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The Landsat 7 spacecraft, launched from Vandenberg AFB on April 15, 1999, has been providing the Landsat user community with highly calibrated multi-spectral images of the earth since it started normal operations in August 1999. Over the past year data products from the Enhanced Thematic Mapper-Plus (ETM+), Landsat 7's earth imaging instrument, have been assessed which indicate the Attitude Control and Determination System (ACDS) performance exceeds mission requirements.

This paper presents an overview of the Landsat 7 mission. The ACDS system hardware, modes, and requirements are described. Significant events of the on-orbit initialization and validation period, which included ACDS sensor activation and calibration, a cross-calibration under-fly with Landsat 5, and orbit acquisition maneuvers, are presented. The paper concludes with a brief discussion of the role that the ACDS performance has on Landsat 7 image generation.

INTRODUCTION

Landsat 7 is part of NASA's Earth Science Enterprise (ESE). The ESE is committed to developing an understanding of the total Earth system, the effects of natural and human-induced changes on the global environment, and how natural processes affect humans and how humans affect them.

The Landsat 7 satellite consists of the spacecraft bus which was provided under a NASA contract with Lockheed Martin Missiles and Space in Philadelphia, PA, and the Enhanced Thematic Mapper-Plus (ETM+) instrument, procured under a NASA contract with Raytheon Santa Barbara Remote Sensing in Santa Barbara, CA.

The Landsat 7 Attitude Control and Determination System (ACDS) provides many essential functions for the operation of the spacecraft bus and for ETM+. The ACDS maintains the required attitude and orbit at the degree of accuracy necessary for power generation, command and telemetry, thermal balance, image acquisition, Gimbaled X-Band Antenna (GXA) pointing and data for image post-processing. Descriptions of the Landsat 7 mission and the ACDS modes and requirements are presented. A brief summary of significant events of the on-orbit initialization and validation period are provided. Finally, the Landsat 7 product generation system is described and the impact that the ACDS performance has on the ground based image processing system is explored.

LANDSAT HISTORY AND MISSION DESCRIPTION

For over 25 years, the Landsat series of spacecraft have continuously provided calibrated Earth science data to a diverse group of users worldwide. Landsat 7 is the seventh in a family of imaging satellites that provide multi-spectral land and coastal images. The first Landsat satellites (1, 2 & 3) were originally called the Earth Resources Technology Satellite or ERTS. They provided images, including the first composite multi-spectral mosaic of the 48 contiguous United States, between July 1972 and March 1978. ERTS 1,2 & 3 were followed by a second generation of imaging satellites that were called Landsat 4 & 5. Landsat 4 was launched in July 1982 and Landsat 5 in March 1984. Landsat 5 continues to receive images to date. Landsat 6 failed to reach orbit. Landsat 7 was launched in April 1999.

LANDSAT 7 ATTITUDE CONTROL AND DETERMINATION SYSTEM

The ACDS controls the spacecraft's attitude and orbit. In addition, the ACDS controls the motion of the solar array and three GXAs relative to the spacecraft.

The ACDS consists of sensors, actuators, software, and support hardware. Included in the sensor package are a Honeywell Inertial Measurement Unit (IMU) and Celestial Sensor Assembly (CSA), nine Adcole Coarse Sun Sensors (CSS), two NASA Tri-Axial Magnetometers (TAM), and a Barnes solid state Earth Sensor Assembly (ESA). The actuator package includes four Honeywell Reaction Wheel Assemblies (RWA), two Ithaco Magnetic Torquer Rods (MTR), and 12 Olin Rocket Engine Assemblies (REAs). Support hardware required for operation of the ACDS includes the Spacecraft Controls Processors (SCPs) and the Controls Interface Unit (CIU) which are the heart of the Command and Data Handling Subsystem (C&DH).

Flight software consists of the Safehold Package (SHP) and Flight Load Package (FLP). The SHP resides in Programmable Read Only Memory (PROM) chips. It was operational in both SCPs at launch and can be reentered in the event of a SCP switch while in SHP, a SCP reset while in either SHP or FLP, or upon ground command. The FLP, the nominal mission software package, was loaded into the SCPs prior to launch and was autonomously transitioned to after the spacecraft's separation rates were nulled. The FLP can be modified by way of uploads from the ground. An additional non-volatile Electronically Erasable Programmable Read Only Memory (EEPROM) with on-orbit Read/Write capability is used to store critical spacecraft component configuration information across Processor Failures and Bus Power Transients.

The ACDS has three modes of operation – Primary Mode, Backup Mode, and Sun Pointing Attitude Mode (SPAM). There are a number of submodes associated with Primary and Backup Modes. Submodes of Primary Mode are Precision, Slew, and Maneuver submodes. Submodes of the Backup Mode are Rate Null, Local Vertical Acquisition (LVA), Yaw Gyrocompassing (YGC), and Earth Search submodes.

Rate Null submode is only used during the end of the ascent profile after launch vehicle separation. In this submode rates about all three axes are nulled using only the IMU to sense body rates with respect to inertial space. The initial separation attitude is used as the attitude reference and the RWAs are the primary actuators. The REAs are also enabled and are ready for use if high tip off rates are encountered. Rate Null submode resides in the SHP only. After successful rate nulling and solar array deployment, the mission transitioned from the ascent phase to the orbit phase. Flight software made the transition from the SHP to the FLP at this time and the ACDS entered the LVA submode.

In LVA, the ACDS acquires the Earth by using ESA data to calculate roll and pitch attitude errors and IMU data for rate damping about all three axes. In LVA the RWAs are used for attitude control and magnetic momentum unloading is activated. Earth Search submode is available, via ground command only, for the anomalous case in which none of the ESA quadrants have acquired the Earth. This submode is essentially LVA with a rate bias added to the roll and pitch axes. The spacecraft remains in this submode until the ESA has acquired the Earth in at least one of its quadrants or until a pre-set time-out is reached. If the Earth is found the submode autonomously re-enters LVA. If the time-out occurs then the spacecraft goes to SPAM, Landsat 7's safe mode. In SPAM the solar array is rotated to the zero degrees position and the spacecraft rotates to a power safe orientation by using the CSSs and RWAs to keep the solar array facing the sun. SPAM is exited by ground commanding the spacecraft to LVA submode. (As of this writing, the spacecraft has never entered SPAM while on-orbit.) In LVA, when pitch and roll attitude errors and roll, pitch, and yaw rates are below prescribed thresholds, the spacecraft autonomously transitions to YGC. YGC can be thought of as LVA with the addition of attitude control in the yaw axis. Yaw attitude error is derived using a gyrocompassing technique. Once the spacecraft has successfully achieved this submode, it is power and thermal safe indefinitely, assuming that the array is articulating properly. When attitude errors and rates have settled below prescribed thresholds, YGC is considered complete.

The Precision Attitude Determination System (PRADS) may be initialized at the Flight Operation Team's (FOT) discretion once YGC is completed. PRADS is a Kalman Filter that computes attitude errors using star transit data from the CSA. The IMU provides rate data. Once PRADS has converged the Primary Mode may be entered by ground command only, placing the spacecraft in the Precision submode. The Precision submode will maintain local geocentric pointing of the spacecraft to a very high degree of accuracy. In the Precision submode, the RWAs are used to control spacecraft attitude and angular rate, and the MTRs are used as the primary actuators for RWA momentum unloading. The ESA no longer provides attitude error data used by the controller. It is now used in an error detection role.

While in the Precision submode, other submodes of the Primary Mode may be selected. The Slew submode may be commanded in preparation for an orbit inclination maneuver. In slew submode, a desired rotation about any navigation axis may be commanded. The Maneuver submode may be commanded from either the Precision or Slew submodes depending on the nature of the desired maneuver. Once the maneuver is complete, the ACDS submode autonomously returns to Precision.

ON-ORBIT INITIALIZATION AND VERIFICAION PERIOD HIGHLIGHTS

The Landsat 7 ninety-day On-Orbit Initialization and Verification Plan (OIVP) was developed to perform a checkout of the spacecraft bus, activate the ETM+ instrument, perform instrument calibration activities including a cross-calibration under-fly with Landsat 5, execute thruster-based maneuvers to position the satellite to its final orbit, and demonstrate a typical Landsat sixteen-day imaging cycle.

Landsat 7 was launched from Vandenberg Air Force Base on April 15, 1999, at 18:32:00 GMT, on time on the scheduled day aboard a Delta II launch vehicle. The ascent mode was nominal, from separation through rate nulling, LVA, YGC, and YGC complete. During rate nulling seventeen thruster pulses were necessary to help reduce the separation rates, after which rates were quickly nulled with reaction wheels.

At approximately 20:15 GMT on the day of the launch the spacecraft dropped out of YGC complete for the first time. It was quickly determined that disturbances resulting from solar array slews were sufficient enough to exceed the YGC complete limits. The solar array drive had been intentionally configured in CSS control mode after initial activation. Under CSS control the solar array, which is driven to null out the array-mounted CSS errors and keep the array pointed normal to the sun, periodically slews fast enough to cause the spacecraft to fall out of YGC complete. The original plan called for the solar array drive to stay in CSS control until the first ephemeris upload. However, it was anticipated that the fast slews would continue to cause this effect on YGC and the decision was made to command the solar array drive to forward-normal open-loop control mode. In this mode of control the solar array is commanded to drive in the forward position at orbit rate. This mode kept the solar array sufficiently pointed to the sun without upsetting YGC submode.

On April 16, at 14:59 GMT, PRADS was initialized and approximately forty-five minutes later the filter had converged. The spacecraft flight team continued to monitor the performance of PRADS for the next twenty-three hours. On April 17, at 14:53 GMT, the spacecraft was commanded to Precision Mode for the first time. At 17:13 GMT the skew wheel bias was enabled.

On April 17 the gyro scale factor test was initiated. The plan was to slew the spacecraft +/- 5 degrees in roll and yaw (one axis at a time), take one or two hours of data, and then use the data to calibrate out gyro biases. The -5 degrees roll was performed and was nominal. However, during the +5 degrees roll slew the spacecraft fell out of Precision Mode into YGC submode, then briefly into LVA submode before settling back to YGC and then to YGC complete. An Anomaly Resolution Team (ART) was convened. After examining housekeeping data it was determined that the increase in ESA detector counts, resulting from the roll angle and the sun's influence during the transition to sunlight, caused the failure detection logic to send the spacecraft to YGC. This condition did not occur during the −5 degrees roll offset because this offset put the ESA in a slightly better orientation with respect to the sun. Error limits were adjusted to correct the problem. However, soon the spacecraft fell out of YGC complete at the moment it exited shadow. Thermal snap of the solar arrays was suspected and confirmed by a thorough review of data. The thermal snap was causing the YGC yaw attitude error (this measurement is derived from pitch and roll rates in this submode) to spike, exceeding preset limits. Earlier in the day YGC limits had been tightened from launch values to operational values. Again, limits were properly adjusted. At no time during the anomaly was the spacecraft unsafe.

On April 18, at 17:04 GMT the first imaging sequence using the ETM+ was executed. The sequence consisted of ten scenes, the first of which was an image of the area encompassing Sioux Falls, SD, where the Landsat data center is located.

On April 22 the propulsion system checkout was conducted. First, a ten-second engineering burn was performed. This burn was followed later in the day by a one-minute calibration burn. Both burns were nominal. From April 27 to June 28 a series of eight orbit adjust maneuvers were performed. The first two maneuvers, performed on April 27 and 30, resulted in delta-Vs of 2.4 m/s and 2.2 m/s, respectively. These maneuvers were executed to position the spacecraft such that it would fly under Landsat 5 from June 1 to June 3. During the under-fly data were taken that were used to perform cross-calibration of Landsat 5 with Landsat 7. Maneuvers three through five, conducted on June 17, 20, and 22, were performed to boost the satellite to its proper orbit. These maneuvers resulted in delta-Vs of 2.5 m/s, 1.0 m/s, and 1.0 m/s, respectively. The remaining three maneuvers were trim maneuvers, used to optimize the spacecraft's orbit position relative to the desired Landsat reference ground track. A summary of the OIVP maneuvers is presented in Table 1.

Instrument and sensor calibration activities were conducted throughout the checkout period. The OIV period concluded with a nominal demonstration of a typical sixteen-day Landsat imaging cycle.

LANDSAT 7 ON-ORBIT ACDS PERFORMANCE REQUIREMENTS

The performance of the ACDS has a direct impact on the geodetic accuracy of Landsat 7 and the amount of data post-processing to meet the desired quality of the end product (scenes). The extent of required post-processing (completely automated vs. manual adjustment + automated) determines the number of level 1 products that can be created and archived in a given period of time.

The ACDS must meet pointing accuracy, attitude knowledge and pointing stability requirements in order to meet the overall 250 m per axis accuracy requirement of the corrected data. Of these three types of ACDS performance requirements, attitude knowledge is the most critical, followed by pointing stability and pointing accuracy (within reason). Ephemeris accuracy also impacts geodetic performance, but it will not be addressed in this section.

Event	Event Times (GMT)	Duration (sec)	Semimajor Axis (km)	Eccentricity	Argument Of Perigee
Injection	990415.19:52:39		7065.80	0.0018039	174.3 deg
Eng. Burn	19990422 00:47:00.000 19990422 00:47:11.700	11.7			
Cal. Burn	19990422 22:11:05.000 19990422 22:12:12.100	67.1			
Burn 1	19990427 02:14:09.000 19990427 02:20:23.900	374.9	7068.37	0.0017233	110.5 deg
Burn 2	19990430 00:51:41.000 19990430 00:57:36.400	355.4			
Under-fly	19990601 21:44:40.888 19990603 23:05:16.754	N/A			
Burn 3	19990617 22:31:28.000 19990617 22:38:29.300	421.3	7075	0.0012655	103.09 deg
Burn 4	19990620 01:34:45.000 19990620 01:37:32.800	167.8			
Burn 5	19990622 00:29:26.000 19990622 00:32:11.200	165. 2	7077.18	0.0011726	87.9 deg
Burn 6	19990624 00:18:33.000 19990624 00:19:49.400	76.4			
Burn 7	19990624 00:18:33.000 19990624 00:19:49.400	76.9	7077.69	0.0011818	90.19 deg
Burn 8	19990628 03:53:00.000 19990628 03:53:23.900	23.9			

Table 1: Summary of OIVP Maneuvers

Pointing accuracy performance determines the line-of-sight intersection with the surface of the Earth. Pointing accuracy errors result in constant along track and cross track errors, as well as angular errors that increase linearly from the center of the image to the edge. The pointing stability performance will determine the distortion of the scene within a scan cycle of the ETM+ scan mirror and the alignment from one scan line to the next. Pointing stability is expressed as rate errors (low frequency) and jitter (high frequency). The pointing knowledge is particularly critical because accurate pointing knowledge can be used to remove pointing errors and distortion due to jitter.

The overall pointing requirements for the Primary (imaging) Mode of Landsat 7 are in Table 2 (entries are in arcseconds and arcseconds per second, with respect to the navigation frame of reference).

Requirement	Roll	Pitch	Yaw
Attitude Knowledge 3σ	135.0	135.0	135.0
Pointing Accuracy 1σ	40.0	40.0	40.0
Attitude Rate Control 1σ	5.0	5.0	5.0
Low Frequency Stability (0.01 to 2.0 Hz)	30	30	30
High Frequency Stability (2.0 to 125 Hz)	24	24	24

Table 2: Landsat 7 Primary Mode Pointing Requirements

Potential low and high frequency disturbance sources on Landsat 7 include the ETM+ scan mirror, magnetic unloading, GXA movement, RWA imbalances, RWA zero-speed crossings, solar array normal operations, solar array speed changes, and solar array snap.

The ETM+ has an oscillating scan mirror that impacts a hard stop at each extreme of the mirror oscillation. The mirror scan rate is 7 Hz. Magnetic unloading is performed with the MTRs utilizing a bang-bang controller. This type of controller imparts torque impulses to the spacecraft. However, during MTR unloading, a feedforward torque command is sent to the RWAs to counter the anticipated impulse associated with MTR turn-on, thus mitigating this disturbance. The GXA disturbances occur each time the antennas are actuated. All three antennas can be commanded individually or simultaneously. Solar array normal operations are defined as the solar array rotating at orbit rate. A stepper motor drives the array with a nominal pulse rate of 3.64 pulses per second. Additionally, solar array speed changes also disturb the spacecraft. Solar array thermal snap torque is imparted to the spacecraft each time the spacecraft crosses the terminator and is quite large. Fortunately thermal snap occurs at times when images are typically not being collected. Two disturbances associated with RWAs are static and dynamic imbalances. Both static and dynamic imbalance disturbances are functions of wheel speed. RWA zero-speed crossings could significantly impart a disturbance to the spacecraft. However, this will not occur during the normal mission unless one of the four RWAs fails.

LANDSAT 7 LEVEL 1 PRODUCT GENERATION SYSTEM

The Landsat 7 Level 1 Product Generation System (LPGS) implements a suite of radiometric and geometric correction algorithms to process Level 0R products from the Landsat 7 archive into Level 1 image products[1]. This system is used for high-volume production operations, generating Level 1R (radiometric correction) or Level 1G (systematic geometric correction) products to fulfill user orders. The LPGS achieves a high level of automation in generating up to 100 products per day.

The geometric correction process involves modeling the relationship between input sensor-space Level 0R image line/sample coordinates and the corresponding ground-space latitude/longitude and, thus, to the corresponding geo-referenced output Level 1 image line/sample. Level 1G products are generated by remapping the input ETM+ sensor-space radiance samples to their corresponding output locations, using this model. The Landsat 7 geometric model includes three main components: 1) generating a sensor line-of-sight from Level 0R line/sample coordinates and the associated sensor telemetry, 2) locating and orienting the line-of-sight in space using the spacecraft position and attitude information, and 3) intersecting the line-of-sight with the Earth[2]. The accuracy of this geometric modeling process is typically limited by the second component: spacecraft position and attitude knowledge. The focus here is on the contribution made by attitude knowledge.

Attitude Knowledge Contribution to Level 1 Product Accuracy

The fundamental Landsat 7 Level 1 processing accuracy requirement is to be able to produce systematically corrected (1Gs) products that are accurate to within 250 meters per coordinate (one sigma) at nadir[3]. An error budget for 1Gs geodetic accuracy performance can be built up using the expected accuracy of the data components that are part of the Landsat 7 ETM+ geometric model. These components include spacecraft ephemeris and attitude knowledge, spacecraft clock errors, knowledge and stability of the alignment of the ETM+ instrument to the Landsat 7 spacecraft, and knowledge and stability of the internal geometry of the ETM+ instrument. Accuracy bounds for most of these data elements are specified in the Landsat 7 System Specification. Allocations for ground processing and test point mensuration are also included in the total geodetic accuracy error budget.

Three types of attitude measurements are available to the LPGS in the Landsat 7 Payload Correction Data (PCD): (1) jitter measurements from the Angular Displacement Assembly (ADA), taken every 2 milliseconds; (2) gyro measurements from the IMU, taken every 64 milliseconds, and; (3) attitude quaternions (and gyro drift estimates) generated by the onboard computer every 4.096 seconds, using the IMU data in combination with stellar observations from the celestial sensor assembly[4]. The LPGS blends the IMU gyro measurements with the attitude quaternions, using a Kalman filter, to provide an absolute attitude reference every 64 milliseconds. This low-frequency attitude is ultimately combined with the high-frequency ADA data, using digital filters, to create an integrated model of the spacecraft attitude with samples every 2 milliseconds.

The expected accuracy of the low-frequency attitude and high-frequency jitter data was combined with the other significant instrument, platform, and ground system error sources to derive a pre-launch estimate of the Landsat 7 system's geodetic accuracy performance. In order to meet the 250-meter absolute accuracy requirement, this estimate included an on-orbit improvement in ETM+ to attitude control system alignment knowledge. The result of this analysis is shown in Table 3. Note that while the 250-meter accuracy requirement is met, spacecraft attitude knowledge is the single largest contributor to the error budget. In fact, attitude knowledge also contributes to the ETM+ to ACS alignment accuracy because it is the principal limiting factor in the accuracy with which the on-orbit sensor alignment calibration can be performed. Thus, improved attitude control system performance (in terms of attitude knowledge) would significantly improve overall geodetic accuracy performance directly, through the more accurate vehicle attitude knowledge, and indirectly through the more accurate alignment calibration capability.

Source	Spec 1 σ	Spec Units	Nadir Meters Along-Track	Nadir Meters Cross-Track
Spacecraft Attitude	45.0	Arcsec	154	154
ETM+ LOS and Jitter	1.1	Arcsec	4	4
ETM+ to ACS Alignment	29.4	Arcsec	101	101
Ephemeris	133.3	Meter	133	133
Clock	5.0	Millisec	38	0
Mensuration and Modeling	15.1	Meter	15	15
RSS Estimate			**231**	**228**

Table 3: Pre-launch Geodetic Error Budget

During the checkout period the initial on-orbit sensor alignment was performed to refine the pre-launch knowledge of the relationship between the ETM+ and Landsat 7 attitude control system. Figure 1 shows the dramatic improvement in geodetic accuracy performance resulting from the initial on-orbit sensor alignment calibration. The point symbols indicate the root-mean-square fit to the ground control test points for each geodetic test site scene. Note that the geodetic accuracy dropped well below the requirement threshold after the initial on-orbit alignment calibration was performed.

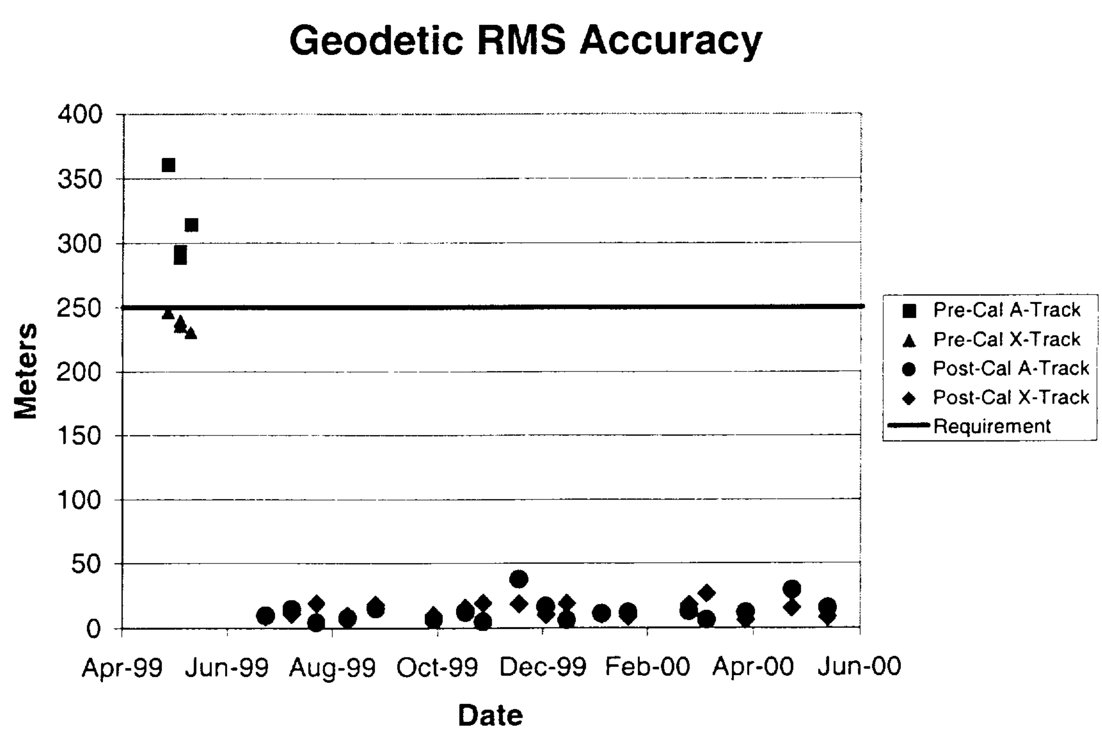

Figure 1: Systematic Geodetic Accuracy Before and After Alignment Calibration

Analysis of the geodetic test site results has shown that the geodetic performance is dependent primarily on the accuracy of the ephemeris data. Processing that uses post-pass definitive ephemeris yields root mean square geodetic accuracy performance better than 50 meters[5]. The improved reliability of the post-pass ephemeris data has prompted an enhancement to the Landsat 7 ground system to routinely use definitive ephemeris data for systematic image product generation.

Comparison of the predicted geodetic accuracy performance shown in Table 3 with the actual results observed in Figure 1 indicates that the actual attitude, ephemeris, and alignment knowledge accuracy must be significantly better than the specifications. An estimated "as-built" accuracy allocation of the pointing and position errors contributing to geodetic accuracy that more closely matches the observed system performance is presented in Table 4. Spacecraft clock and ephemeris performance information from the Landsat 7 Mission Operations Center and alignment stability measurements from the Landsat 7 Image Assessment System were used to guide these allocations. As the table shows, this analysis implies that the spacecraft attitude knowledge accuracy is on the order of 8 arcseconds vice a requirement of 45 arcseconds.

Source	**Estimate 1 σ**	**Estimate Units**	**Nadir Meters A-track**	**Nadir Meters X-track**
Vehicle Attitude	8.0	Arcsec	27	27
ETM+ LOS and Jitter	1.1	Arcsec	4	4
ETM+ to ACS Alignment	6.0	Arcsec	21	21
Ephemeris	30.0	Meter	30	30
Clock	2.0	Millisec	15	0
Mensuration and Modeling	7.8	Meter	8	8
RSS Estimate			**49**	**46**

Table 4: Estimated As-Built Geodetic Accuracy Allocation

CONCLUSION

An overview of the Landsat 7 mission and history was presented. The ACDS system hardware, modes, and requirements were described. Significant events of the on-orbit initialization and validation period, including ACDS anomalies and orbit maneuvers, were discussed. Results of on-orbit geodetic performance analyses indicate that the ACDS pointing requirements have been achieved with significant margin.

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