the band edges to shift to shorter wavelengths. As a result, depending on when and under what conditions the filters were measured, their actual on-orbit bandpasses could be shifted from the measurements made prior to launch. The IAD or related hardening process was used for the spectral filters of the Landsat-7 ETM+ and Landsat-8 OLI and TIRS.

For the MSS sensors, combinations of absorption and interference filters were used. For bands 1-3, absorption (colored) glass determined the lower band edges and interference filters determined the upper band edges. For band 4, an interference filter determined the lower band edge and the upper band edge was determined by the detector response. The interference filter layers were deposited on a colored glass substrate. For example, for MSS band 2, the interference filter layers designed to give a 700 nm long wave cut-off were deposited on a substrate of a colored glass like Schott OG590 (Figure 17). The OG590 glass cuts on at 590 nm and in combination with the interference layers makes a bandpass of about 590 to 700nm, similar to what is observed. Though it does not typically produce as sharp a band edge, colored glass does give good out-of-band blocking below its cut-on wavelength. On the long wavelength side, where the interference filter determines the band edge, there is a risk of leakage at longer wavelengths. The measured filter response of Landsat-5 MSS band 2 out to 800 nm does not indicate any leakage above ~0.1%. Though the detectors used in the MSS for band 2 are dropping in response by 800 nm, (Figure 18) the actual cut-off is closer to 900 nm, so there appears to be a portion of the spectral range where there could be uncharacterized out-of-band response.

The design of the MSS filters tends to make the band 1-3 bandpasses narrower under vacuum conditions on orbit than measured prior to launch in ambient conditions as the upper band edge shifts to shorter wavelengths and the lower band edge, which is absorption determined, remains relatively stable. The MSS band 4 can be expected to get wider in vacuum as opposed to ambient conditions (for the same temperature), as the lower band edge is interference filter determined and the upper edge is detector determined. Additionally, the MSS used fiber optics to transmit light from the focal plane to the detectors. Each of the six detectors per band has its own fiber optics and spectral filter, which would allow for significant variation in spectral response between the six channels within the band.

<insert Figure 17 near here with the following caption>

Figure 17. Schott Glass OG590 Transmission – 3 mm normal incidence on linear scale (left) and log scale (right). Data provided by Schott North America, Inc., <u>www.us.schott.com</u>.

#### <insert Figure 18 near here with the following title/caption>

**Figure 18. Spectral Responses of Detector types used for Landsat reflective band spectral bands.** Note that InSb peaks at about 5 µm and then drops off rapidly. Barsi et al., 2014 (*37*) and RCA Corp. (*46*).

For the TM instruments flown on Landsats-4 and -5, filter design had progressed to where colored glass was used more to help with out-of-band blocking and less to determine band edges, though it still contributed in some cases. Colored glass was used for the VNIR bands, but clear glass or fused silica was used for the SWIR bands. Residual filter material for bands 1-4 from the TM program was measured in 1993 (*36*) for evidence of vacuum-related spectral band shifts

(note that residual material was not available for bands 5-7). The following shifts were observed after 7 days in vacuum relative to initial testing in ambient:

- Band 1 lower edge: -5.45 nm/7days; upper edge: -5.62 nm/7 days.
- Band 2 lower edge: +0.23 nm/7days; upper edge: -3.48 nm/7 days.
- Band 3 lower edge: +0.22 nm/7days; upper edge: -3.72 nm/7 days.
- Band 4 lower edge: -7.35 nm/7days; upper edge: -6.38 nm/7 days.

These shifts suggest that the lower band edges of bands 2 and 3 are not primarily produced by interference filters. Design drawings indicated that the colored glass used for the Landsat-4 TM had cut-on wavelengths of ~520 nm for band 2 and ~620 nm for band 3, which could produce this result. Note, however that TM band 4 substrate design information indicated an ~765 nm cut-off that should have limited the lower band edge shift in this band. For the TM (and ETM+), although there were typically 16 detectors per band, just one small piece of filter material covered all detectors, limiting detector-to-detector spectral variability.

For ETM+, filter designs similar to TM were used, with interference filter layers deposited on colored glass for the VNIR bands though the colored glass filters have cut-ons significantly below the desired band edges, leaving the interference filter to determine the band edge. Like for TM, the ETM+ SWIR bands used a clear substrate. IAD techniques were used to deposit the interference filter layers. Measurements of the ETM+ filters showed shifts of less than 1 nm in band edges between ambient and vacuum exposure (of > 24 hours) (*36*).

For OLI on Landsat-8, interference filters were used to determine both the upper and lower band edges and to provide most of the out-of-band blocking. The OLI is a pushbroom sensor as opposed to the whiskbroom sensors on earlier Landsat sensors. With a focal plane spanning about 25 cm in length and 14 separate focal plane modules each with its own piece of spectral filter material, the potential for spectral differences between the detectors increases. In addition, the slight non-telecentricity of the OLI telescope causes the bandpass to shift up to 0.5 nm towards shorter wavelengths as the view angle moves away from the center of the field of view. For some OLI bands, notably bands 3 and 4, filter material from the same manufacturing wafer was used for all focal plane modules, making these bands somewhat more uniform than others (*37*). Tests of the OLI filters showed negligible shifts in band edges between ambient and vacuum, as is expected for the IAD technique.

For TIRS, a pushbroom sensor like OLI, the interference filter layers were deposited on a germanium substrate. The TIRS focal plane was considerably smaller than on OLI, with three modules spanning roughly 5 cm cross-track. For both bands, all three filter sticks were cut from the same wafer, improving spectral uniformity (*38*).

## 3.4.1.1.3 Detectors

The Landsat sensors have used a range of detector materials as technology has evolved and requirements for spectral coverage shifted. The detectors typically are not a big contributor to the shape of the in-band response beyond a slowly varying function. The detectors respond beyond the range of interest, requiring blocking from other elements to obtain the desired response. Figure 18 shows the range of detector types used in the reflective portions of the electromagnetic spectrum. The MSS sensors used a multi-alkali type of photomultiplier tube (PMT) with a long wavelength cut-off of about 900 nm for bands 1-3 and an ambient temperature silicon photodiode (Si) for band 4 with a long wavelength cut-off of about 1000 nm (depending on temperature). As indicated in the filter discussion, the detector response determines the upper band edge in band 4. This cut-off is generally not as sharp as an interference filter and is also a fairly strong function of temperature, so that for the MSS, where

the temperature of the focal plane is not strictly controlled, there will be some variation in spectral response. TM and ETM+ similarly used ambient temperature silicon detectors for the VNIR bands (1-4) while indium antimonide (InSb) detectors cooled to ~90K were used for the SWIR bands. OLI also used silicon detectors for its VNIR bands (1-5), but controlled to a temperature of ~205K, which noticeably reduces sensitivity beyond 1000 nm. Mercury cadmium telluride (HgCdTe) detectors are used for the SWIR bands.

In the thermal spectral region, HgCdTe detectors were used for the TM and ETM+ instruments (Figure 19) (and also for the MSS instrument for Landsat-3, which will not be discussed as very little image data from it are available). The formulation of the detectors varied, resulting in some differences in the long wavelength cut-offs between instruments. The HgCdTe detectors for the Landsat-4 TM had a shorter wavelength cut-off than the spectral filters used for that band, resulting in the upper band edge being determined by the detectors as opposed to the filters and the response being temperature sensitive. On the Landsat-5 TM, the HgCdTe detectors had a longer wavelength cut-off that the filters, so the filter upper band edge dominated. For TIRS, Quantum Well Infrared Photodetector (QWIPS) detectors were used. The spectral response for these detectors was tuned for the 10.5-12.5  $\mu$ m region (Figure 19). The QWIPS technology results in a less smooth spectral response, giving detector-related structure to the in-band response.

## <insert Figure 19 near here with the following caption near>

**Figure 19. Spectral Response of Detector types used for Landsat thermal spectral bands for Landsat-7 ETM+ and TIRS thermal bands.** Landsat-4 and -5 TM detector responses are similar to ETM+, but may be shifted to shorter or longer wavelengths due to detector formulations and sensitivities.

## 3.4.1.2 Characterizing Spectral Response

Part of the normal pre-launch characterization of the Landsat sensors is measurement of their spectral response. Often this is performed to determine compliance with the specifications of band edges, bandwidths, etc., but also this characterization is important to the scientific users of the data, particularly for any quantitative applications.

The relative spectral response can be evaluated at multiple levels of integration of the instrument: (1) component level, (2) focal plane level, and (3) integrated instrument level. The measurement process gets increasingly difficult at the higher levels of integration, so all are not routinely performed. Also, the in-band measurements may be performed at different integration levels than the out-of-band measurements.

## 3.4.1.2.1 Component Level Characterization

All of the Landsat instruments were characterized by at least a partial roll-up of component level spectral measurements, as the instrument builders wanted to assure that once the instrument was assembled that it would meet its spectral response requirements. As indicated in the previous sections, these components are optics, filters and detectors. Because the filters are the primary component for defining in-band response, these were routinely measured. The theoretical curves were sometimes used for the detectors and sometimes the optics were ignored as they contributed little to the response. The filter measurements may have been made on the original material before being sized for flight use (e.g., the spectral filters wafers before cutting), the actual flight parts, or alternatively, witness samples of the same material. The flight parts are often small and difficult to measure, hence the preference for measurement prior to cutting. The precision of the component level measurements is typically higher than at the assembly level and above measurements, but difficulties arise as the components often cannot be measured under the exact

angular and temperature conditions that they will be subjected to in the instrument. Adjustments thus need to be applied to the data to better match flight conditions. The extent to which the component level measurements provided a complete out-of-band characterization varied greatly across the program. For the earlier sensors, out-of-band requirements, if they existed, were only on the filters, so only the filters extended transmission was measured. If out-of-band leaks were found, other components may have been considered if they could contribute to reducing the impact of the leaks. For the later sensors, component level characterization was required out to when the detector response was down to  $10^{-3}$ .

All of the TM/ETM+ class instruments were only characterized at the component level, both inband and out-of-band response. This was largely a result of extreme schedule pressure on the initial Landsat-D TM development that propagated to the latter instruments. In fact, for all the other instruments exclusive of the Landsat-8 OLI, the out-of-band characterization was only successfully performed at the component level. For example, the TIRS band 10 out-of-band characterization based on component level measurements is shown in Figure 20. Table 8 summarizes the knowledge of the component level characterizations of the various sensors.

<insert Figure 20 near there with the following title/caption>

**Figure 20.** Landsat-8 TIRS band 10 component spectral responses along with the full system rollup based on these components. Note the flat line in filter transmission is the limit of the precision of the measurements, (i.e., actual transmission may be less). NASA, unpublished data.

#### <insert Table 8 near here with the following title and footnote>

# Table 8. Spectral characterizations performed on the Landsat sensors.

## <insert table>

Ambient means normal pressure and room temperature; <sup>1</sup> flight parts measured at ambient/ witness samples measured at 77 K which were used to adjust flight measurements; <sup>2</sup>Witness samples measured down to 300nm, as the substrates were transparent for these filters; <sup>3</sup>Models used to predict angular and temperature shifts; <sup>4</sup>Focal plane window measured from 200-2600 nm; <sup>5</sup>Witness samples measured at 45K used to adjust flight part measurements while theory used to produce f/4.2 versus f/1.64; \*\* MSS band 4 on Landsat-4 upper band edge shifted 33 nm between two tests, probably due to focal plane

temperature differences; \*\*\* ~10% of detectors measured with partial aperture, partial field illumination; \*\*\*\* ~1% of detectors measured with partial field illumination

#### 3.4.1.2.2 Focal Plane Assembly Level Characterization

When the spectral filters are mated to the detectors, the primary spectral characteristics of the instrument are determined. Characterization at this level accounts for any interaction between the filters and the detectors. In addition, testing here is typically considerably less complicated than testing at the integrated instrument level and signal levels needed for testing out-of-band response are more readily obtainable. The Landsat-8 OLI instrument was the only Landsat instrument to date where spectral testing was performed at this level of integration. That testing was specifically designed to measure out-of-band spectral response, though a coarse measurement of in-band response was also performed. The measurements were performed at the focal plane module level, meaning that the optics were not included (they were added in analytically to produce predicted system level response) and the flight focal plane electronics were not used (Table 8).

## 3.4.1.2.3 Integrated Instrument Spectral Response

The integrated instrument level is, in principal, the correct level at which to characterize the instrument's spectral response, as all of the effects are captured. In addition, the instrument should be tested under the conditions that it will experience in normal operation, (i.e., thermal vacuum and the appropriate operating temperatures) and the light used to stimulate the instrument for the testing should enter the instrument in the same manner as when viewing the Earth, (i.e., full aperture and full field). This type of testing was performed on the MSS instruments, though under ambient conditions, and not performed again until the OLI and TIRS

instruments on Landsat-8. Although this testing was performed for the Landsat-8 instruments under simulated on-orbit conditions (thermal vacuum), spectral response testing was not full field (i.e., all detectors), nor was the full field characterized in multiple partial field tests, and the source was not full aperture (Table 8).

## 3.4.1.2.4 Summary Bandwidth Parameters

There are several variants on determining band edges, for example, the 50% relative response points (FWHM) and the quadratic moments bandpasses. Historically the Landsat FWHM bandwidths have been provided (Table 6). Here we also provide the quadratic moments bandpasses. If one is using just the bandpasses to represent the instruments spectral response, the quadratic moments bandpasses provide a better measure of the equivalent square wave response than the 50% response points (*39*).

#### 3.4.1.2.5 Relative Spectral Response data for Landsat Sensors

The relative spectral responses (RSRs) of the Landsat instruments exist in the most original form in contractor reports or data files that may not be readily available. For the MSS instruments, the only remaining sources of RSR data are plots in these reports. Particularly for the Landsat-1 through -3 MSS instruments, although these reports can be retrieved from various archives, they are multiple photocopy generations removed from the originals. There have been concerted efforts to digitize these data by South Dakota State University personnel and make them available on the Landsat Science website, and this is the best source for the early MSSs. Data for the Landsat-4 and -5 MSS are available from Markham and Barker, 1983 (40), as well as the NASA Landsat Science website (http://landsat.gsfc.nasa.gov/?p=12163 ). The quality of the

Landsat-4 and -5 MSS data plots was considerably better than for the earlier MSSs. The Landsat-4 and-5 TM spectral responses were released to the public via Markham and Barker, 1983, 1985 (40, 41) and the data can be retrieved from the Landsat Science Data Users Handbook (http://landsathandbook.gsfc.nasa.gov/inst\_cal/prog\_sect8\_2.html). The Landsat-7 ETM+ RSR's are in the Landsat Science Data Users Handbook. For Landsat-8 OLI and TIRS, the spectral characterization processes are discussed in Barsi et al. (2014) (37) and Montanaro et al. (2011) (42), respectively and the data are on the NASA Landsat Science website (see website list).

## 3.4.1.3 Impacts of spectral response variation/differences

Because the targets that are observed by the Landsat sensors are invariably not spectrally flat, variations in the spectral responses of the sensors produce variations in the output data. These variations will differ depending on the spectral nature of the targets, resulting in artifacts that cannot be readily identified or removed. When these variations occur within a sensor, they can contribute to striping (individual detector) and banding (multiple detector) artifacts in the data products. When the variations occur between sensors (and consequently vary with time in long-term data records), they produce inconsistencies or discontinuities in the trends observed over time. These variations increase the noise in the data, though in some cases the noise can be reduced by compensation techniques.

## 3.4.1.3.1 Within-Band Spectral Variation

Studies have been conducted on the MSS sensors, the OLI sensor and the TIRS sensor to understand the impact of the within-band spectral variation. As early as 1979, the variation in the MSS spectral response was predicted to produce as high as a 16% variation in the response to vegetation for the red band of the Landsat-2 MSS (*43*). A later study that included Landsat-4 and -5 MSS sensors indicated smaller, though still significant variations of ~5% in vegetated targets, in both the Landsat-4 MSS and the Landsat-2 MSS red band. Given the relatively low signal from vegetated targets and coarse digitization of the Landsat MSS data, the predicted differences rarely exceeded one 7-bit count and were not readily apparent in the imagery (*40*). This is to say that the spectral contribution was not separable from other detector-to-detector responsivity and noise effects.

For the Landsat-8 OLI, a similar analysis was done and the results showed a much decreased maximum difference of ~0.2% for vegetated targets within each of the bands, though up to 0.35% to a soil target in the SWIR-2 band (*37*). Though much reduced in magnitude, this effect has roughly the same relative impact on the data quality for OLI as it did for MSS since OLI is a 12-bit system with significantly better SNR. For the Landsat-8 TIRS instrument, a simulation showed that the spectral variations within a band will lead to less than 0.1 K variation within and between the three focal plane modules (*42*).

## 3.4.1.3.2 Out-of-Band effects on Response/Calibration

Often when a radiometric calibration was performed on the Landsat sensors, only the in-band and near in-band response was considered in integrating the source radiance function. Sometimes this was out of necessity as the out-of-band information was lacking, but also it was assumed that the out-of-band response would be a small contributor to the radiometric error. However, the effect of out-of-band radiance can be magnified when the source used to calibrate the sensor during pre-launch testing has a significantly different spectral shape than the targets observed on on-orbit. This has typically been the case in prelaunch testing. Prior to launch, tungsten sources with a color temperature around 3000 K are used; on-orbit, the sun with a color temperature of about 6000 K is the illuminator. The effect is often most pronounced in the calibration of the shortest wavelength channels, for example, the coastal aerosol band on OLI.

## 3.4.1.3.3 Between-Sensor Spectral Differences

Differences between similar bands on different sensors are a similar but often more significant issue than within-band spectral variation. These differences can arbitrarily be separated into cases where the spectral bands were intended to be the same, but varied due to manufacturing differences and where bands, although similar, were intentionally altered to improve sensitivity to various phenomena. Across the five MSS sensors, the spectral bandpass variations due to manufacturing processes produced differences up to ~10% between matching bands, roughly twice as large as the within spectral band variation for one instrument (40). For the two TM instruments, whose spectral filters came from the same production lot, calculations of the differences in top-of-atmosphere (TOA) reflectance over the Railroad Valley (RRV), showed less than 0.1%. For Landsat-7 ETM+, which had nominally the same bandpasses as TM, differences from Landsat-5 TM were up to  $\pm 2\%$  in the VNIR and  $\pm 5\%$  in the SWIR at RRV (44). Some of the OLI bandpasses were intentionally adjusted from the ETM+ bandpasses. For example, the OLI NIR and SWIR-1 bands were narrowed to avoid atmospheric water vapor absorption features. Differences between Landsat-8 OLI and Landsat-7 ETM+ are  $\pm 2\%$  in the visible bands, up to 10% in the NIR, and up to 6% in the SWIR over a specific Saharan test site (45). The challenge with spectral differences is that they are target and atmosphere dependent, so they need to be accounted for in studies that use data from different sensors.

#### 3.4.1.4 Spectral artifacts

Striping (individual detectors) and banding (groups of detectors) can be introduced into Landsat imagery due to within-band spectral differences noted above. Striping is more likely when the spectral filter is different for each detector, such as the MSS, and banding is more likely when the spectral filter varies between groups of detectors, for example, focal plane modules for OLI or TIRS.

## 3.4.1.4.1 Spectral-Spatial crosstalk

Another spectrally-related artifact that is also a spatial artifact is crosstalk. Here signal leaks either optically or electrically between the detectors or electronics of different bands. This is different from spectral leakage through the optical filter, as it results when light passes through the filter of a nearby different spectral band and is scattered between the filters and the detectors. The scattered light of one band hits the detector of another band. This is believed to be happening in the Landsat-8 OLI focal plane. Approximately 0.2% of the light that has passed through the SWIR-1 bandpass filter is internally reflected and reaches the cirrus band detectors. The SWIR-1 detectors are physically displaced from the cirrus band detectors on the focal plane so are viewing a different spot on the Earth's surface at any given time. When the crosstalk is visible, the SWIR-1 scattered light appears in the cirrus band image as a geometrically misregistered ghost (37). In the example shown in Figure 21, the image appears to show a coastline that isn't registered properly across the module boundaries. When that image is processed as if it were a SWIR-1 image, the shoreline is properly registered, indicating that the signal is originating in the SWIR-1 band not in the cirrus band. This weak ghost is only evident as there is essentially no in-band signal in the cirrus band when there are not cirrus clouds and the atmosphere is moderately moist.

< insert Figure 21 near here with the following caption>

**Figure 21.** A subset of a geometrically registered cirrus band image of the coastline of North Africa, showing a large misregistration between the focal plane modules (left). The same cirrus band image processed as if it were a SWIR-1 image (right). The coastline is now aligned, indicating that the signal originated within the SWIR-1 bandpass. The signal level within the cirrus band is less than 0.2 W/m<sup>2</sup> sr  $\mu$ m while the SWIR-1 band signal is as high as 40 W/m<sup>2</sup> sr  $\mu$ m. This atmosphere is so clear that the crosstalk signal is the only visible feature in the cirrus band. Barsi et al., 2014 (*37*).

## 3.4.2 Spatial Characteristics of Landsat Sensor Data

One key concern about imaging systems, beginning with the earliest ones, was whether the image was in focus. After focus, the next concern was how much detail could be discerned. These characteristics are part of the larger area of imaging system spatial performance. The way in which we measure, define, and evaluate a system's spatial performance, both pre-launch and on orbit, has evolved over the more than 45 years of Landsat missions. Landsat data are resampled to, for example, 30-meter pixels in product generation. Often this product pixel size is referred to as the "spatial resolution" of the data. When scientific analysis of the data across the various Landsat missions is desired, an understanding of the relationship between this 30 m value and the real spatial resolution of the payload is important. The Point Spread Function (PSF) is the fundamental descriptor of the sensor's spatial response, providing the sensor's output for a point source everywhere within the field of view. From the PSF, the sensor's output to an arbitrary input source (an array of point sources) can be determined. Mathematically this process is a convolution. For purposes of simplification and without too much loss in generality, for this discussion, the PSF will be separated into along-track and across-track Line Spread Functions (LSF's). The interested reader may also want to review the comparable spectral domain (Fourier Transform of the spatial domain representation) transfer functions (e.g., Modulation Transfer Function and Phase Transfer Function), but these will not be discussed in detail here. This segment will present the various elements that are involved in determining the

sensor's spatial characteristics and provide summary tables for the related performance characteristics for all the Landsat missions.

The segment is organized as follows: a general description of the aspects of spatial response, (i.e., near-field and far-field); the factors involved in determining the spatial response in both the near-field and far-field; characterizations and modeling of the payload near-field and far-field response, and some interleaved discussions on impact of the spatial response on data analysis and scientific usage. Summary tables of performance parameters for all Landsat missions are provided. These illustrate the evolution in the level of characterizations and the knowledge of the spatial image quality. In-depth discussions of background material, such as the various sources and types of stray light, the FFT and the near-field types of aberrations and diffractions effects will not be covered.

# 3.4.2.1 Aspects of Spatial Response

The complete spatial response of an imaging system involves two domains: the near-field and the far-field. The terms near and far used here are given in reference to the distance from the center of the spread function as illustrated by Figure 22. For the purposes of this discussion, the near-field response extends to about  $\pm 3$  Instantaneous Field of Views (IFOVs), with the far-field response beyond that. Far-field response can be further broken down into generalized stray light that typically just lowers the overall contrast in the image and ghosting, where a weaker image of the target appears displaced from its desired location. Some stray light requirements consider the far-field response for the purpose of controlling generalized stray light as beginning farther out, (e.g., ~ $\pm 100$  IFOV or 0.25° for OLI and extending to around 25°). Figure 23 provides an example near-field line spread function, Figure 24 the far-field response.

## <insert Figure 22 near here with the following caption> Figure 22. Near-field and far-field spatial response domains.

#### <insert Figure 23 near here with the following caption>

**Figure 23. Landsat-8 OLI band 6 measured on orbit along- and across-track near-field response shown as line spread functions with along-track motion analytically included**. Storey, personal communication, 2016. (47)

#### <insert Figure 24 near here with the following title/caption>

**Figure 24. Landsat-8 OLI telescope far-field response, both predicted and measured.** The measurements are the average of three scans during the pre-launch test for stray light. The modeled version was generated by the FRED Optical Model. Modified from Knight and Kvaran, 2014 (23) and Grochocki and Fleming, 2010 (48).

# 3.4.2.2 Factors determining spatial response

## 3.4.2.2.1 Near-Field Response

A simple model of the near-field spatial response of the instrument consists of its optics, its collectors at the optical focal plane (e.g., detectors), the motion of the imager or object, and the temporal response of the light collectors and their electronics. The ground processing of the data also may significantly impact the spatial response. Atmospheric transmission effects on near-field response are generally small and will not be considered here. Uniformity of the spatial response across the scene field of view and stability of the response over time are other important aspects of the spatial performance. The extent to which each of these factors was considered, and to which spatial testing and analyses were performed, have evolved over the Landsat mission history.

## 3.4.2.3 Optics

Three aspects of the optical design and fabrication process are primary contributors to the nearfield spatial response of the Landsat sensors: diffraction, aberrations, and focus. Generally, the Landsat sensor telescopes are designed to be nearly diffraction limited. The diffraction PSF for the Landsat sensor telescopes can be analytically calculated and is an Airy Disc (49) from the limiting aperture, modified by the various obscurations in the system (Table 9). For the whiskbroom Landsat instruments (Landsat-7 ETM+ and earlier), the telescopes are large relative to what would be required for a system of their spatial resolution. Their larger size is driven by the need to capture more light, which the whiskbroom systems require due to the short dwell time for the detectors. As such, the optics on these systems are relatively small contributors to the overall spatial response. However, the diffraction becomes a larger effect at longer wavelengths and the higher resolution bands, so the thermal band is more affected than the reflective bands (Figure 25) and the pan band is more affected than the multispectral bands. Also, when the system spatial response is measured, any difference from the expected design response is often treated as a general blur function and lumped into the optical response, the blur considered to be the combined aberrations and defocus. The ETM+ had a focus issue: the incorrect installment of a focal plane shim combined with the shrinkage of the optical structure with outgassing of water resulted in the system being somewhat out of focus and worsening with time on orbit (50). This particularly affected the highest resolution pan band. The pushbroom designs, as used by OLI and TIRS, do not necessitate as large optics due to the greater dwell time available for the detectors. As such, the optics are smaller and have a more significant impact on the spatial response (Figure 26). Additionally the optics for pushbroom systems have a significantly larger field of view  $(15^{\circ} \text{ versus } \sim 0.5^{\circ} \text{ for the Landsat whiskbroom})$ systems) which may result in more variation in the spatial response across the focal plane.

<insert Table 9 near here with the following title>

#### Table 9. Telescope parameters for Landsat Sensors.

*<insert Figure 25 near here with the following title above the figure and the caption below the figure, as noted>.* 

# Figure 25. Contributions to spatial response from system components for the TM, a whiskbroom system.

< *insert figure 25 here>* Left: TM band 3 component theoretical spatial responses (optics, detector, electronics). Right: TM band 6 component theoretical spatial responses (optics, detector, electronics).

<insert Figure 26 near here with the following title above the figure and caption below the figure, as noted below>

# Figure 26. Contributions to spatial response from system components for the OLI and TIRS, pushbroom systems.

#### <insert Figure 26 here>

Left: OLI band 4 component theoretical spatial responses (optics, detector, motion blur). Right: TIRS band 10 component theoretical spatial responses (optics, detector, motion blur).

#### 3.4.2.4 Detectors

For the Landsat sensors, the detector element usually resides at the focal plane and delimits the geometric IFOV. The MSS instruments are the notable exception, where the terminations of the fiber optics at the focal plane define the IFOV and transfer the light to the detectors that reside some distance away. The linear IFOV dimensions at the focal plane divided by focal length of the telescope gives the angular dimensions of the IFOV. Table 10 provides angular and projected dimensions on the ground at nadir for the IFOV's. A generally good first order assumption is that the spatial response across this element is uniform and thus the LSF is a square wave of the same dimensions. This will be used here to represent such a response (Figures 25 and 26).

<insert Table 10 near here with the following title and footnote as noted below >

#### Table 10. Geometric IFOV Parameters for Landsat Sensors

<insert table>

\* use 919 km altitude for Landsats-1 to -3, 705 km for Landsats -4 to -8; \*\* Typical, some variation between bands. Storey, personal communication (47); Reuter et al. 2015 (24); Lauletta et.al. 1982 (52); Markham, 1985 (53).

#### 3.4.2.5 Electronics

The optical and detector effects are generally similar in the along-track and across-track directions for the Landsat sensors, although there are some variations due to factors like non-square detectors. The electronic effects, however, are different between the two directions. For whiskbroom systems, the analog output of the detector is low-pass filtered and the filtered signal is sampled nearly instantaneously. The low pass filtering in the time domain translates to a blurring in the spatial domain, but only in the across-track direction (Figure 25). Table 11 provides general information about the electronic filtering in the MSS, TM and ETM+ instruments. Note that the electronic LSF is asymmetric; this asymmetry contributes to some overshoot in the response of the whiskbroom systems to step functions. For the pushbroom systems, the detectors integrate the signal for a period of time: 3.6 msec for OLI (0.66 msec for Pan band) and 3.49 msec for TIRS. During this time period, the spacecraft moves, resulting in a blurring in the along-track direction only. This blur can be modeled as a square wave LSF with dimensions equal to the angular distance moved by the spacecraft during this period of time (Figure 26).

< insert Table 11 near here with the following title>

Table 11. Electronic filter parameters for whiskbroom Landsat sensors. Markham, 1985 (53).

## 3.4.2.2.2 Far-Field Response

The far-field spatial performance of an instrument is impacted by surface quality and smoothness of the telescope optics and related optical path components, baffle geometry and coatings, and

other surfaces that can scatter light onto the detectors. In the early designs of Landsat missions this aspect was addressed by applying what was considered good practices to control stray light and internal scattering but no formal system level requirements or goals had been set. In later missions, stray-light performance was better defined and it impacted the need for testing and modeling efforts both pre-launch and on orbit. As technology evolved, surface finish quality, cleanliness control, and stability has improved significantly enhancing the quality of the far-field response performance, nevertheless is it one of the more challenging performance evolved simultaneously with the Landsat missions, thus, for later missions, stray light performance were better characterized (Figure 27).

#### <insert Figure 27 here with the following title>

**Figure 27. Stray light modeling tools and measurements standards relative to Landsat missions**. (partially from the NASA Landsat Science website).

# 3.4.4 Characterizing Spatial Response

## 3.4.4.1 Near-Field Response

## 3.4.4.1.1 Component Level

During the instrument design stage the spatial performance is evaluated to ensure that the completed instrument meets its spatial performance requirements. As the instrument is being developed and optical, detector, and electronic components are fabricated, the components are measured to determine compliance with their specifications. These measured parameters are used to update the performance prediction models that estimate overall system performance. Compliance with the telescope's optical prescription, the actual sizes of the active areas of the

detectors or focal plane to detector relay optics, and the temporal responses of the detector electronics are all items that are tracked. Historical information about these measurements is relatively limited, but includes physical dimensions of the focal plane fiber optic terminations for the MSS instruments, physical detector dimensions for the TM, ETM+, OLI, and TIRS instruments, some measurements of the actual active detector area of the TM detectors, and the temporal responses of the electronics responses, (e.g., the frequency response of the TM and ETM+ preamplifiers). These measurements, some of which are reflected in Tables 9, 10, and 11, are used in the system model to predict performance. For the TM instrument, the transient response of the electronics revealed a spatial response that deviated from the design, hypothesized being due to parasitic capacitance in the circuit (*54*). An example of this roll-up is shown in Figure 28 for the TM.

<insert Figure 28 near here, with the following caption>

Figure 28. Landsat TM Net Line Spread Functions based on component analyses (band 3).

#### 3.4.4.1.2 Instrument Level

Once the instrument is completely assembled, its spatial response is tested for compliance with requirements. This process has evolved over time, in part due to changing attention to requirements and part to changes in technology and methodologies. The earliest MSS sensors had requirements only on the along-track Modulation Transfer Function (MTF). The later MSS sensor requirements used Square Wave Response (SWR) instead, while the TM and ETM+ added requirements on overshoot and settling times after an edge was crossed. The OLI and TIRS requirements were specified in terms of response to an edge (steepness of response, overshoot, settling time, etc.).

Although the early MSS requirements were on MTF, the measurements performed were SWR. The SWR was measured by scanning across bar patterns of various spacings placed at the focus of a collimator. A similar test procedure was used for the later MSS. For the TM and ETM+ sensors a phased knife-edge was used. A specialized reticle, where alternating dark and light bars were placed a non-integral number of pixels apart, was placed at the focus of the collimator. The TM data acquired across these knife edges allowed for a well-sampled edge response function to be developed. This edge response function could be differentiated to provide a line spread function and a SWR calculated for comparison to the requirements. For OLI and TIRS, the edge response was measured directly by moving a square target across the detectors and recording the detectors' output.

Although sufficient for determining compliance with requirements, the system level test results generally do not provide sufficient characterization of the line spread functions in both along-track and along-direction to understand the spatial response. What has been done in the past, and will be done for this presentation, is to adjust the instrument's spatial response model to match the system level measurements and use the model to provide the characterizations. This is done by replacing the diffraction-limited performance of the optical system with a Gaussian blur function of proper sigma, that when combined with the detector sizes and electronics responses, matches the measured system level response in the provided directions. This blur function is assumed to be circularly symmetric and therefore has the same effect on the along-track and across-track optical LSF, the same across- track and along-track detector LSF (assuming square detectors), an along-scan only electronic filtering effect for the whiskbroom systems, and an along-track image blur function for the pushbroom systems. Sample LSF's determined this way

for the TM and OLI (Figure 29) illustrate the differences between whiskbroom and pushbroom systems responses for nominally the same spatial resolution. These LSF's should be considered conservative (i.e., somewhat worse than the actual performance) as degradations in the performance are all attributed to the instrument as opposed to the test equipment or procedures.

#### <insert Figure 29 near here, with the following title/caption>

**Figure 29.** (Left) TM band 4 along-track and across-track line spread functions. Markham, 1985 (*53*). (Right) OLI band 5 along-track and across-track line spread functions. Storey, personal communication (*47*).

## 3.4.4.1.3 Instrument Level LSF's and summary Spatial Response Measures

Pre-launch instrument level LSF's have been generated for all the sensors and some have been published (*52*) (*53*). With a model of the target area these LSF's can be convolved with the target spatial pattern and a simulated sensor output generated. The user can thus understand how the sensor's response is affecting the data. Few users are prepared to do this, but simply treating the response as a square the size of the projected IFOV, may be inadequate. An alternative is to use the modeled LSF's to generate more representative summary measures for the spatial response. The one used here is the 50% response points of the LSF, akin to the 50% response points of the relative spectral response discussed earlier (Table 12). Two notable observations about the various sensors: (1) The whiskbroom sensors all have a wider LSF in the across-track direction than the along-track direction (pushbroom systems are the opposite) and (2) The TIRS LSF widths are 60-70% wider than the nominal projected IFOV of 100 meters. This difference has not been well explained.

<insert Table 12 near here with the following caption>

 Table 12. Landsat Sensor Line Spread Function FWHM.
 From pre-launch measurements, except where noted.

#### 3.4.4.1.4 On-orbit LSF's Measurements

Beginning with the Landsat-4 TM, there have been a number of efforts to characterize the onorbit spatial response of the Landsat sensors (56) (57). However, it wasn't until the Landsat-7 ETM+ that these efforts demonstrated sufficient repeatability to be used for regular monitoring of on-orbit performance (49). As indicated earlier, it was known prior to launch that the focus for ETM+ was not as intended and was expected to degrade over the mission due to moisture outgassing from the telescope structure. Also, the contract for ETM+ provided incentives to the manufacturer for on-orbit MTF performance. This provided additional impetus for the on-orbit MTF monitoring. The technique developed used several linear bridge targets over water, notably the Lake Pontchartrain Bridge. The off-perpendicular scanning of the target generated a phased impulse, analogous to the pre-launch phased knife edge. Results for the ETM+ showed degradation in several of the bands over the mission, with the largest change in the Pan band, as expected (Figure 30). The Landsat-8 OLI has also been monitored on-orbit using the same targets, though its performance has been stable over the mission so far (Figure 31). It has been a challenge to find targets suitable for characterization of the thermal bands of any of the instruments. Recently an effort by Wenny (55) has shown promise for estimating the on-orbit spatial response of the TIRS instrument.

<insert Figure 30 near here with the following caption>

**Figure 30**. Landsat-7 ETM+ along-scan LSF widths from on-orbit measurements. Left: Pan band Right: Multispectral bands. Storey, personal communication (*54*).

<insert Figure 31 here with the following caption>

Figure 31. Landsat-8 OLI on-orbit spatial response. Storey, personal communication (54).

#### 3.4.4.1.5 Other aspects affecting image product spatial characteristics

In addition to the instrument's spatial response as represented by the LSFs, the sampling of the original data, the spatial content of the Earth scenes, and the resampling process that is used to take the original data and place them into a georeferenced product affect the image product spatial quality. With the exception of the early MSS sensors in the across-track direction, the sampling interval is roughly equal to the IFOV. This means that, in general, the instrument still has significant spatial response at frequencies higher than the Nyquist frequency. Image content above these spatial frequencies will not be unambiguously captured in the data so aliasing will occur during the resampling process, which means that the original spatial content will not be correctly reconstructed. The resampling algorithm is also an approximation of the idealized Sinc function and therefore has its own spatial response. The typical cubic convolution algorithm used for Landsat data processing produces a phase dependent smoothing of the data. When the original samples match the resampled locations there is no effect, but when the resampled data are midway between the original data points the effect is largest.

#### 3.4.4.2 Far-Field Response

#### 3.4.4.2.1 Component level measurements

It wasn't until the TM development stage that much attention was given to the stray light rejection characteristics of the Landsat imaging sensors (or at least we do not have any record of the MSS stray light studies). And for the majority of the systems, with the OLI and TIRS as exceptions, the only stray light characterizations were performed by analysis using stray light

models based on the system design and the reflectance characteristics of the systems' components. The key types of component measurements that were made included mirror and window reflectance/transmission and surface roughness, spectral filter large angle scatter, baffle and structure dimensions (particularly the thickness of the knife edges), and bidirectional reflectances. The results of these modeling analyses were used to demonstrate that the various instruments met the stray light rejection requirements. These requirements typically state something to the effect of "the signal measured by the sensor from the center of a circular target of radius r1, shall not be changed by more than 1% of the change in the brightness of the surrounding annular target of inner radius r2 and outer radius r3". Though real targets similar to the requirement conditions can be envisioned, in general the stray light analysis results presented do not give a good appreciation of the level of contamination for particular scenes.

#### 3.4.4.2.2 Telescope Assembly level measurements

For the Landsat-8 OLI, the fully assembled telescope without the flight focal plane was tested in a stray light test facility (58) where a point like source was scanned across its full field of view. These results were used to adjust the stray light model (Figure 24), in turn used to verify the OLI stray light requirement.

## 3.4.4.2.3 Integrated Instrument measurements

Verification of the general stray light requirements for any of the Landsat instruments was never completed strictly by testing at the integrated instrument level. Tests had been envisioned that involved viewing a hole in an integrating sphere and observing the effect of turning on lights within the sphere on the signal observed from the dark hole, but these tests were never implemented. TIRS testing included moving a ~1° target across  $\pm 15^{\circ}$  across-track and  $\pm 5^{\circ}$  alongtrack, which although it does not cover the full out-of-field region (~50°), came closest to directly testing the requirement. The results were not satisfactory, in part because the test equipment required putting the TIRS in a non-flight pointing configuration to do the test. In addition, the results may have been indicating the presence of the ghosts observed after launch (see below), though it was not recognized at the time.

Specific tests were designed to look for ghosts in OLI in the relatively close-in portions of the far-field response, (i.e., within the bounds of the instruments' focal planes), about  $\pm 8^{\circ}$  across-track and  $\pm 1^{\circ}$  along-track. On the EO-1 ALI (Advanced Land Imager) instrument, (an OLI-like technology demonstration instrument), ghosts were observed in this angular range and were attributed to reflections off various focal plane component surfaces. The offending surfaces were redesigned for OLI and test procedures were developed to capture any effects in these regions. While testing showed minor deviations from requirement levels, these violations were not clearly attributable to the instrument (*48*).

## 3.4.4.2.4 On-orbit Measurements

As in the laboratory, no good generalized stray light sources are readily available on orbit. Even the moon, against the dark space background, is relatively dim. The moon, however, is a decent source for detecting and characterizing ghosts. Landsat-8 was the first Landsat mission intentionally pointed to observe the moon. In addition to looking for ghosts, this allowed monitoring the stability of the instruments radiometric response over time, particularly for OLI, where a lunar irradiance model provided a source for comparison. The response from OLI near the moon was very clean and although there were some ghosts discernable, they were very weak and well within requirements (59).

The TIRS instrument imaging of the moon revealed a ring of ghosts about  $15^{\circ}$  off axis (Figure 32) (60). These ghosts were determined to be the cause of the discrepancies in the TIRS retrieved surface temperatures relative to water surface buoy measured temperatures. The ghosts were contributing extra signal to the detectors. Depending on the temperature of the area surrounding the target, these signal contributions emanated from as far as ~200 km away. For typical conditions the temperatures were around  $2^{\circ}$  high for band 10 and  $4^{\circ}$  high for band 11, though in extreme conditions they could be upwards of  $5^{\circ}$  for band 10 and  $10^{\circ}$  for band 11. For an otherwise very well-behaved instrument, these ghosts have been the largest challenge in using TIRS data quantitatively. The origin of the ghosts has been traced to the some of the lens housing and retaining structure. At least part of the failure to catch and correct this issue prelaunch was due to the failure to use appropriate directional reflectance data for lens retaining materials. An algorithm to partially compensate for the ghosting effect on the absolute calibration has been described (*61*) and is scheduled for implementation into the operational processing system in 2016.

<insert Figure 32 near here with the following title/caption>

**Figure 32. Illustration of the path of the moon (gray lines) relative to the focal plane array spectral filters during the special lunar scans.** Moon locations where a ghost signal was detected on any of the band 10 detectors (left) or the band 11 detectors (right) are highlighted in blue. Angles are relative to the optical boresight. Montanaro et al., 2014 (60).

# 3.4.3 Radiometric Characteristics of Landsat Sensor Data
Key aspects of the radiometry of Landsat sensor data are precision, accuracy, and dynamic range. Factors that influence the radiometry include the detectors' noise, sensitivity, stability and linearity, the light capturing ability and optical transmission of the telescope and filters, the gain, stability, noise and linearity of the electronics, the linearity and number of bits in the A/D convertor(s), contamination, and the data processing. This section provides details on the primary radiometric characteristics of all Landsat sensors and short descriptions of characteristics unique to specific instruments. The absolute and relative calibration uncertainties of all instruments are summarized at the end.

#### 3.4.3.1 Random Noise /Precision

Here we are concerned about variations in the response of the detectors and electronic chain as a function of time for a constant signal input. Various processes within the detectors and signal processing chain affect the overall noise level. In most cases all noise sources are lumped together into a Noise Equivalent Delta Radiance (NE $\Delta$ L), (i.e., the standard deviation of the signal from a constant target converted to radiance, or a Signal to Noise Ratio (SNR)). The NE $\Delta$ L may be alternatively expressed as a Noise Equivalent Delta Reflectance (NE $\Delta$ p) or Temperature (NE $\Delta$ T). Noise is a function of the signal level. For many of the Landsat sensors, noise was characterized only for specified radiance levels prior to launch. Monitoring post-launch was not feasible due, in part, to lack of appropriate on-board calibration systems. A comparison of the noise levels for the various Landsat sensors generally indicates a progressive improvement in the systems from the early MSSs, through the TM's to the Landsat-8 OLI and TIRS (Figure 33, Tables 13, and 14). The most dramatic improvement, a factor of 4-8x, came in the transition from the whiskbroom ETM+ sensor to the pushbroom OLI and TIRS

sensors. The Landsat-4 and Landsat-5 MSS instruments were somewhat better than the earlier MSS instruments, primarily a result of the redesigned larger collection area at the focal planes for operation at the lower Landsat-4/-5 orbital altitude. The ETM+ SNR values show a small decrease from the Landsat-4/-5 TM values in some of the VNIR bands, largely due to a change in the focal plane design. The earlier TM instruments had individual VNIR detector modules for each band and thus the detectors could be selected to optimize radiometric response in each band. The ETM+ had a monolithic focal plane and a compromise was made to select detectors to provide good performance in all bands. It should be noted that these SNR improvements occur even as the spectral bandwidths are being progressively narrowed, reducing the available signal. For example, the red band was ~100 nm wide for MSS, ~60 nm wide for TM and ETM+ and ~40 nm for OLI (see spectral discussion above).

The reflective band SNR values provided here are for a fairly bright target, and as such do not represent what would be obtained for a dark target like dense vegetation in the visible part of the spectrum. Noise models that can predict SNR at any signal level are available for the Landsat-7 ETM+ (*62*), and Landsat-8 OLI (*63*). Noise levels at various signal levels are available for TIRS (*64*). The ground processing also affects the noise levels, particularly the geometric resampling, which typically produces a phase dependent smoothing of the noise. On average, the typical cubic convolution resampling reduces the noise by ~20% (*62*).

On-orbit evaluations of noise were routinely performed for the Landsat-7 ETM+ using its onboard solar diffuser, Landsat-8 OLI using its internal lamps and solar diffuser and Landsat-8 TIRS instrument using its blackbody source. Some characterizations, though less extensive, have been performed on the Landsat-4/-5/-7 TM/ETM+ thermal band using its internal shutter. These analyses have shown small, if any, change in the noise performance of systems over time, with the exception of the Landsat-4/-5 TM instruments. On the TM instruments, a contaminant slowly built up on the cold focal plane window reducing the transmission of this window by up to 50% in the thermal band (see Section 3.4.3.3). Warming up the focal plane temporarily drove off this contaminant. The transmission loss is reflected in the nearly factor of 2 range of noise levels for the TM instrument thermal band (Table 14). This contaminant had a small effect on the transmission (circa  $\pm 5\%$ ) in the other two SWIR bands and would be expected to produce a small effect on the SNR.

<insert Table 13 near here with the following title/caption and footnote >

# Table 13. Typical SNR for Reflective Bands of Landsat Sensor for MSS specified signal levels, or earliest sensor having specified band.

<insert table>

<sup>1</sup>Pre-launch for low-gain, linear mode (Felkel et al., 1977 (*65*)), though compressed mode was normally used on-orbit; the SNR differences between linear and compressed mode should be small at high signal levels like these. <sup>2</sup>Pre-launch for low-gain, linear mode (Lauletta et al., 1982, (*52*)), though compressed mode was normally used on-orbit; the SNR differences between linear and compressed mode should be small at high signal levels like these. <sup>3</sup>Pre-launch interpolated from data in Mika et al. (1997) (*22*). <sup>4</sup>On-orbit results based on model from Scaramuzza et al. (2004) (*62*). <sup>5</sup>On-orbit results from model from Morfitt et al (2015) (*63*).

<insert Table 14 near here with the following title>

**Table 14. Noise Equivalent Delta Temperatures for Thermal Bands of Landsat Sensors at 280 K.** Barsi et al., 2014 (66).

<insert Figure 33 near here with the following title/caption>

**Figure 33. Typical SNR for Reflective Bands of Landsat Sensor for MSS specified signal levels** (**typically full scale radiance**) **for the earliest sensor having specified band.** The TM-OLI NIR band most closely resembles the MSS NIR-2 band, so those comparisons are grouped under NIR-2.

## 3.4.3.2 Electronic Instabilities and Related Effects

Electronic factors influencing the precision of the data include:

(1) Spikes due to cosmic ray hits, which are most common over the South Atlantic Anomaly

and polar regions (62) (63).

- (2) Recovery from saturation after exposure to a very bright target (e.g., fires in the SWIR or specular reflection off of greenhouse roofs) where the detector A/D output may go to zero and recover to normal response over multiple samples (62) (63).
- (3) A relatively rare (~1% of scenes during the first four years of ETM+ operations) ringing pattern of up to 150 counts that occurs in a few detectors in bands 1 and 8 of ETM+; the response alternates high and low with the magnitude damping over an interval of up to 2000 samples (62).
- (4) Hysteresis in the MSS photomultiplier tubes with a time constant of about 15 seconds (67), where the gain of the detectors varies by up to ~15% with the brightness of the objects previously viewed. The sampling every other scan (~0.14 sec) of the internal calibrator provides sufficient data to characterize and correct this effect in processing.
- (5) The memory effect in the TM instruments, also a hysteresis, where the radiometric biases vary with the brightness of the targets previously viewed. This effect has a time constant of about 1000 detector samples, so it varies across a scan line (about 6000 samples). The visual impact is that forward scans and reverse scans appear at different brightness and the differences vary with scan position; forward to reverse differences as large as 8 DN are possible (68). Current generation processing corrects for the memory effect, though residual artifacts may be present.
- (6) Scan-correlated shifts in the TM instruments, where the bias shifts between scans by up to 2 counts. This effect is corrected with scan-by-scan bias adjustments (68).
- (7) Coherent or patterned noise in some bands of the some of the Landsat sensors, visible when heavily stretched over uniform dark areas. Examples include the Landsat-4 MSS (69), Landsat-4/-5 TM (68) and Landsat-7 ETM+ (62). In most cases the coherent noise

is not a major contributor to the overall noise level. Also, the coherent noise levels may vary over the life of the mission, for example, some of the Landsat-7 ETM+ coherent noise decreased significantly after the scan line corrector failure in 2003 and sometimes vary with time within an acquisition interval. No correction for the coherent noise is currently performed in processing.

#### 3.4.3.3 Optical System Throughput Variability and Other Effects

Like the electronics, the optical system and its variability affect the radiometry. Key examples include:

- Contamination on the optical surfaces that affects their transmission or reflectance. This was most evident on the cold focal plane window of the TM instruments, where over time a thin film contaminant built up. This contaminant produced a thin film interference effect on the two TM SWIR bands, where the transmission oscillated with the material thickness by ~±5% and in the thermal band, the effect was strictly a transmission loss. A lifetime model for this effect was developed for both TM's and used to correct for it in standard image processing (70).
- 2) Outgassing from optical filters. As indicated in the spectral section, the spectral filters on the TM and earlier sensors were subject to the absorption of water in ambient conditions and, later, to outgassing in vacuum conditions. This absorption and release of water shifts the related band edge of the instrument and will lead to sensitivity changes, particularly if one band edge changes and the other does not. Most of this change typically occurs during launch and early activation, prior to turning on the instrument, so it cannot be monitored as it progresses. This change, in combination with possible

simultaneous changes in the internal calibrator system, is one of the largest sources of uncertainty in the early Landsat sensor radiometric calibration.

- 3) Stray light and optical crosstalk. Although discussed in the spatial section, the radiometry is interrelated. The first Landsat sensors that looked at the moon were OLI and TIRS. The TIRS lunar scans revealed light from about 13° off axis was reaching the detectors and contaminating the signal (60). This stray light was detector dependent, contributing to the non-uniformity of the processed images as well as introducing absolute calibration errors. OLI images exhibited some weak ghosts as expected, but were generally very clean (59).
- 4) Polarization sensitivity. When the target signal is polarized, polarization sensitivity in the observing system creates a radiometric error. Many Earth targets are not highly polarized, but Rayleigh atmospheric scattering and specular reflections are, (e.g., from water surfaces). Beginning with the TM sensors, a requirement for less than 5% polarization sensitivity was levied on the instruments and compliance was demonstrated by modeling and analysis. The OLI sensor was the first sensor to be tested at the integrated instrument level for polarization sensitivity. Measured performance was better than 2% and typically around 1% (23).

## 3.4.3.4 Radiometric Processing and Resulting Precision and Accuracy

Relative radiometric correction matches the response of each detector to the average response of all the detectors. The goal is to produce a product that does not exhibit striping (individual lines or columns that are brighter or darker than adjacent ones) or banding (groups of lines or columns (e.g., all columns produced by detectors in a focal plane module), that are brighter or darker than

adjacent groups). This process is typically integrated into the overall absolute calibration approach, but needs to be performed to higher standards than the typical 5% radiometric calibration accuracy. An image where each detector had a 5% independent uncertainty would be extremely unsatisfactory. The residual uncorrected non-uniformity between detectors is an additional noise source in the final data product in the cross detector direction in the image, (i.e., along-track for the whiskbroom systems and across-track for the pushbroom systems). Absolute radiometric correction scales the final data so that a given count corresponds to a known radiance or reflectance value, typically for all images acquired by a given sensor.

#### 3.4.3.4.1 Reflective Bands

#### 3.4.3.4.1.1 MSS

There have been quite a few changes in the processing goals and strategies for remote sensing data since Landsat-1 launched in 1972. Most of these changes are not relevant here as users are only interested in the data products currently obtained from the USGS. The processes continue to evolve, even some 20 years after the last operational MSS data were acquired, as old MSS data are brought back to USGS from the archives of various international ground stations. Much of these old MSS data are in unprocessed form, making a complete reprocessing possible, enhancing the understanding and potentially the quality of the data. As of this writing this process was still in flux, with some MSS data products generated from the original raw data and some from archived radiometrically processed data.

The radiometric correction for all the MSS data used the sensor's responses to multiple neutral density filtered light levels from the on-board calibration lamp (radiance levels determined prior to launch and assumed stable over the mission) to determine the gain and bias for each detector

on a subset of an individual scene. These parameters were averaged or smoothed along the scene and then applied to the data to convert to radiance. Additional details on the process are provided in Markham and Barker (1987) (71) and Helder (1993) (72) and discussed above. Destriping parameters (i.e., relative gains and biases) based on scene statistics were applied to reduce detector-to-detector residual differences. For the earlier MSSs, these parameters were only occasionally updated, whereas for Landsat-4 and -5 MSS, scene-statistic-based relative gains and biases were calculated and applied on a scene-by-scene basis. The data were then rescaled to a fixed radiance range.

Striping or lack of adequate detector-to-detector radiometric normalization has been an issue throughout the life of the Landsat MSS instruments (and many other instruments). This was particularly true for the early MSS data, though reports of striping in the data are generally poorly documented, or at least difficult to retrieve at this point in history. A very early report (73) on the first six months of operation of Landsat-1 MSS (then ERTS), reported peak-to-peak striping of about 0.5 DN (out of 64) at low radiance and about 2 DN (out of 64) at high radiance. Though not indicated, presumably this was for the NIR-2 band, which was quantized to 6-bits in the data product and, being the only band with silicon photodiode detectors, probably the best behaved. A later report indicated that striping as high as 8 DN peak-to-peak at about 75 DN in NIR-1 on the Landsat-1 MSS was reduced to about 2% in 1975 following an update to the MSS radiometric processing parameters (74). With the initiation of the scene based statistics approach on the Landsat-4 MSS, striping was generally reduced to the same magnitude as the quantization noise, that is, about 0.3 DN (75). Published reports on the radiometric quality of currently available Landsat MSS data are difficult to find, but the quality is expected to be variably dependent on the origin of the data used to generated the product, for example, already partially

processed versus raw data, etc. Additionally, most measures of detector-to-detector uniformity are tied to the same measures used to define the coefficients to remove the striping, and are therefore biased. Reasonable uniformity values are 0.5% (1 $\sigma$ ) for the early MSSs and 0.4% for the last two MSSs. This non-uniformity is essentially an additional noise in the data above the inherent noise in each detector's response that only applies in the cross detector direction. Around 2010, the consistency and stability of processed MSS data were reexamined using data collected over the most stable sites that could be found on the portion of the Earth surface routinely imaged by the MSS sensor. These studies showed that the calibrated data were generally consistent over time within a particular sensor, but that discontinuities were apparent between the MSS sensors (Figure 34) (76). Coefficients were determined to normalize for these differences and tie the absolute calibration to the Landsat-5 TM instrument. These adjustments were incorporated into the data processing in 2011 (Figure 34). The estimated  $1\sigma$  uncertainties for the various bands and instruments are shown in Table 15, based on an estimated uncertainty of 7% in the Landsat-5 TM absolute calibration which was derived by cross calibration with Landsat-7 ETM+ with an estimated uncertainty of 5%. As noted in Markham and Helder (2012) (84), the largest uncertainty in the calibration transfer occurs in MSS NIR-2 band, where the large water vapor absorption limits the accuracy of the transfer with non-simultaneous data. *<insert Table 15 near here with the following title>* 

Table 15. Reflective Band Absolute Radiometric Calibration Uncertainties –  $1\sigma$  (%). L1-L5data from Markham and Helder, 2012 (84).

<insert Figure 34 near here with the following caption>

Figure 34. Landsat MSS responses to desert test site before (left) and after (right) cross calibration to Landsat-5 MSS. Modified from Helder et al., 2012 (76).

3.4.3.4.1.2 TM

The TM processing has gone through several iterations to improve both the absolute and relative radiometry. For early TM processing, the on-board lamp system was used similar to MSS along with individual scene-statistic-based matching of the relative gains, though this was changed in later years. Concurrent with the operational data processing using the lamps, vicarious data began to be collected. For several years this occurred on a rather ad hoc basis then, beginning around the launch of Landsat-7, on a more systematic basis. In the 2000s some divergence was observed between the vicarious and lamp-based calibrations, which led to the reexamination of the assumptions in the calibration. Multiple iterations in the processing strategy were implemented to improve the radiometric calibration. The first iteration began using the bias as measured with the shutter directly (after correction for the memory effect) and a model of the instrument response based on the best behaved of the internal calibration (IC) lamps (78). Nearly simultaneously, the Landsat-5 TM response was cross-calibrated with the ETM+ to provide an initial lifetime model. Pseudo invariant calibration sites (PICS), most notably "Libya-4" (79), which was regularly imaged and the data downlinked to ESA ground stations in Italy began to be examined. After a lifetime history of response to the Libya-4 site had been generated and the vicarious calibrations and the internal calibrator responses were compared, it became evident that the lamps data were not indicative of the instrument changes. A new lifetime model using the PICS was developed and implemented to replace the IC model (80). This lifetime model only showed degradation in TM bands 1-3. In band 4 a constant was used. For bands 5 and 7, a constant was used, modified by a irregularly reset periodic functions representing the time varying interference filter effects of the contamination build up on the cold focal plane window (70). A lifetime relative gain model also replaced the scene-by-scene statistical flat fielding approach. Somewhat later in the game, Landsat-4 TM data, which also had memory effect and

scan correlated shifts, were corrected in a similar manner. The Landsat-4 TM calibration was tied to Landsat-5 TM calibration by comparison of PICS. In its "final" implementation, the Landsat-5 TM bias for each detector was based on a lifetime model rather than the per-scene bias as the memory effect correction was shown to be inadequate at very low signal levels and the biases were otherwise extremely stable over time (see USGS Landsat 4-5 TM Calibrations website: <u>http://landsat.usgs.gov//science\_L4-5\_Cal\_Notices.php</u>)

Current generation products generally show roughly  $\pm 0.5\%$  peak-to-peak range of detector-todetector variation after radiometric calibration, though in some cases one detector may be up to 1% different from the average detector, particularly in the SWIR bands (Figure 35). Notice that late in the mission history (around year 26) the two outlier detectors were corrected to better match the other detectors. The graph should thus be considered a snapshot of data products at the time. Once the Landsat-5 TM history is reprocessed, the adjustment should be applied to the full mission history. One sigma values based on image statistics indicate normalization to ~0.2% in the VNIR and ~0.3% in the SWIR (1- $\sigma$ ); again, this should improve with reprocessing. In terms of absolute calibration, as indicated above, Landsat-5 TM data were tied to the absolute radiometric calibration of the Landsat-7 ETM+ using near-simultaneous data and PICS sites. Landsat-4 TM were tied to Landsat-5 TM data using PICS sites. Table 15 presents the estimated uncertainty in the TM reflective radiometric calibrations based on a 5% uncertainty in the ETM+ calibration (77).

<insert Figure 35 near here with the following title/caption>

**Figure 35. Landsat-5 TM Band 5 post-calibration detector-to-detector uniformity based on image statistics**. Relative gains of each detector (1-16) are shown relative to detector average.

#### 3.4.3.4.1.3 ETM+

The ETM+ is a derivative of the TM, and as such, has a similar design. With the origins of several of the main artifacts in TM data established, the ETM+ was reengineered to remove these effects and the data were considerably cleaner. In particular, very few traces of contamination of the cold focal plane window, the memory effect, and scan-correlated shift appeared in the ETM+. Additionally, technological improvements in the 15 years since the design of the TM were evident, particularly in terms of A/D convertors. The data processing system was also redesigned and the capability to routinely assess the instrument performance and data quality was built into the processing system via the Image Assessment System (IAS).

The calibration processing involved determining the bias directly from the shutter measurements at the end of the scan, subtracting a scene-averaged bias, applying a pre-launch gain value adjusted by any on-orbit observed changes to convert the signals to radiance, and then rescaling this radiance back into an 8-bit number using fixed scaling parameters. Various sources were used to assess changes in absolute gain, including the on-board calibrators, vicarious measurements, and PICS. Only the PICS sites results were deemed more stable than the instrument itself (Figure 36). About 14 years after launch, enough PICS results were available to convince the team that the ETM+ calibration should be updated by about 0.1-0.2%/year in all bands (77).

<insert Figure 36 near here, with the following title/caption>

**Figure 36. Landsat-7 ETM+ Band 2 gain stability as measured by various calibration techniques.** The degradation in the solar diffuser is thought to be due to changes in the panel; in the IC, changes in the lamps. The PICS trend are derived from top-of-atmosphere reflectances, scaled to gain.

Given the inherent stability of the ETM+ instrument, the ability to normalize the detector responses to each other was enhanced. Solar diffuser data taken monthly are routinely used to assess the detector-to-detector uniformity and individual detectors relative gains are adjusted if

they exceed 0.2% deviation. Scene statistic based estimates of the precision of the detector-todetector normalization is better than 0.1% (1 $\sigma$ ). The current estimates of the ETM+ absolute calibration uncertainties are shown in Table 15.

#### 3.4.3.4.1.4 OLI

The OLI, a pushbroom design, required a somewhat different strategy for calibration, though the process was fundamentally the same. The bias values for the detectors were determined by closing the shutter before and after every acquisition interval. The average of the pre- and post-(when available) shutter acquisitions were used to process all the intervening data. The pre-launch non-linearity characterizations were used to correct the non-linearities on orbit. Radiance gains from pre-launch measurements and reflectance gains from the initial post-launch diffuser observations were modified as necessary based on the observations of the on-board calibrators, the moon, PICS, and vicarious calibrations. The relative gains were assessed using the diffuser measurements and generally updated on a quarterly basis.

The OLI has been very stable since launch, with only the CA band showing a small ~1% band average response degradation over 3 years on-orbit (Figure 37). The responses to all the calibration sources are generally consistent to within a few tenths of a percent. Image statistics for a pushbroom instrument are more challenging to use to evaluate detector-to-detector uniformity, as each detector generally does not see the same distribution of target radiances in any given scene. Evaluations of the magnitudes of the changes in relative gains between diffuser collects suggest that the detectors are typically normalized to better than 0.1%, at least relative to their immediate neighbors, though occasionally a detector in one of the SWIR bands changes by 1% or more and is not updated until the beginning of the next quarter. Unless very large changes

take place, the calibration is not updated in the middle of a quarter. Although the localized correction of OLI data is excellent, errors may build up across the focal plane, primarily because each detector module views the diffuser at a different angle, has a different spectral filter, and a different A/D convertor. A roll-up of these uncertainties indicates about a 0.2% (1 $\sigma$ ) across-track non-uniformity in the data. An additional banding-like artifact (variation across-track as opposed to along-track for the whiskbroom sensors) may occur as the odd FPMs are pointed slightly forward along-track and the even ones slightly aft. In areas of strong BDRF variation, (e.g., in the principal plane over water), there may be odd-even FPM banding that is due to true variations at sensor radiance as opposed to deficiencies in the normalization process. Absolute calibration of the reflective bands appears to be good to ~3% in the reflectance mode and ~5% in the radiance mode. Current plans call for tying all the previous Landsat sensors to the Landsat-8 OLI reflectance calibration in 2016-2017.

#### *<insert Figure 37 near here with the following title/caption>*

**Figure 37. Landsat-8 OLI Band 1 gain trends based on multiple calibration techniques**. There is general agreement between all calibrators and so the CA band calibration was updated to remove the presumed instrument degradation.

#### 3.4.3.4.2 Thermal Bands

#### 3.4.3.4.2.1 Landsat-4/5 TM and Landsat-7 ETM+

On orbit, the TM and ETM+ instruments acquire the internal blackbody (roughly 315 K) and shutter flag (roughly 285 K) data at the end of each scan line. These data and the temperatures of the sources are used with a pre-launch model and parameters to calculate a gain and bias for each detector for every Landsat scene. In ground processing, these gains and bias are applied to calibrate the image data and generate data products that are consistently scaled to fixed radiances (*81*). Beginning in 1999, on-orbit satellite radiances were regularly compared to predicted at-

satellite radiances based on measured surface water temperatures propagated through the atmosphere. Additional work was done to mine the archive of NOAA buoy data to validate the Landsat-4 and Landsat-5 TM calibration from 1982-1999 (82). When multiple measurements indicated a consistent gain or bias error, the calibration model parameters were updated. Additionally, per-detector scene statistics were regularly calculated for a subset of image data for ETM+ starting at launch and for both TM instruments beginning in 2008 for data back to the beginning of the mission. When these means and standard deviations indicated a mismatch between the multiple detectors, the parameters were adjusted as necessary to match the statistics and decrease image striping. Current data products from the USGS EROS Landsat Data Product Generation System are generally accurate to about  $\pm 0.5$  K ( $\pm 0.7\%$ ) across a temperature range of 275 - 300 K for the years since 1984 (Table 16), with relative calibration at  $\pm 0.2\%$  ( $\pm 0.2$ K) or better (Table 17).

#### 3.4.3.4.2.2 Landsat-8 Thermal Infrared Sensor (TIRS)

Prior to launch the TIRS bands are radiometrically calibrated using an external blackbody source. A Radiometric Look-Up-Table (RLUT) was developed to account for the electronic and detector non-linearities to convert image data to radiance. On-orbit, deep space, and blackbody observations are made, typically before and after each data acquisition interval. The deep space observations are used to estimate the biases. Observations of the onboard blackbody are used to make a relative adjustment to the RLUT to account for relative gain changes that occurred after launch, though no overall absolute calibration update was required based on the blackbody measurements. Further relative gain adjustments are made based on Earth scene statistics and 'yaw-scan' maneuvers (*38*).

The absolute calibration was verified through a vicarious method involving in-situ measurements of large water bodies and modeling of the top-of-atmosphere radiance in the TIRS spectral channels (66). After several months on orbit, it was determined that the instrument suffered from a stray light problem in which radiance from outside the direct field of view of the instrument was adding a non-uniform signal to the detectors (60). This additional stray light signal produced a varying banding effect in Earth imagery and also produced a season-dependent absolute calibration error (66) (60). Preliminary efforts to mitigate the effects of stray light have included removing an average bias from each channel based on vicarious calibration data to force an average error of zero (66). However, the significant spread in the errors and the banding effects still remain, which has led the calibration team to recommend that users only utilize Landsat-8 band 10 data for now as the errors in band 10 are roughly half the magnitude of the errors in band 11 (66) (60). Typical calibration uncertainties for the currently calibrated data product are indicated in Table 16 and relative calibration uncertainties in Table 17. A more involved correction algorithm has been developed that reduces the residual errors to magnitudes for the TIRS band 10 data to be on the level of previous Landsat instruments (61). This correction algorithm will be implemented operationally into the Landsat product generation system in 2016. *<insert Table 16 near here with the following caption>* 

#### Tabl

e 16: Thermal Band Absolute Radiometric Uncertainties in K (1 $\sigma$ ) (275~300K).

<insert Table 17 here with the following title and footnote>

## **Table 17. Thermal Band Relative (across detector) Radiometric Uncertainties, 1σ (K), 275 ~300K.** *<insert table>*

\* Typical, varies due to stray light effects.

### 3.4.3.5 Useful Dynamic Range

The dynamic range of the instrument extends from the minimum detectable radiance, or NE $\Delta$ L, up to the detector's saturation radiance. In reality for Landsat data, the useful range of radiances is also limited by how the signal is quantized for transmission to the ground and how the data are processed and converted into a data product. As all the Landsat instruments have more than one detector per band and each detector responds somewhat differently, the upper end of the dynamic range is often set by the most sensitive detector (i.e., the one that saturates first). All the other detectors are typically rescaled to this detector so that in the final data product all pixels will have the same maximum potential value. The OLI is the exception to this rule where, in the data products, all bands are scaled the same in reflectance space with the maximum reflectance set to 1.21 and the minimum to -0.1 (1 DN =  $2 \times 10^{-5}$  reflectance units). This leads to a case in the SWIR-2 band, for example, where the actual detectors saturate as low as 26.6  $W/m^2$  sr µm while the data products are scaled to 31 W/m<sup>2</sup> sr  $\mu$ m. The high-end saturation radiances (L<sub>MAX</sub>) values are provided in Table 18 for the reflective bands, converted to top-of-atmosphere reflectances in Table 19. The low-end saturation radiances (L<sub>MIN</sub>) and L<sub>MAX</sub> values for the thermal bands are provided in Table 20 and converted to Top-of-Atmosphere T<sub>MIN</sub> and T<sub>MAX</sub> in Table 21. Data from outside the temperature range over which the instrument was calibrated prior to launch, shown in Table 21, should be used with caution.

#### *<insert Table 18 here with the following title and footnote>*

Table 18. Landsat Reflective Band Data Product High-End Saturation Radiances ( $L_{MAX}$ ) ( $W/m^2$  sr  $\mu$ m). From Calibration Parameter Files available at <u>http://landsat.usgs.gov//science\_calibration.php</u>. Data processing changes over the life of the missions means that some products may have different saturation radiances. Refer to the data product for actual  $L_{min}$  and  $L_{max}$ . *<insert table>* 

\* OLI radiance scaling varies with the Earth Sun Distance; these are for 1 Astronomical Unit. SWIR-1 and SWIR-2 band data saturate before reaching data product saturation (65535).

<insert Table 19 near here with the following title and footnote>

# Table 19. Landsat Reflective Band Data Product High-End Saturation Reflectances ( $\rho_{MAX}$ ) for Zenith Sun at Earth-Sun Distance = 1 A.U.\*

<insert table>

\* Landsats-1 to -3 had a nominal equatorial crossing time of 0930 with a minimum equatorial solar zenith angle of ~ 37°; Landsat-4/-5 of 0945, SZA min ~34°; Landsat-7 of 1000, SZA min ~30°; Landsat-8 1013, SZA min ~26°.

#### <insert Table 20 near here with the following title/caption>

Table 20. Landsat Thermal Band Data Product Low and High-End Saturation Radiances ( $L_{MIN}$ ,  $L_{MAX}$ ) ( $W/m^2 sr \mu m$ ). From calibration parameter files available at the USGS Landsat-8 Calibration and Bias Parameter Files page online: <u>http://landsat.usgs.gov//cpfbpf.php.</u>

<insert Table 21 near here with the following title/caption>

Table 21. Landsat Thermal Band Data Product Low and High-End Saturation Temperatures  $(T_{MIN}, T_{MAX})$  (K). The data were calibrated over specific temperature prior to launch: TIRS 180 K to 360 K; ETM+ 180 K to 350 K; TM 260 K to 320 K. The on-orbit vicarious calibration validates the temperature range from 275 to 305 K.

## 3.4.4 Geometric Characterization and Calibration of Landsat Data

#### 3.4.4.1 Overview

The objectives of the geometric characterization and calibration of the Landsat instruments have fundamentally stayed the same across the Landsat missions. The main objectives have been to make each band geometrically sound in that each detector within a band is accurately located, each band has good, consistent, geometric registration to a reference source, and the bands for each instrument are aligned to each other in order to obtain good band-to-band registration. Where there are multiple instruments on board a single spacecraft, good sensor-to-sensor alignment is also necessary. The alignment between the sensor and the attitude control system (ACS) of the satellite is estimated as accurately as possible in order to minimize systematic detector line-of-sight pointing and positional errors associated with any misalignment between these two coordinate systems. By accurately relating the sensor line-of-sight coordinate system to the spacecraft navigation coordinate system, only slowly varying scene-to-scene bias and rate errors associated with the spacecraft attitude and ephemeris information remain within the image products generated. The residual errors inherited from the supporting spacecraft navigation data are present on a scale that allows mensuration between a geometrically corrected image and a set of ground control points (GCPs) or other reference imagery.

This section describes the post-launch geometric characterization and calibration processes adapted for the multiple Landsat sensor architectures, explains how the availability and quality of supporting information both from the sensor or spacecraft (e.g., ephemeris and attitude data) and external sources (e.g., GCPs, digital elevation models (DEMs)) influence Landsat image geometric accuracy and concludes with a "snapshot in time" summary of some of the geometric performance metrics derived from these processes.

#### 3.4.4.2 Geometric Characterization and Calibration

Geometric characterization refers to the processes that measure aspects of geometric performance that are reflected in the image data products. Product geometric accuracy reflects the stability of the sensing platform (sensor and spacecraft) and the fidelity and accuracy of the geometric model used to process and correct the sensor data. Geometric model accuracy relies on the availability and quality of supporting sensor and spacecraft telemetry as well as accurate knowledge of static or quasi-static model parameters such as sensor-to-spacecraft alignment, scanning mirror profiles, and detector locations. Once these key geometric properties are measured and characterized, systematic errors in the data products can be attributed to elements of the underlying geometric correction model and used to improve knowledge of the corresponding model parameter values. The instrument and spacecraft can thus be geometrically "calibrated" by adjusting the geometric model parameter values to account for measured deviations reflected in the processed image data.

Akin to radiometric characterization and calibration, the geometric characterization and calibration process is facilitated by the IAS. The geometric processing component of the IAS characterizes aspects of geometric performance, uses these characterization results to calibrate key geometric model parameters to better fit the measured response, and propagates these measurements and changes into the Level-1 product generation system. Details on the IAS and LPGS are provided in Section 3.4.5

#### 3.4.4.2.1 Dependencies on Instrument Design

There have been two different instrument architectures used during the Landsat program. Landsat-1 through -7 used whiskbroom architecture while Landsat-8 uses pushbroom architecture (*84*).

For the Landsat-1 through -7 instruments, the along-scan layout of the bands and subsequent mirror scanning motion associated with these bands ensures that all the bands cover essentially the same image area within a short amount of time. For the Landsat-7 ETM+ and Landsat-4/-5 TM instruments this is an approximately 2.1 and 1.8 millisecond time period respectively. As a results of this limited amount of time very little spacecraft motion, or even jitter, occurs between the times when the same image point on the ground is acquired by the different spectral bands, leading to a stable band-to-band registration. Also there is little difference in the effects of terrain parallax associated with the scanning mechanism between bands within these instruments.

However the scanning mirror mechanisms produce scanning pattern variations and there is a small amount of mirror-related jitter complicating the task of providing good internal geometric accuracy for every scene. The combination of the mirror model, on-orbit measures of the scanning motion of the mirror, the individual band and detector location, and the spacecraft positional and attitude information, establishes the line-of-sight relationships between the individual detectors of a given band and the Earth's surface (*85*), as represented by a standard Earth model such as the World Geodetic System 1984 (WGS84). (http:// http://earth-info.nga.mil/GandG/wgs84/) These lines of sight are the key to being able to characterize and calibrate these systems.

For the pushbroom architecture aboard the Landsat-8 spacecraft, there is no mirror scanning mechanism; however, there is a different set of geometric challenges. Instead of a single small focal plane, the OLI and TIRS focal planes are made up of 14 separate sensor chip modules for OLI and 3 separate modules for TIRS. This allows the instrument fields of view to cover the full Landsat swath in the across-track direction. The detectors for the different bands are separated out in the along-track direction leading to a substantial time delay between the times when bands image the same location on the Earth. This time delay is approximately 1.1 and 1.9 seconds between the leading and trailing spectral bands within the OLI and TIRS instruments respectively. This leads to a substantial change in spacecraft position and attitude between bands when imaging the same location on the Earth along with a substantial difference in the terrain parallax that must be accounted for by using both the spacecraft telemetry and a DEM during processing. Each band on each module has its own set of higher order polynomials (4<sup>th</sup> order) that describe both band and detector locations which are used to establish their line of sight relationship. As with the whiskbroom instruments these lines of sight are combined with the

spacecraft positional and attitude information to determine the relationship between the raw image pixels and the corresponding locations with respect to the Earth model (*86*). As with whiskbroom systems, these lines of sight are the key to being able to characterize and calibrate these systems.

#### 3.4.4.2.2 Data Formats Dependencies

The ability to register Landsat imagery to a reliable reference source and produce internally accurate geometry within that product is highly dependent on the telemetry data provided for both the instrument and the spacecraft.

For MSS instruments, archived data exist in formats that contain only the raw imagery with no spacecraft position or pointing information. Under these conditions positional information is generated using orbital parameters in the form of Two Line Elements (TLEs) sets combined with orbital prediction software using Simplified General Perturbation (SPG4). These L1T products will be less accurate geometrically when compared to some of the other MSS formats for which at least some of this information is provided. For TM there are formats for which the spacecraft jitter information is not present, leading to high-frequency image disturbances that cannot be corrected with ground control. These products may have the larger biases removed from their data products but will be unable to correct for any spacecraft jitter that is present. These are two examples from the Landsat archive where lack of the proper spacecraft and instrument support data has a direct effect on the geometric quality of the products produced.

All of the Landsat missions contain at least one format for some subset of the USGS Landsat archive which includes an adequate set of spacecraft and instrument telemetry for accurate L1T product generation. As a general rule, the quality of the telemetry data has greatly improved from the Landsat-1 through -8 missions, allowing for considerably better geometric accuracy.

### 3.4.4.2.3 Supporting Data

Landsat product generation makes use of GCPs to correct for residual bias and rate errors in the supporting ephemeris and attitude telemetry and DEMs to correct for image offsets due to terrain relief. In addition to the GCP and DEM data, geometric characterization and calibration operations require supporting reference images that cover the full sensor field of view. Having full swath reference image coverage makes it possible to measure image deviations at the level of an individual scan (Landsats-1 through-7) or module (Landsat-8).

Two sets of reference imagery and associated GCPs are used for Landsat geometric characterization and calibration. The global ground control library used for product generation is supplemented by a more accurate high resolution data set available at selected calibration sites, called the Geometric Supersites. With respect to global coverage the Geometric Supersites extent is considerably less than that of the product generation's ground control. To keep the L1T imagery consistent the same ground control library is used for product generation for all missions globally. The Global Land Survey (GLS) geometric framework originated from a global subset of Landsat-7 scenes (GLS2000) from which the image registration chips were extracted (*89*) (*90*) (*95*). The Geometric Supersites are derived from USGS Digital Orthophoto Quadrangle (DOQ) data and GPS controlled SPOT. These high resolution images are downsampled from their native pixel resolution to match the highest resolution of a given instrument. Historically the GLS framework has been described as having a 25 meter root-mean-squared-radial error (*89*) (*90*). However, starting in 2014, the USGS initiated an effort to improve upon this accuracy of

the GLS framework using first OLI imagery and then the Sentinel 2A Geographic Reference Imagery (GRI) as it becomes available (USGS Landsat Mission, Geometry website <u>http://landsat.usgs.gov/.geometry.php</u>). Even with these planned improvements being made to the GLS framework, the Geometric Supersite imagery will continue to be used for geometric characterization and calibration purposes as they serve as an independent reference that covers the full Landsat WRS-2 swath width of the instruments.

#### 3.4.4.2.4 Geometric Characterization and Calibration Processes

Whiskbroom and pushbroom architectures require fundamentally different characterizations with respect to geometric characterization and calibration. The whiskbroom requires that the scanning mirror behavior be characterized and then calibrated while the pushbroom requires the module-to-module alignment within the instrument focal plane to be characterized and calibrated (*84*) (*85*) (*86*) (*92*) (*93*). Both of these steps take a geometrically stable known reference image and measure any differences between it and a radiometrically-geometrically corrected Landsat image. These measurements can be used to calibrate the corresponding geometric modeling parameters used in data processing.

Regardless of the instrument architecture, an important geometric property of all Landsat instruments is the between-band registration. Any band-to-band misregistration is characterized and the bands' focal plane placement is estimated relative to one individual band within the instrument, thus calibrating the alignment of all bands to that given reference band. In the case of Landsat-8 and the two instruments on board (OLI and TIRS), a between-sensor alignment is also performed where the misregistration between two bands, one from each sensor, is characterized and differences can be accounted for by adjusting the TIRS-to-OLI sensor alignment parameters, a rotation matrix, to better align the data from the two instruments. Another less obvious geometric characterization and calibration step is that which aligns an instrument's detector lines of sight with the attitude control system of the spacecraft. This step helps remove any bias errors associated with the orientation of the instrument relative to the attitude control system that show up as consistent systematic offsets in the L1G and L1Gt products. For the Landsat-1 through Landsat-5 instruments this alignment helps with the mensuration of the product generation ground control within the L1G products, which, in turn helps facilitate the ground control matching processes ultimately allowing for generation of a greater number of L1T products. For the Landsat-7 and Landsat-8 instruments this step allows for better registration of a L1G to the DEM allowing for the generation of the much more accurate L1Gts rather than L1Gs. In the case of Landsat-8, which has the previously mentioned module-to-module terrain parallax properties, this helps improve the band-to-band registration in the products for which L1Ts could not be generated.

These are the main processes and steps needed to insure that the instruments and platforms can be geometrically characterized and calibrated, thus providing the user community with as accurate geometric products as possible which are based on the system requirements and dependent on the support data provided during product generation (*85*)(*86*). A key point to make regarding these steps is that in cases where a good stable reference set of images is needed, specialized very specific data is supplied. This stable reference data set is often not available globally, requiring these processes to be performed only over a limited set of geographic locations, basically the Geometric Supersites.

Several other processes are performed for the characterization and calibration of the instruments and platform which more directly provide the user community with vital information directly related to the geometric accuracy of their products. These accuracy characterization processes are referred to as geometric accuracy, geodetic accuracy, and image registration accuracy. Geometric accuracy as used here relates to a product's internal accuracy. This characterization process is performed by comparing L1T products to one of a number of possible reference (image) data sets. Geodetic accuracy refers to the accuracy of the image products without the use of ground control and excludes the effects of terrain height. Finally, image registration accuracy refers to the temporal component of registering multiple acquisitions of the same site, keeping consistent the features that are being compared over time or producing what is often referred to as stackable data. All three of these processes can be done while referencing the product to the GLS framework, the Geometric Supersites, or to previously acquired mission imagery (*87*) (*88*) (*91*) (*94*).

The remaining portions of the Landsat geometry section address some of the more important product-related results produced from these processes.

## 3.4.4.3 Landsat Geometry Level-1T

The goal of the geometric characterization and calibration steps is to provide users with reliable geometrically-corrected products that allow for data analysis, in particular time series analysis, to be performed. The major representation of these geometric characterization steps with respect to product generation is how well the L1T imagery registers to the GLS framework. The results are analyzed to produce residual statistics as to how well the imagery compares to the GLS framework. The geodetic accuracy statistics illustrate how well the systematically corrected image fits to the ground control prior to adjustment and provide a measure of the sensor/spacecraft systems' absolute geolocation accuracy and therefore excludes the offset

effects of terrain height. The geometric accuracy statistics represent any residual errors present after the satellite's ephemeris and attitude are adjusted to correct for any bias or first order rate errors and to account for any geometric distortions associated with terrain. Therefore the geometric accuracy residuals measure how well the L1T registers to the GLS framework along with how well products register to one another. Due to updates to the GLS framework, the elevation imagery used, and improvements to the Level-1 product generation system itself, the statistics associated with the L1T images within the Landsat USGS archive have changed over time and will continue to evolve. In the late fall to winter of 2015, statistics were calculated for these residuals for the archive along with the percent of the USGS Landsat archive that produced L1T imagery (USGS Landsat Missions, Landsat Collections online,

http://landsat.usgs.gov/landsatcollections.php).

### 3.4.4.3.1 MSS

Table 22 shows percentages of the MSS L1T products within the USGS Landsat archive that are at or fall below a given net radial RMSE with respect to the GLS framework.

#### <insert Table 22 near here with the following caption>

### Table 22. Percent of MSS L1T Products at or Below a Net Radial RMSE.

From Table 22 it can be seen that 50% of the archive is registered to the GLS framework to within approximately 1 TM/ETM+/OLI pixel, while 90% of the archive is registered to the GLS framework to within a little over 1 MSS pixel. Taking this type of analysis one step further the overall mean RMSE for each WRS path/row was calculated within the archive and was plotted based on the WRS scene center coordinate. This type of plot helps show globally how these residuals are distributed geographically. This plot is shown in Figure 38 for Landsat-5 with

respect to WRS-2 and shown in Figure 40 for Landsat-1 through Landsat-3 with respect to WRS-

1.

## <insert Figure 38 near here with the following caption> Figure 38. Landsat-5 MSS L1T Archive Mean RMSE with Respect to the GLS Framework for WRS-2 Path/Row.

### <insert Figure 39 near here with the following title/caption> Figure 39. Landsat-1 through -3 MSS L1T Archive Mean RMSE with Respect to the GLS Framework for WRS-1 Path/Row.

From Figures 38 and 39 it appears as if Landsat-5 MSS registers better to the GLS framework than Landsat-1 through Landsat-3 MSS. However, inspection of some of the more problematic areas during the GCP improvement process has shown these areas to be difficult to register to the GLS framework in general due to the large amount of cloud cover and temporal changes present. At the time of the generation of these statistics there was not the same degree of global coverage of the Landsat-5 MSS as there was for the Landsat-1 though Landsat-3 MSS within the USGS Landsat archive, especially with respect to some of the areas known to be the problematic regions.

No rigorous band characterization campaign has been performed for MSS. Due to the nature of the instrument, with all bands residing within the same focal plane, no real measureable band misregistration was expected and none was detected upon inspection while integrating the MSS instrument into the product generation system. Note that at the time of the generation of these statistics there was still an influx of new MSS data arriving from the International Cooperators (ICs), with respect to those data being available within the USGS Landsat archive. These data would be of the "raw" data format type lacking any satellite positional or pointing information and typically representing the geometrically less accurate of the MSS data formats.

## 3.4.4.3.2 TM and ETM+

Tables 23 and 24 respectively show percentages within the USGS Landsat archive of the TM and ETM+ L1Ts that are at or fall below a given net radial RMSE with respect to the GLS framework. The tables also show the same percentages of ETM+ and TM IAS imagery that are at or fall below a given net radial RMSE with respect to the Geometric Supersites. *<insert Table 23 near here with the following caption>* 

#### Table 23. Percent of TM L1T Imagery at or Below Net Radial RMSE.

<insert Table 24 near here with the following caption> Table 24. Percent of ETM+ L1T Imagery at or Below Net Radial RMSE.

The generated statistics associated with the Geometric Supersites show a better registration fit than that associated with the GLS framework. This better fit is due to the GLS framework being less accurate than a Geometric Supersite with respect to an absolute geolocation of the Earth's surface and partly because of within scene internal inaccuracies associated with the GLS framework. The USGS GCP improvement plan will help reduce these GLS framework statistics by making the GLS framework more accurate in both respects, internally and absolute with respect to Earth's surface. It should be mentioned that the Geometric Supersite results also benefit from the image quality of the data processed when compared to that of the GLS framework. Essentially only cloud-free data are processed through the IAS over the Geometric Supersites whereas any scene regardless of cloud cover will be processed through the product generation system.

In some aspects comparing products across instruments, even when the reference imagery is the same, is not a truly equivalent study for each instrument. There could be major changes in the

instrument data due to changes on board the spacecraft. These changes, as is the case in going from Scan Angle Monitor (SAM) to bumper mode operations, can cause a decrease in the expected geometric accuracy. Also, as in the case of both the switch to bumper mode operations and the Scan-Line-Corrector failure, they can cause changes to the processing algorithms within

the product generation system (93) (USGS Landsat Missions, SLC-off\_Products website:

<u>http://landsat.usgs.gov/products\_slcoffbackground.php</u>). However, from a user perspective and being able to determine the overall temporal registration characteristics of the imagery of a given instrument, the comparison still holds.

The mean of the radial RMSE of the ETM+ and TM L1Ts in the USGS Landsat archive based on the WRS-2 scene center coordinates is shown in Figures 40 and 41 respectively. Note the change in the color bar scale compared to Figures 38 and 39.

<insert Figure 40 near here with the following caption> Figure 40. Landsat-4/-5 TM L1T Archive Mean RMSE with Respect to the GLS Framework Plotted for WRS-2 Path/Row.

<insert Figure 41 near here with the following caption> Figure 41. Landsat-7 ETM+ L1T Archive Mean RMSE with Respect to the GLS Framework Plotted for WRS-2 Path/Row.

Figures 40 and 41 help demonstrate some of the issues associated with using the GLS framework in particular and ground control in general. In areas such as Greenland that lack consistent and in many cases any static discernable landscape features, registration is difficult as the image correlation methods used to measure the Landsat products against the GLS framework will fail within these areas. Also there are regions with seasonal or temporal issues where ETM+ appears to register better than Landsat-5 TM. This better registration more than likely is due to the fact the GLS-2000 framework is based on images from 1999-2003 and the ETM+ lifetime aligns better with this period than the 29+ years of Landsat-5 TM. As part of the USGS GCP improvement plan "historical" GCPs will be added in these temporal or seasonal problematic areas and these results should improve for TM.

For both the ETM+ and Landsat-5 TM instrument, band characterization and calibration are monitored. The initial check-out period post launch of the satellite is particularly important as the stress of the launch could change the relative focal plane displacement between the two focal planes. The TM and ETM+ instruments have separate prime (warm) and cold focal planes associated with the VNIR (warm) and SWIR/thermal (cold) bands. This makes band characterization and calibration of the TM and ETM+ instruments an important process because although the instrument design provides for good and stable band-to-band registration within a single focal plane, the separation of the two focal planes produces a measureable difference with respect to band alignment, which must be accounted for through the band characterization and calibration processes (*89*) (*91*). Tables 25 and 26 provide the band alignment for each instrument measured in the net RMSE given in terms of 30 meter pixels after band calibration and associated with the L1Gs that are processed through the IAS.

<insert Table 25 near here with the following caption> Table 25. Landsat-7 ETM+ Band Alignment Registration Listed in Units of 30 Meter Pixels.

<insert Table 26 near here with the following caption> Table 26. Landsat-5 TM Band Alignment Registration Listed in Units of 30 Meter Pixels.

## 5.4.4.3.3 OLI and TIRS

Table 27 shows percentages of Landsat-8 OLI L1Tsin the USGS Landsat archive that are at or falls below a given net radial RMSE with respect to the GLS framework and also shows the same percentages of IAS imagery that are at or fall below a given net radial RMSE with respect to the Geometric Supersites.

#### <insert Table 27 near here with the following caption>

#### Table 27. Percent of OLI L1T Imagery at or Below Net Radial RMSE.

As with the TM and ETM+ instruments, the GLS framework-related statistics for the OLI instrument show higher net RMSEs when compared to the Geometric Supersite statistics. The same reasons for this being the case with the TM and ETM+ instruments would apply to the OLI statistics. Based on differences noted when comparing statistics across instruments as well as differences noted when comparing within-instrument statistics between control types, and considering that OLI statistics are slightly better with respect to the Geometric Supersites than those same statistics for the ETM+ might suggest that the GLS framework also contains characteristics associated with the data from which they were extracted (i.e., the whiskbroom scanning ETM+ sensor). This could manifest itself as higher-order errors belonging to the scanning mechanism of the ETM+, therefore matching the whiskbroom type architecture better than the pushbroom type architecture. However with the addition of OLI GCPs to the product generation system during the USGS GCP improvement plan it is likely there will be a lowering of these numbers belonging to the GLS framework statistics for the OLI instrument while slightly increasing those same statistics for ETM+ and TM.

Figure 42 shows the geographic distribution of the mean radial RMSE plotted with respect to WRS-2 center coordinates for the OLI instrument for each WRS-2 path/row.

*<insert Figure 42 near here with the following caption>* 

Figure 42. Landsat-8 OLI L1T Archive Mean RMSE with Respect to the GLS Framework Plotted With Respect to WRS-2 Path/Row.

Another factor that can influence the statistics is that the steps involved with the product generation system in comparing the Landsat imagery to the GLS framework are not exactly the same across all instruments. Finally, the OLI instrument acquires essentially all cloud-free data that are available over a pass during its operations, whereas during operations of much of the ETM+ and TM instruments an acquisition plan for a given pass would include only acquiring cloud-free imagery or in a portion of the TM lifetime cycle acquiring data associated with the full-cost covering era. The USGS GCP improvement plan which will add OLI GCPs is expected to reduce these statistics for OLI imagery so they will become more equivalent to that of the ETM+ or quite possibly even better.

Because of the design of the OLI and TIRS instruments band characterization and calibration is monitored for both instruments. This is especially true with respect to the initial check-out period post launch of the satellite as the stress associated with the launch could change the focal plane module-to-module alignment slightly from what was measured on the ground pre-launch (*87*)(*88*). Tables 28 and 29 show the band alignment for each instrument measured in the net RMSE, given in terms of a pixel size of 30 meters, after calibration and associated with the L1Ts that are processed through the IAS.

<insert Table 28 here with the following caption>

#### Table 28. OLI Band Alignment Registration in Units of 30 Meter Pixels.

<insert Table 29 near here with the following caption> Table 29. TIRS Band Alignment Registration in Units of 30 Meter Pixels.

Table 27 and Figure 42 lists OLI statistics, specifically the relationship between band 6 and either the GLS framework or Geometric Supersites. Table 28 relates the within-band accuracy of the OLI instrument and Table 29 relates the within-band accuracy of the TIRS instrument. Table 30 lists the OLI-to-TIRS alignment, or the Landsat-8 sensor-to-sensor alignment. Knowing this sensor-to-sensor alignment along with the band registration for each instrument allows for a geometric accuracy assessment of the overall Landsat-8 platform including both instruments. *<insert Table 30 near here with the following caption>* 

#### Table 30. OLI-to-TIRS Band Alignment in Units of 30 Meter Pixels.

#### 3.4.4.5.4 Product Generation L1T Status

Another important aspect to the USGS Landsat archive is how much of the archive can achieve a L1T product status. Unlike the measures of how well the L1T products match the reference imagery, the ability to create a L1T is much more dependent on characteristics such as the cloud cover present within the scene and temporal changes between the Landsat and the reference imagery. These effects are for the most part beyond the control of the processing system and its algorithms. Table 31 lists the percentage of the archive that reaches a L1T status by cloud cover and using a 30 meter radial post-fit RMSE threshold relative to the GLS framework.

#### *<insert Table 31 here with the following caption>*

# Table 31. Success Rate in Percentages of L1T Landsat Archive broken down by Cloud Cover and Product Type.

Table 31 shows what may be considered obvious: cloud cover can greatly affect the ability to mensurate the GLS framework relative to the systematically (L1G or L1Gt for OLI data only) corrected Landsat imagery, thus preventing the generation of a L1T. It is also worth noting that imagery between the 90-100% cloud cover can at times generate a L1T. There are a number of reasons that allow these scenes to be processed to a L1T including: (1) because the amount of cloud-free ground area in the scene fortuitously includes enough GCPs for registration; (2) the inability to generate an accurate cloud cover assessment for that scene so that there is more cloud

free area than the cloud score indicates; or (3) because often the SWIR band used for registration can see through the thin cloud cover. As of early 2016, thresholds for marking a given data set as a L1T are: (1) a geometric accuracy assessment with a net RMSE of less than 30 meters in the x and y directions for the ETM+ and OLI instruments; (2) a geometric accuracy assessment with a standard deviation of 45 meters for the TM instruments; and (3) a standard deviation of 160 meters in the x and y directions for MSS. The measurements shown in Table 31 are net radial RMSEs, determined from the x and y RMSEs reported within the product generation system, which on rare occasions may be greater than the individual x and y 30 meter components. As with the previous figures and tables, interpreting Table 31 for each instrument, or mission, can be challenging. For missions involving Landsat-1 through Landsat-7, due to several historical reasons, a required minimum of 30 of the GLS framework GCPs must be used in the precisionterrain correction process whereas for Landsat-8 a required minimum number is based on a percentage of the GCPs available during the precision-terrain correction process (86). Therefore, Landsat-1 through-7 have a number of WRS-2 path/rows for which a precision solution will not be attempted due to the number of GCPs (minimum 30) present within the scene. Scenes that contain control but fail to achieve the minimum number of GCPs are categorized as fallbacks (FB). The USGS GCP improvement plan, which includes the step of increasing the number of GCPs available by adding OLI GCPs, will eventually help with this minimum GCP constraint for the Landsat-1 through -7 missions. Also the ability to generate L1Ts has continued to evolve, particularly for MSS. Issues with multiple archive formats, lack of historical documentation and errors in the software, algorithms, and parameters are slowly being worked through. Therefore, as time progresses, the MSS success rate for generating a L1T as well as the geometric quality will improve as changes are made to the MSS algorithms and processes. To a much lesser

degree this would apply to the TM instruments and an even less degree to the ETM+ instrument and OLI instruments and the data products associated with those instruments.

## 3.4.5 Landsat Data Processing

The fundamental backbone of the modern-day Landsat processing system is the IAS, from which the Landsat Product Generation System (LPGS) is derived. The IAS was developed with a robust set of algorithms designed to evaluate and track calibration, product quality, and sensor performance, as well as generate calibrated image data. The LPGS consists of a subset of the IAS algorithms, stripped down to the ones necessary for generating the end-user science product. The IAS and LPGS were originally developed for the evaluation and processing of Landsat-7 ETM+ data. They were expanded to include processing capability for the TM instruments in the mid-2000s and the OLI and TIRS instruments when they were launched. In about 2010, the ability to process MSS data has also been added so the whole suite of Landsat instruments can be processed under the same umbrella of algorithms.

Many of the results presented in previous sections are derived from IAS characterizations. This section presents a basic outline of the steps the LPGS takes to generate a calibrated image product and some of the specialized algorithms the IAS runs to generate the characterization and calibration data. This section deals only with the current processing system, which has been in place for all Landsat sensors since about 2010.

There were many other processing systems throughout the Landsat mission and there may be products in existence from individual user archives. However, the calibration and processing has improved dramatically with the use of the IAS and LPGS and older products are not guaranteed to meet the performance levels quoted in this chapter.
## 3.4.5.1 LPGS processing

The conversion of the raw instrument data to a calibrated science product is fundamentally the same across all Landsat instruments. The radiometric correction involves subtracting the background signal (bias) and dividing by the gain of the instrument which converts the raw instrument output (in counts) to a radiance (in  $W/m^2$ sr µm). Each operation is performed at the per-detector level. The details of the process are slightly different between sensors: the biases and gains may vary line by line as for the whiskbroom instruments, and there may be adjustments involved to the biases due to hysteresis (a.k.a. memory effect for TM). The OLI and TIRS instruments additionally require a correction for response non-linearity before the conversion to radiance.

The geometric processing uses Earth ellipsoid and terrain surface information in conjunction with spacecraft ephemeris and attitude data along with knowledge of the instrument and satellite geometry to relate locations in instrument image space (band, scan, detector, sample) to geodetic object space (latitude, longitude, and height). In the final step, the data are resampled to the object space grid and rescaled to an 8-bit (MSS) or 16-bit data product TM. Starting with Landsat-8, scaling coefficients to convert to at-satellite reflectance are provided in addition to radiance scaling coefficients. This is being implemented for the older sensors' products as well. The LPGS performs this processing on every image from every Landsat satellite, taking into account the particularities of each sensor, to generate a standard calibrated image product.

### 3.4.5.2 IAS processing

The IAS algorithms are focused on characterization and calibration for the purpose of monitoring the stability and changes so the Level-1 science products remain consistent with up-to-date calibration. Detailed statistics from each scene processed are stored in an extensive database (the LPGS also populates the database, but fewer parameters are tracked). Data in the IAS database are regularly queried and analyzed to monitor instrument performance and to derive updated calibration coefficients to keep products consistent.

Only a subset of Earth scenes was processed through the IAS for ETM+ and earlier sensors (which were added later), meaning that only a subset of internal calibrator data were processed. All radiometric calibration data from the solar calibrators were processed. For Landsat-8, the IAS hardware and database were sized to include data from every Earth scene as well as data from every calibrator interval.

The following processing algorithms are used to convert the raw satellite data into a radiometrically corrected, geographically registered science product (the order of application of these algorithms varies between sensors):

- Dropped frame/scan/line detection: These algorithms detect if there are missing data and flag it so that the data can be replaced (interpolation from adjacent detectors) or left as fill in the final products.
- Bias determination: the calibration systems change between Landsat sensors, but all have the capability of determining a background signal over some short period of time. For the whiskbroom instruments, biases are generally determined from shutter data at the end of each scan line. For the pushbroom instruments biases are measured either from shutter or deep space data before and after each acquisition interval. These dark data are scanned for impulse noise and affected pixels are excluded from further processing. The bias

determination averages these data appropriately (per scan, per scene, per interval) depending on the instrument. In some cases, a lifetime history of biases is stored in the calibration parameter file for use in lieu of an instantaneous measure.

- Non-linearity Correction: Several Landsat sensors have detector or electronic nonlinearities. The non-linearity correction applies a previously determined look-up table to adjust for these non–linearities.
- Artifact Correction: The TM sensors, in particular, have a hysteresis (a.k.a. memory effect) and line-by-line shifts in the biases that are algorithmically corrected.
- Dead detector replacement: For the instruments that have detectors marked as inoperable, the detector values are replaced by an adjacent detector or interpolated.
- Bias application: The biases from the bias determination algorithm or from a calibration parameter file are subtracted from the data values.
- Gain determination: The on-board calibration systems changed over the sensors but all have a capability to estimate a calibration gain (counts/radiance). Only for the MSS (all bands) and TM band 6 (thermal) are the simultaneously generated on-board calibration gains used directly in processing. The MSS data require the simultaneous gain due the hysteresis of the photomultiplier tubes; TM band 6 data require the simultaneous gains to compensate for contamination build up that strongly effects the thermal band optical throughput. In all other cases, the on-board calibration gain is monitored over time using on-board and external sources but the processing system uses a predetermined gain stored in a calibration parameter file for generating images.
- Gain application: The gain from the calibration parameter file or the gain determination is applied to convert the sensor digital counts to radiance.

- Relative gain determination: The histograms for each detector for each band are calculated as a metric of how well the detectors are calibrated relative to each other. MSS processing may use these statistics on a per-scene basis to determine relative gains, meaning every Earth scene could have a different normalization. The TM, ETM+, OLI and TIRS detectors were all stable enough that the processing system could use a relative gain model, as opposed to individual scene statistics, to provide the relative gains for processing. The TM relative gain model was based on Earth scenes, but the OLI and ETM+ relative gain models were based on solar diffuser data. TIRS used a combination of on-board blackbody and Earth scenes to derive relative gains.
- Relative gain application: The scene-specific relative gain adjustment is applied to improve uniformity.
- Ancillary data processing: Satellite ephemeris and attitude telemetry and sensor pointing telemetry are validated and corrected as necessary.
- Sensor / platform geometric model creation: The ancillary data are processed to provide sensor location and pointing as a function of time.
- Sensor LOS generation and projection: The geodetic latitude and longitude for a point on the Earth, which corresponds to the entered line, sample and band of the input image are determined.
- Output space / input space correction grid generation: The piece-wise (gridded)
  geometric transformation of imagery in satellite perspective to corrected imagery in the
  output projection is generated.
- Geometric model precision correction using ground control (when possible) and with terrain correction (when possible).

- Image resampling: Original data are resampled to the output grid, usually with cubic convolution interpolation.
- Image Rescaling: the resampled data are converted to integer values that are scaled to radiance or reflectance.

There is a suite of characterization algorithms that are run on some or all scenes that go through the IAS system. Some keys ones are:

- Scan line artifacts: Several different tools correct for scan line artifacts particular to MSS data.
- Coherent noise: This is run on dark data. A frequency analysis detects if there are coherent noise sources in the instrument. If a coherent noise source was strong enough, a correction algorithm could be developed based on this information. As yet, that hasn't been necessary.
- Random noise: The overall noise level within the raw data is calculated from the standard deviation of the signal to a uniform target which, on-orbit, is generally the dark target.
- Calibrator statistics: Data from all the Landsat calibrators are recorded to the IAS database for tracking short and long term trends. Results can be seen in the Radiometric and Geometric sections.
- Streaking/Banding: The non-uniformity across the pushbroom focal plane is characterized on a per-detector level (streaking) and a regional level of 100 detectors (banding). The banding characterization is primarily intended to monitor changes between adjacent modules.

- Geodetic accuracy: Verifies the absolute accuracy of the systematic and precision products by analyzing the GCP measurement residuals before and after the precision correction solution.
- Image registration accuracy: Checks the quality of the registration over time by comparing two images of the same scene.
- Band-to-band registration: Checks the quality of the registration between the bands of a single image.
- Focal plane alignment: Performed just after launch, this algorithm provides the reference coordinates for the band-to-band registration.
- Sensor alignment: Performed just after launch, this algorithm provides the reference coordinates for the registration between the sensor and the satellite positions.
- Modulation Transfer Function (MTF) Characterization: Using long, straight bridges over water as an approximation for a line source, the MTF of the sensor can be estimated.

There are a number of analyses that are run regularly based on the results stored in the IAS database. Many of these analyses trend various parameters as a function of time, orbit position or temperature. These include: bias, absolute gains, relative gains noise, band-to-band registration, geodetic and geometric accuracy, sensor and module alignment, scan mirror characterization, and MTF characterization.

#### 3.4.5.3 Data products

Landsat imagery has been processed by various systems and a number of different products have been generated over the 44-year plus years of Landsat. The very first products were distributed on film, intended for analysis visually, though product format changed quickly through the 1970s and 1980s with the advancement of computing technology. This section will focus on the system products currently available from the USGS via the LPGS. Earlier products are only mentioned to the extent to which they affect the currently available data products quality.

### 3.4.5.3.1 Archive Formats

The most useful data format for a long-term archive is the raw data which includes all the ancillary data required for processing. Unfortunately, not all the historical Landsat data are available in this form. Data were downlinked to ground stations all over the world and stored in archives in various formats. There were many archives where the raw data and ancillary data were stored together, but particularly for MSS, the archive format was not standardized, including within the U.S. archives.

The archived products range from raw data to fully processed Level-1 products. For the bulk of the U.S. archive from TM through OLI/TIRS, data are stored in the raw bits downlinked from the satellite along with the corresponding radiometric and geometric correction data. However, there are archive formats for MSS and TM that were not archived as raw data. Sometimes, raw image data were archived without their corresponding radiometric or geometric correction data. In these cases, the corrections must be approximated from external sources, (i.e., two line elements and/or a radiometric model). Some data were archived with the radiometric corrections applied and the geometric grid included though not applied. If possible in these cases, the applied radiometric correction is undone so that the newly generated Level-1 product will be calculated with updated radiometric calibration.

The IAS and LPGS now have the capability to process nearly all archive products to the same levels as the TM, ETM+ and OLI data. The original source data will affect the data quality, since products that are missing calibration or geometric information will not be as accurate; an indication of the data quality is in the metadata quality scores.

## 3.4.5.3.2 LPGS Products

The LPGS standard product for all instruments is a radiometrically and geometrically calibrated image product, where the level of geometric processing is dependent on the quality of the ancillary data available. As was already mentioned, the MSS corrections are highly dependent on the source of the archive data.

The IAS can produce intermediate products, either raw digital counts or radiometric correction only, but those products are intended for assessment of the instrument only and are not widely distributed.

The processing level is provided in the metadata that comes with the product, (DATA\_TYPE in the metadata file). All products listed here have radiometric calibration applied. The different levels are:

• Precision, terrain-corrected product (L1T): These products have been geometrically resampled using GCP for precision geolocation and a DEM for parallax correction. For every scene processed, an attempt will be made to generate the precision, terrain-corrected product. If the registration errors (net radial RMSE) are greater than the instrument-specific threshold (See Section 3.4.4.5.4), the precision, terrain-corrected product will be abandoned for one of the other products.

- Systematic, terrain corrected product (L1Gt): Generated when the precision GCP geolocation fails, the georegistration of these products is based on the line-of-sight model only. The terrain correction is still performed using the DEM. This product is the fallback product for Landsat-8 OLI and TIRS and Landsat-7 ETM+ data.
- Systematic product (L1G): These products have been geometrically resampled based only on the instrument ancillary data, with map projection registration. These systematic products are the fallback for TM and MSS data.

Note that in 2016 with the implementation of Collections processing, the USGS is changing the abbreviations for the product levels: L1T will become L1TP, L1Gt will become L1GT and L1G will become L1GS.

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# List of relevant websites:

EO Portal Satellite Database:

https://eoportal.org/web/eoportal/satellite-missions

Landsat-7 Image Assessment System Radiometric Algorithm Theoretical Basis Document, June 2003:

http://landsat.usgs.gov//documents/LS\_IAS\_02.pdf

Landsat-7 Image Assessment System Geometric Algorithm Theoretical Basis Document, Dec 2006:

<u>http://landsat.usgs.gov//documents/LS-IAS-01\_Geometric\_ATBD.pdf</u> Landsat 8 Calibration Parameter Files (CPF) and Bias Parameter Files (BPF):

http://landsat.usgs.gov//cpfbpf.php

- LDCM Cal/Val Algorithm Description Document, Feb 2013: http://landsat.usgs.gov//documents/LDCM\_CVT\_ADD.pdf
- NASA Landsat Chronology website: <u>http://geo.arc.nasa.gov/sge/landsat/lpchron.html</u> NASA Landsat Science website:

MSS Spectral responses: <u>http://landsat.gsfc.nasa.gov/?p=12163</u> Landsat-8 Sensor Spectral Responses, in-band response: <u>http://landsat.gsfc.nasa.gov/?p=5779</u>

Landsat-8 Sensor Spectral Responses, out-of-band response: <u>http://landsat.gsfc.nasa.gov/?p=8829</u>

NASA Landsat Science Data Users Handbook containing Landsat-4,-5,-7 TM spectral responses: <u>http://landsathandbook.gsfc.nasa.gov/inst\_cal/prog\_sect8\_2.html</u>

NASA LDCM Launch Press Kit: https://www.wmo.int/pages/prog/www/wigos/wir/oscar.html

National Geospatial Intelligence Agency, Office of Geomatics: World Geodetic System 1984: <u>http://earth-info.nga.mil/GandG/wgs84/</u>

Scheffner Landsat Program Chronology online: http://geo.arc.nasa.gov/sge/landsat/lpchron.html

Schott North America, Colored glass transmission data:

www.us.schott.com

- Thorlabs website, Optical window spectral transmission data: www.thorlabs.com
- USGS Landsat 4-5 Thematic Mapper (TM) Calibration Notices: http://landsat.usgs.gov//science\_L4-5\_Cal\_Notices.php
- USGS Landsat Documentation: http://landsat.usgs.gov//tools\_project\_documents.php
- USGS Landsat Mission Calibration: http://landsat.usgs.gov//science\_calibration.php
- <u>USGS Landsat Mission History:</u> <u>http://landsat.usgs.gov/about\_mission\_history.php</u>
- USGS Landsat Missions, Landsat Collections; http://landsat.usgs.gov/landsatcollections.php
- USGS Landsat Missions, Geometry http://landsat.usgs.gov/geometry.php
- USGS Landsat Missions, SLC-off Products: Background http://landsat.usgs.gov/products\_slcoffbackground.php
- USGS Landsat Missions, Geometry: http://landsat.usgs.gov/.geometry.php
- USGS Landsat Missions, Global Land Surveys (GLS): <u>https://landsat.usgs.gov/science\_GLS.php</u>
- USGS Long Term Archive, Return Beam Vidicon (RBV) Film Only: https://lta.cr.usgs.gov/rbv.html
- WMP Oscar Tool: <u>https://www.wmo.int/pages/prog/www/wigos/wir/oscar.html</u>

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