AIAA-2000-2902

THERMAL PERFORMANCE OF LANDSAT-7 ETM+ INSTRUMENT DURING FIRST YEAR IN FLIGHT

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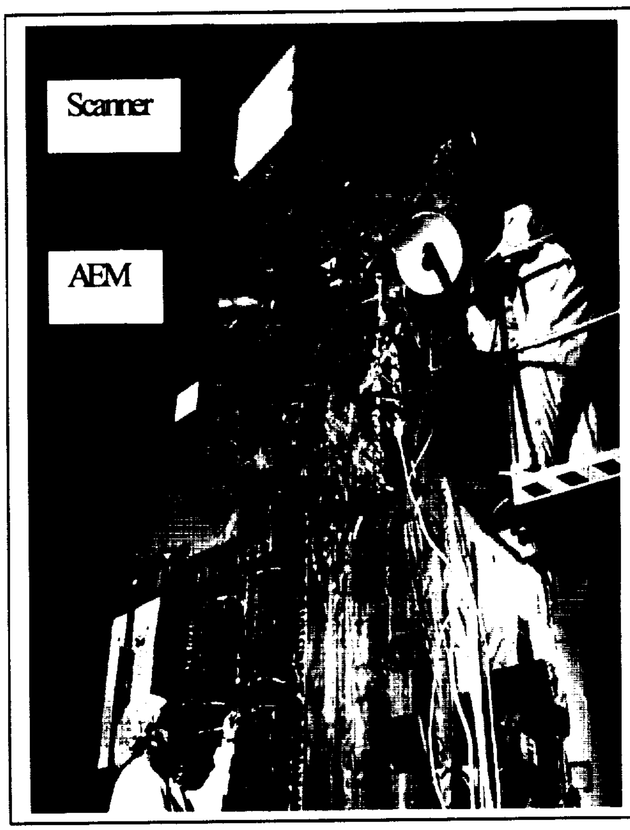
ABSTRACT

Landsat-7 was successfully launched into orbit on April 15, 1999. After devoting three months to the bakeout and cool-down of the radiative cooler, and on-orbit checkout, the Enhanced Thematic Mapper Plus (ETM+) began the normal imaging phase of the mission in mid-July 1999. This paper presents the thermal performance of the ETM+ from mid-July 1999 to mid-May 2000. The flight temperatures are compared to the yellow temperature limits, and worst cold case and worst hot case flight temperature predictions in the 15-orbit mission design profile. The flight temperature predictions were generated by a thermal model, which was correlated to the observatory thermal balance test data. The yellow temperature limits were derived from the flight temperature predictions, plus some margins. The yellow limits work well in flight, so that only several minor changes to them were needed. Overall, the flight temperatures and flight temperature predictions have good agreement. Based on the ETM+ thermal vacuum qualification test, new limits on the imaging time are proposed to increase the average duty cycle, and to resolve the problems experienced by the Mission Operation Team.

INTRODUCTION

ETM+ is the instrument on the NASA Landsat-7 spacecraft, which was successfully launched into orbit on April 15, 1999. The spacecraft performs wide-area multi-spectral imaging of the Earth's land mass from a sun-synchronous near polar orbit (altitude 705 km, 98.2° inclination). Figure 1 shows the ETM+ on the spacecraft. It consists of two units: scanner and Auxiliary Electronics Module (AEM). The scanner is an advanced version of the Thematic Mapper (TM) flown on Landsat-4 and -5. The AEM is a new component and has no flight heritage. Both units are conductively isolated from the spacecraft. During the nominal imaging phase of the Landsat-7 mission, the scanner mapper aperture always points at the Earth. Figure 2 shows the scanner.

Figure 1. ETM+ on Landsat-7 Spacecraft.



The major power dissipation, 159 W measured in 1998, was in the Main Electronics Module (MEM), which consists of two power supplies (P/S) and twenty-eight printed wiring boards (PWBs). Heat dissipated by the MEM power supplies and PWBs is conducted to a white-paint radiator, which has a thermal louver. In flight, the radiator/louver is on the anti-sun side of the spacecraft, and the louver base-plate radiates heat to space. The initial louver set points were 15°C fully closed, and 25°C fully open.

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Prior to the ETM+ thermal vacuum test, the louver set points were reduced to 7°C fully closed, and 17°C fully open. The purpose of the set point change was to decrease the temperature of the MEM power supplies. Except for the MEM thermal louver, the opening of the scanner mapper aperture sunshade, and radiative cooler aperture, the ETM+ scanner is insulated with 7 m^2 of multi-layer insulation (MLI) thermal blankets. The remainder of the power dissipation, 65 W, is in the electronics components inside the scan cavity. Albedo and Earth infrared radiation enter the mapper aperture sunshield opening.

Except for a .0716 m^2 white paint radiator, the AEM is insulated with 2 m^2 MLI blankets. The AEM has a total power dissipation of 113 W, measured in 1998, when the instrument operates. Heat dissipated by the electronics is conducted to the white-paint radiator. In flight, the radiator is on the anti-sun side and it radiates heat to space.

The Full Aperture Calibrator (FAC) is a new component and has no flight heritage. When deployed, the FAC is in front of the external opening of the sunshield, and when stowed, it is in front of the FAC stow cover. Figure 3 shows the FAC and FAC motors.

FLIGHT TEMPERATURE PREDICTIONS FOR IMAGING

Modifications to the scanner and AEM thermal models were performed after the observatory thermal balance test in 1998 to give good agreement between the temperature predictions and the test results. The correlated ETM+ thermal model was used to obtain flight temperature predictions. Table 1 presents the worst cold case and worst hot case flight temperature predictions generated before launch.[1]

Figure 2. ETM+ Scanner.

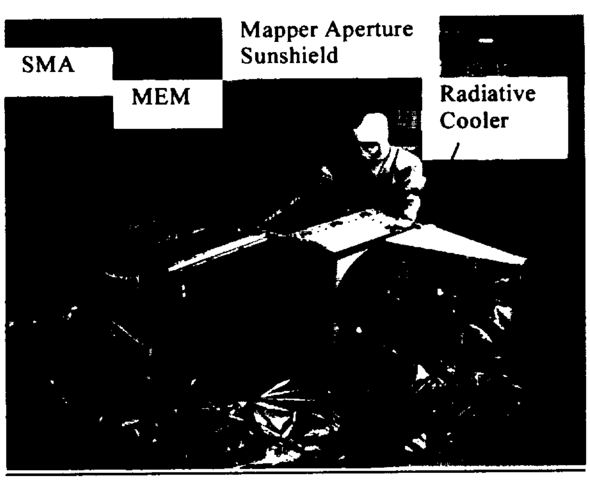
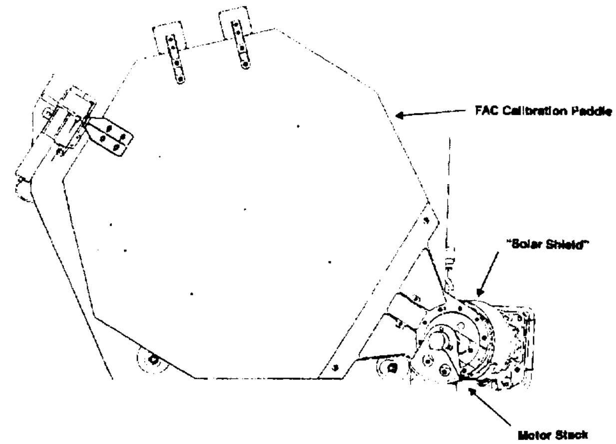


Figure 3. FAC and FAC Motors.



YELLOW TEMPERATURE LIMITS IN FLIGHT

The flight temperature predictions in the nominal 15-orbit mission profile, plus margins, were used as the yellow limits for most of the ETM+ components. Table 2 presents the lower and upper yellow temperature limits generated before launch.[1]

FLIGHT TEMPERTURES

After Landsat-7 was successfully launched into orbit, the first three months were devoted to the bakeout of the ETM+ scanner radiative cooler, cooler cool-down and on-orbit checkout. In mid-July 1999, the ETM+ began the normal imaging phase of the Landsat-7 mission. The flight temperatures[2] are presented in Figures 4 through 17. Note that day "0" is July 15, 1999 in these figures. The minimum temperatures are in the standby mode, and the maximum temperatures are in the imaging mode.

MEM Power Supply Heat Sink

Figure 4 presents the flight temperatures of the MEM heat sink for the power supplies. The thermal louver on the MEM radiator has new temperature set points. The flight temperatures of the MEM power supply heat sink are 13.4°C minimum and 15.9°C maximum. The flight temperature predictions were 13°C minimum and 15.9°C maximum for P/S 1, and 13°C minimum and 16.4°C maximum for P/S 2. Therefore, the flight temperatures and flight temperature predictions have excellent agreement. The louver prevents the MEM P/S heat sink temperatures from falling below 13.4°C in the nominal imaging mode in flight. The ETM+ instrument test and observatory thermal vacuum test verified that the standby heater on the MEM radiator turns on when the MEM heat sink temperature reaches 12.6°C.

Therefore, the MEM standby heater does not turn on in either the imaging mode or standby mode in the imaging phase.

Table 1. ETM+ Imaging Temperature Predictions (°C Except when Noted in K).

Component	Worst Cold Case	Worst Hot Case
MEM Heat Sink (PS #1)	13	15.9
Band 4 Post Amp	14.3	21.8
FAC Primary Motor	-1.7	23.8
AEM Heat Sink	-1.7 /5.3	14.0
Low Chan Amb PreAmp	4.7	28.4
Sunshield	21.6	27.2
Cold PreAmp (Band 7)	-8.5	1.5
Radiator Fin (+Y)	-15.4	-11.3
Baffle (Heater)	25.9	27.0
Baffle Tube	20.6	21.7
Baffle Support	19.6	20.8
MEM Heat Sink (PS #2)	13	16.4
Pan Band Post Amp	14.2	21.5
FAC Redundant Motor	7.6	22.4
High Chan Amb PreAmp	4.7	28.5
MUX 1 Electronics (Active)	3.8 /25.8	26.0
MUX 1 P/S (Active)	3.8 /25.8	25.0
Scan Ang Monitor	23.7	23.3
Cooler Amb Stage	-12.4	-9.2
Cooler Door	-65.0	-35.2
Primary Mirror Mask	11.8	14.5
Secondary Mirror Mask	18	21.5
Primary Mirror	11.8	14.5
Secondary Mirror	18	21.5
SLC Temp	14.1	24.7
SLC 1 Electronics	14.3	24.9
Cal Shutter Hub	7.2	13.9
Cal Lamp Drive	15.4	23.0
Cal Lamp Housing	8.6	14.3
CFPA Control	91.4 K	91.4 K
SiFPA	8.2	16.8
CFPA Monitor	91.4 K	91.4 K
SMA +X Flex Pivot	23.7	23.2
SMA -X Flex Pivot	23.7	23.2
SMA +Z Housing	23.1	25.0
SMA -Z Housing	23.1	25.0
SMA Electronics	24.6	27.8
SMA Torquer	23.7	23.3
Telescope Housing	14.9	18.8
Telescope Baseplate	7.6	11.5

Table 2. Yellow Temperature Limits in Flight (°C Except when Noted in K).

Component	Lower Yellow	Upper Yellow
MEM Heat Sink (PS #1)	12	21
Band 4 Post Amp	12	25
FAC Primary Motor	-4	30
AEM Heat Sink	0	20
Low Chan Amb PreAmp	5	30
Sunshield	16	27
Cold PreAmp (Band 7)	-10	4
Radiator Fin (+Y)	-19	-6
Baffle (Heater)	25	30
Baffle Tube	19	25
Baffle Support	18	25
MEM Heat Sink (PS #2)	12	21
Pan Band Post Amp	12	25
FAC Redundant Motor	-4	30
High Chan Amb PreAmp	5	30
MUX 1 Electronics	0	42
MUX 2 Electronics	0	42
MUX 1 Power Supply	0	42
MUX 2 Power Supply	0	42
Scan Ang Monitor	22	25.5
Cooler Amb Stage	-16	-5
Cooler Door	-65	-25
Primary Mirror Mask	10	17
Seconadry Mirror Mask	15	25
Primary Mirror	10	17
Secondary Mirror	15	25
SLC Temp	10	29
SLC 1 Electronics	10	29
Cal Shutter Hub	5	19
Cal Shutter Flag	5	19
Cal Lamp Drive	15	26
Cal Lamp Housing	5	19
CFPA Control	90 K	93 K
SiFPA	10**	20
CFPA Monitor	90 K	93 K
SMA +X Flex Pivot	21.5	25
SMA -X Flex Pivot	21.5	25
SMA +Z Housing	21.5	25
SMA -Z Housing	21.5	25
SMA Electronics	21.5	33
SMA Torquer	21.5	25
Telescope Housing	10	24
Telescope Baseplate	2	17

** 10°C is the telemetry saturation temperature.

Figure 4. Flight Temperatures of MEM Heat Sink.

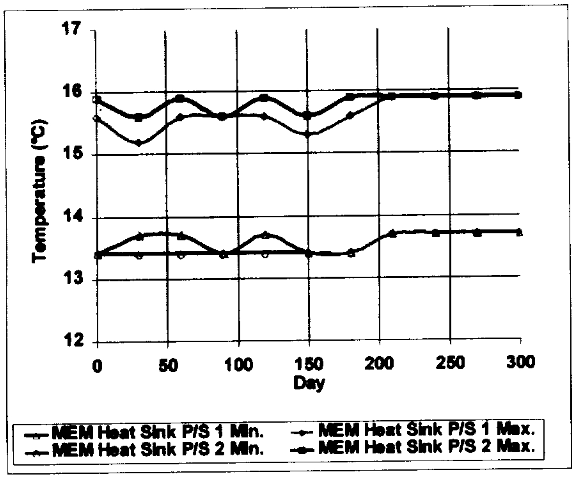
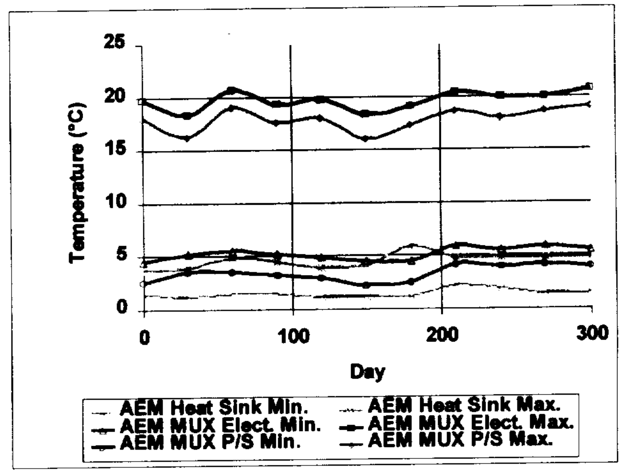


Figure 5. Flight Temperatures of AEM.



AEM

Figure 5 presents the flight temperatures of the AEM. The AEM heat sink temperature is 1.5°C minimum and 6°C maximum. It is within the yellow temperature limits of 0°C to 20°C. The flight temperature predictions were 0°C minimum in the worst cold case, and 14°C maximum in the worst hot case.

The AEM MUX 1 electronics flight temperature is 4°C minimum and 21°C maximum. It is within the yellow temperature limits of 0°C to 42°C. The flight temperature predictions were 3.8°C minimum in the worst cold case, and 26°C maximum in the worst hot case.

The AEM MUX 1 P/S flight temperature is 2.5°C minimum and 19°C maximum. It is within the yellow temperature limits of 0°C to 42°C. The flight temperature predictions were 3.8°C minimum in the worst cold case, and 25°C maximum in the worst hot case.

The explanations for the differences between the flight temperatures and flight temperature predictions are as follows. The worst cold case temperature predictions were based on the interface temperature measured during the observatory cold thermal balance test. The worst hot case temperature predictions were based on the interface temperature measured during the observatory hot thermal balance test. However, the interface temperature in flight is in between. Although the AEM is thermally isolated from the spacecraft by six titanium washers, the interface temperature still has an effect on the AEM temperatures. Also, the worst hot case maximum temperature prediction was based on the end of life absorptance of the white paint on the radiator. Despite the AEM is on the anti-sun side of the spacecraft, there is albedo incident on the radiator.

Scan Mirror Assembly

The quality of the ETM+ science data is dependent on the temperature of the Scan Mirror Assembly (SMA), including the mirror itself and the flexible pivots. Active control heaters on the SMA bulkhead are designed to maintain the SMA +Z Housing and –Z Housing at 24°C±0.5°C in the standby and imaging modes.

Figures 6 and 7 present the flight temperatures of the SMA. From Figure 6, the SMA +Z and –Z Housing temperatures are as low as 22°C. It occurs during the standby mode. The SMA standby heaters have insufficient heater capacities. Due to the Landsat-4 and 5 heritage design, the capacity of the standby heaters on the SMA bulkhead remains unchanged, which is 62.8 W at 28 V. However, the ETM+ has more radiative heat loss from the scan cavity to space than the Landsat-4 and 5 Thematic Mapper (TM) due to the following reasons. As mentioned earlier, the FAC is a new component on the ETM+, which has no Landsat-4 and 5 heritage. First, heat is conducted from the scanner bulkhead to the FAC motor stack and calibration paddle and is then radiated to space. Secondly, there is also a parasitic heat loss by conduction from the scanner mainframe to the FAC stow cover, despite that they are thermally isolated from each other. Thirdly, the mapper aperture of the ETM+ is slightly larger than that of the TM. Therefore, the view factor from the scan cavity to space is larger.

From Figure 6, the temperatures of the SMA +Z and –Z Housing are 23.2°C to 25.1°C in the imaging mode. This explains why the quality of the science data has not been affected. The temperatures in the imaging mode are warmer than the standby mode because the SMA Electronics box, which is mounted to the SMA bulkhead, operates in the imaging mode only.

The minimum flight temperature of the SMA is about 1°C colder than flight temperature predictions.

Figure 6. Flight Temperatures of SMA.

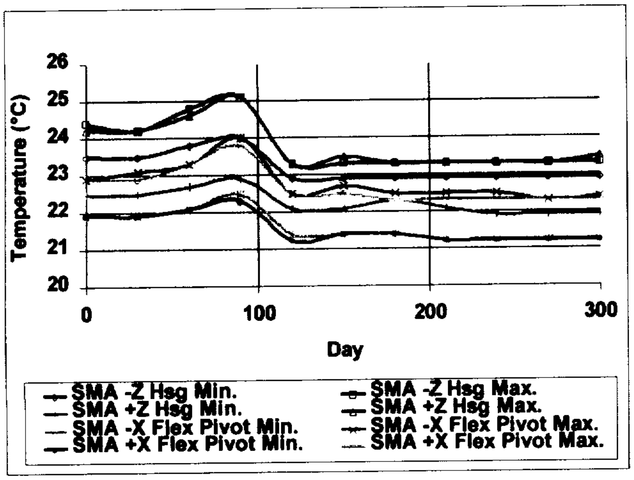
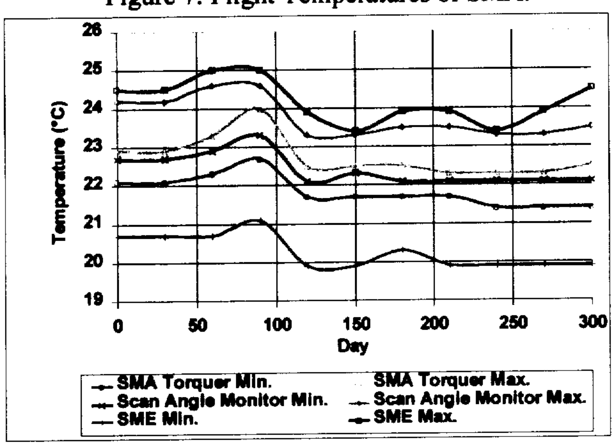


Figure 7. Flight Temperatures of SMA.



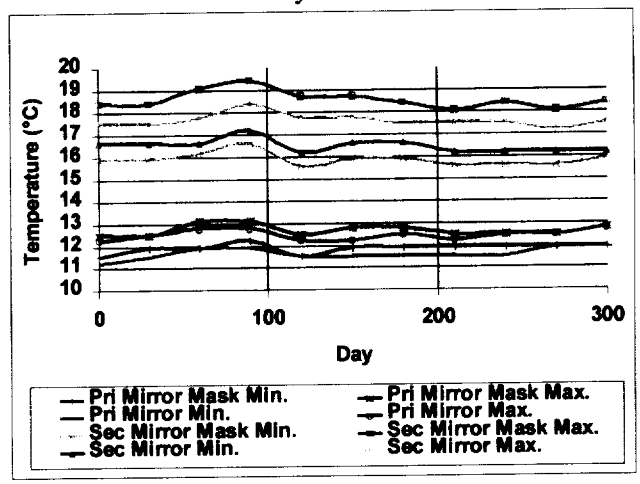
Primary and Secondary Mirrors

Figure 8 presents the flight temperatures of the primary and secondary mirrors, and the masks of these mirrors. The temperatures of the primary mirror and primary mirror mask are 11.5°C minimum and 13.2°C maximum. They are well within the yellow limits of 10°C to 17°C. The flight temperature predictions were 11.8°C minimum in the worst cold case, and 14.5°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

The flight temperatures of the secondary mirror and secondary mirror mask are 15.5°C minimum and 19.5°C maximum. They are within the yellow limits of 14°C to 25°C. The flight temperature predictions were 18°C minimum in the worst cold case, and 21.5°C in the worst hot case. The flight temperatures and flight temperature predictions have good agreement.

The worst hot case temperature predictions are slightly warmer than the flight temperatures because the end of life solar absorptance was used for kapton, which is the outer cover of the MLI blankets on the ETM+ scanner.

Figure 8. Flight Temperatures of Primary and Secondary Mirrors.



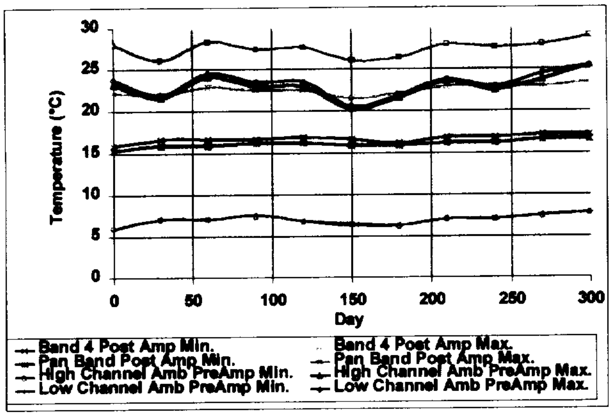
Post Amplifiers and Pre Amplifiers

Figure 9 presents the flight temperatures of the post amplifiers and ambient pre amplifiers. The temperature of the Band 4 Post Amp is 15.9°C minimum and 23.5°C maximum. It is within the yellow limits of 12°C to 25°C. The flight temperature predictions were 14.3°C minimum in the worst cold case, and 21.8°C maximum in the worst hot case. The flight temperatures and flight temperature predictions have good agreement.

The flight temperature of the Pan Band Post Amp is 15.3°C minimum and 29°C maximum. It is within the lower yellow limit of 12°C, but exceeds the upper yellow limit of 25°C. Note that the upper red limit is 55°C. The flight temperature predictions were 14.2°C minimum in the worst cold case, and 21.5°C in the worst hot case. The worst hot case temperature prediction is 7.5°C colder than the maximum flight temperature. The upper yellow limit has been increased to 31°C.

The temperatures of the High Channel PreAmp and Low Channel PreAmp are 5.9°C minimum and 25.4°C maximum. They are well within the yellow limits of 5°C to 30°C. The flight temperature predictions were 4.7°C minimum in the worst cold case, and 28.5°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement. The worst hot case flight temperature predictions are slightly warmer than the flight temperatures because the end of life solar absorptance was used for kapton, which is the outer cover of the MLI blankets on the ETM+ scanner.

Figure 9. Flight Temperatures of Post Amps and PreAmps.

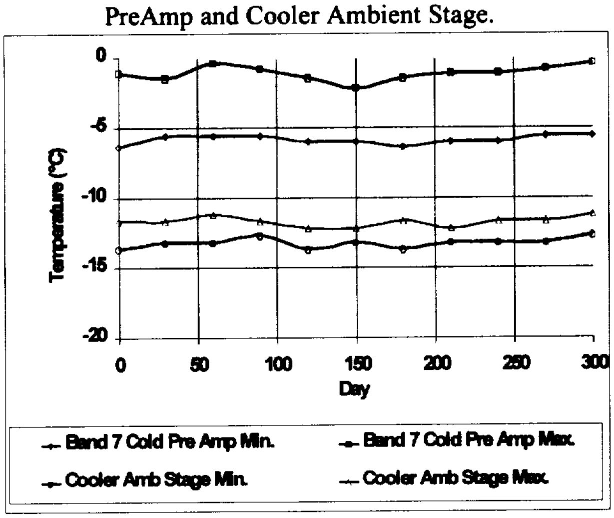


Band 7 Cold Pre Amplifier and Cooler Ambient Stage

Figure 10 presents the flight temperatures of the Band 7 Cold PreAmp and Cooler Ambient Stage. The flight temperature of the Band 7 Cold PreAmp is –6.4°C minimum and –0.4°C maximum. It is well within the yellow limits of -10°C to 4°C. The flight temperature predictions were –8.5°C minimum in the worst cold case, and 1.5°C maximum in the worst hot case. The flight temperatures and flight temperature predictions have good agreement.

The flight temperature of the Cooler Ambient Stage is –13.7°C minimum and –11.2°C maximum. It is well within the yellow limits of -16°C to -5°C. The flight temperature predictions were –12.4°C minimum in the worst cold case, and –9.2°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

Figure 10. Flight Temperatures of Band 7 Cold PreAmp and Cooler Ambient Stage.



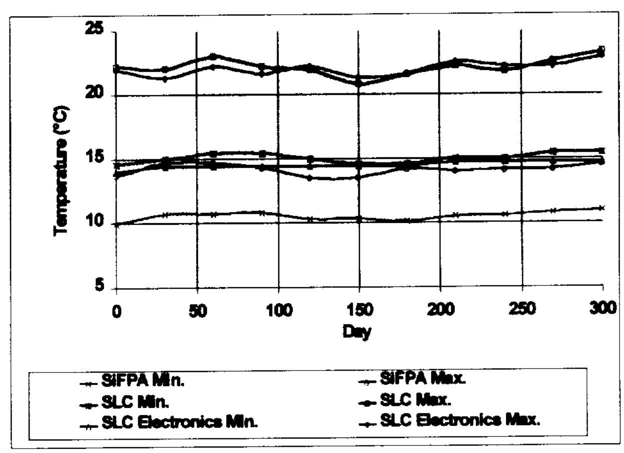
Silicon Focal Plane Array and Scan Line Corrector

Figure 11 presents the flight temperatures of the Silicon Focal Plane Array (SiFPA), Scan Line Corrector (SLC) and SLC Electronics. The flight temperature of the SiFPA is 10°C minimum and 14.7°C maximum. It is well within the yellow limits of 8°C to 20°C. The flight temperature predictions were 8.2°C minimum in the worst cold case, and 16.8°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

The flight temperature of the SLC is 14.6°C minimum and 23.3°C maximum. It is well within the yellow limits of 10°C to 29°C. The flight temperature predictions were 14.1°C minimum in the worst cold case, and 24.7°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

The flight temperature of the SLC Electronics is 14°C minimum and 22.9°C maximum. It is well within the yellow limits of 10°C to 29°C. The flight temperature predictions were 14.3°C minimum in the worst cold case, and 24.9°C. The flight temperatures and temperature predictions have good agreement.

Figure 11. Flight Temperatures of SiFPA and SCL.



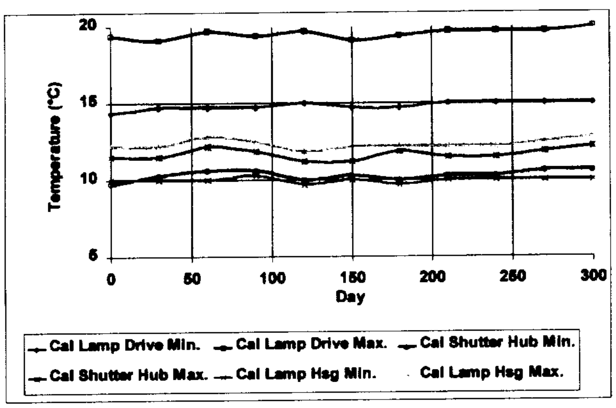
Cal Lamp and Cal Shutter

Figure 12 presents the flight temperatures of the Cal Lamp Drive, Cal Lamp Housing, and Cal Shutter Hub. The flight temperature of the Cal Lamp Drive is 14.4°C minimum and 20°C maximum. The minimum temperature exceeds the lower yellow limit of 15°C, but the maximum temperature is within the upper yellow limit of 26°C. The flight temperature predictions were 15.4°C minimum in the worst cold case, and 23°C maximum in the worst hot case. The minimum flight temperature is 1°C colder than the lower yellow limit. The lower yellow limit has been decreased to 13°C. The maximum flight temperature is 3°C colder than the worst hot case flight temperature prediction. An explanation is the end of life solar absorptance was used for Kapton, which is the outer cover of the MLI blankets on the ETM+ scanner.

The flight temperature of the Cal Shutter Hub is 10°C minimum and 12.2°C maximum. It is well within the yellow limits of 5°C to 19°C. The flight temperature predictions were 7.2°C minimum in the worst cold case, and 13.9°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

The flight temperature of the Cal Lamp Housing is 9.7°C minimum and 12.8°C maximum. It is well within the yellow limits of 5°C to 19°C. The flight temperature predictions were 8.6°C minimum in the worst cold case, and 14.4°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

Figure 12. Flight Temperatures of Cal Lamp and Cal Shutter.



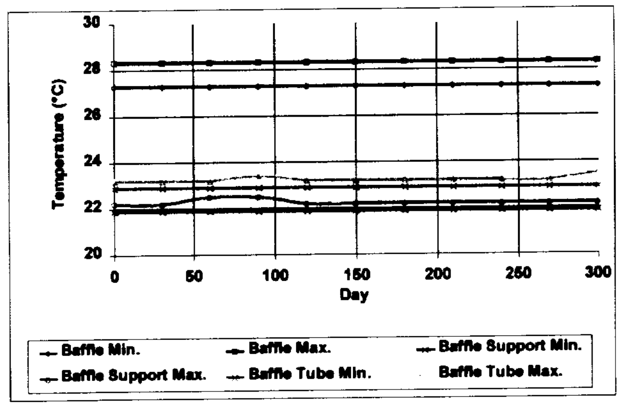
Baffle, Baffle Tube and Baffle Support

Figure 13 presents the flight temperatures of the Baffle, Baffle Tube and Baffle Support. The Baffle has active control heaters. The flight temperature of the Baffle is 27.3°C minimum and 28.3°C maximum. It is well within the yellow limits of 25°C to 30°C. The flight temperature predictions were 25.9°C minimum in the worst cold case, and 27.0°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

The flight temperature of the Baffle Tube is 21.9°C minimum and 22.2°C maximum. It is well within the yellow limits of 19°C to 25°C. The flight temperature predictions were 20.6°C minimum in the worst cold case, and 21.7°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

The flight temperature of the Baffle Support is 22.9°C minimum and 23.5°C maximum. It is well within the yellow limits of 18°C to 25°C. The flight temperature predictions were 19.6°C minimum in the worst cold case, and 20.8°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

Figure 13. Flight Temperatures of Baffle, Baffle Tube and Baffle Support.



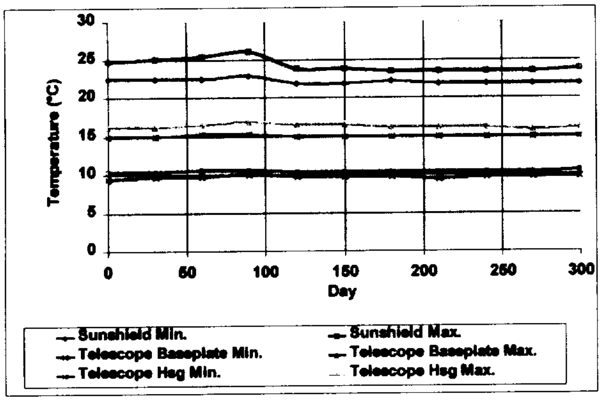
Sunshield, Telescope Baseplate and Telescope Housing

The mapper aperture sunshield prevents direct sunlight from entering the scan cavity. It is painted black on the interior and insulated with MLI on the exterior. Albedo and Earth infrared radiation enter the opening of the sunshield. Figure 14 presents the flight temperatures of the Sunshield, Telescope Baseplate and Telescope Housing. The flight temperature of the Sunshield is 21.9°C minimum and 26.1°C maximum. It is well within the yellow limits of 16°C to 27°C. The flight temperature predictions were 21.6°C minimum in the worst cold case, and 27.2°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

The flight temperature of the Telescope Baseplate is 9.4°C minimum and 10.6°C maximum. It is well within the yellow limits of 2°C to 17°C. The flight temperature predictions were 7.6°C minimum in the worst cold case, and 11.5°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

The flight temperature of the Telescope Housing is 15°C minimum and 16.9°C maximum. It is well within the yellow limits of 10°C to 24°C. The flight temperature predictions were 14.9°C minimum in the worst cold case, and 18.8°C maximum in the worst hot case. The flight temperatures and temperature predictions have good agreement.

Figure 14. Flight Temperatures of Sunshield, Telescope Baseplate and Telescope Housing.



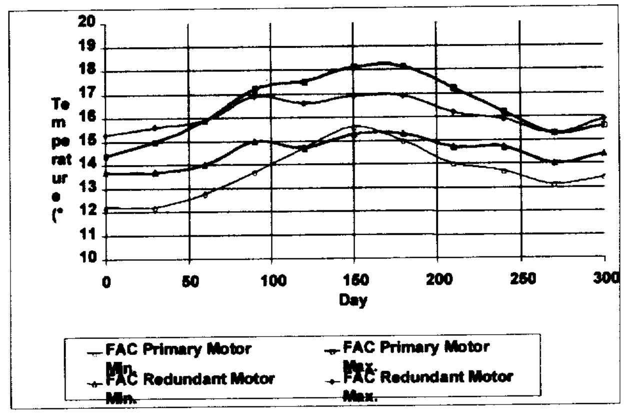
Full Aperture Calibration Motors

As mentioned earlier, the FAC is a new component and has no flight heritage. Figure 15 presents the flight temperatures of the FAC primary motor and redundant motor. The flight temperature of the FAC primary motor is 12.2°C minimum and 18.1°C maximum. It is well within the yellow limits of -4°C to 30°C. The flight temperature predictions were −1.7°C minimum in the worst cold case, and 23.8°C maximum in the worst hot case.

The flight temperature of the FAC redundant motor is 13.7°C minimum and 16.9°C maximum. It is well within the yellow limits of -4°C to 30°C. The flight temperature predictions were 7.6°C minimum in the worst cold case, and 22.4°C maximum in the worst hot case.

An explanation for the difference between the minimum flight temperature and the worst cold case temperature prediction is that the ETM+ cold limiting interface temperature in the observatory cold thermal balance test was used in the worst cold case thermal analysis. Similarly, the hot limiting interface temperature in the observatory hot thermal balance test was used in the worst hot case thermal analysis. The primary motor is mounted to the optics bulkhead, which interfaces with the spacecraft. The redundant motor is mounted on the top of the primary motor, and is thermally coupled to the FAC paddle. Both motors are external to the mapper aperture sunshield. As a result of observatory thermal balance test, a MLI blanket, with black kapton as the outer cover, was added to the "solar shield" of the motor stack at the launch site in March 1999. The MLI minimizes the heat radiation from the motor stack to space to meet the temperature requirement in the sun-pointing safehold cold case. Black kapton minimizes stray light into the scan cavity. The thermal model, with the MLI added, has not been correlated. The motors are warmer in the winter solstice than in the summer solstice because the solar flux, albedo and Earth infrared radiation are higher in the winter solstice.

Figure 15. Flight Temperatures of FAC Motors.



Cold Focal Plane Array

Figure 16 presents the flight temperatures of the Cold Focal Plane Array (CFPA). The flight temperature of the CFPA is 91.4 K minimum and 91.5 K maximum. It is well within the yellow limits of 90 K to 93 K. The flight temperature predictions were 91.4 K in both the worst cold case and worst hot case because the CFPA temperature is maintained at 91.4 K by active control heaters.

Figure 17 presents the CFPA flight heater current. It is 4.43 mA minimum and 5.23 mA maximum. It is significantly higher than the 2.1 mA measured during the observatory thermal vacuum test. It implies that the radiative cooler has an adequate design margin. Both the minimum and maximum currents are steady. Therefore, the parasitic heat flow to the CFPA is steady.

Figure 16. Flight Temperatures of CFPA.

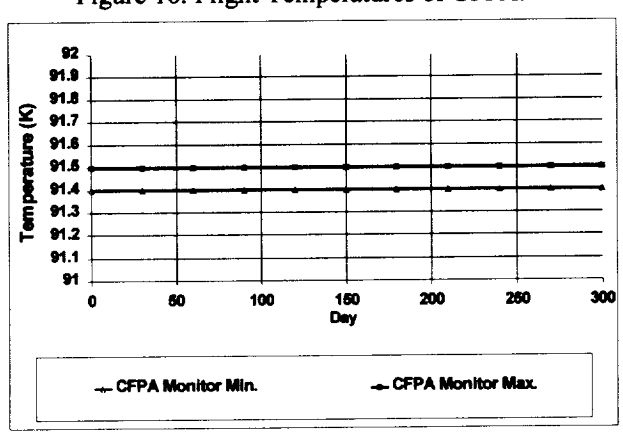
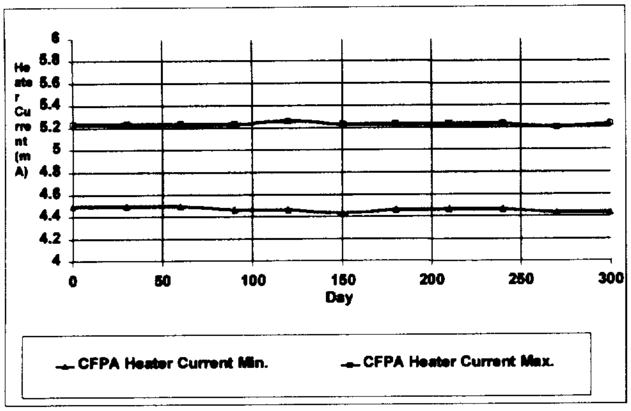


Figure 17. Flight CFPA Heater Current.



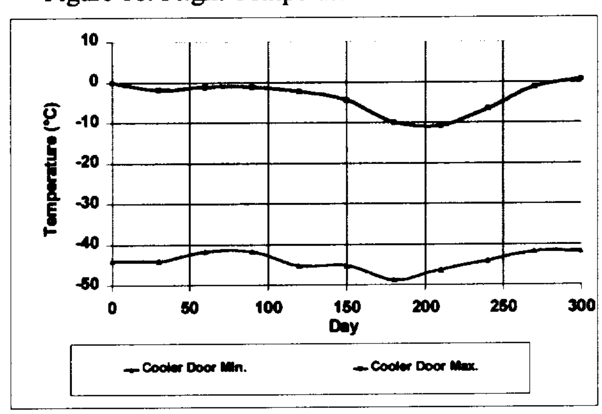
Cooler Door

Figure 18 presents the flight temperatures of the radiative cooler door. The flight temperature of the cooler door is -49°C minimum and 0°C maximum. It is within the lower yellow limit of -65°C, but exceeds the upper yellow limit of –25°C by 25°C. The flight temperature predictions were –65°C minimum in the worst cold case, and -35°C maximum in the worst hot case. The thermal coating on the Earth facing side of the cooler door is white paint, and that on the reverse side is polished aluminum. The 0°C maximum temperature in flight is significantly warmer than the maximum flight temperature prediction. An explanation for this difference is that direct solar radiation impinges on the polished aluminum side of the cooler door, when it is fully open.[3] Since the surface is specular, the solar radiation is reflected to space. It increases the cooler door temperature significantly because the ratio of solar absorptance to emittance for polished aluminum is larger than 3.0. The author showed that direct sunlight reaching the cooler door in the outgas position in 1999 because the ETM+ MEM radiator is smaller than that of the Landsat-4 and 5 Thematic Mapper.[3] Nearly 5 cm of the top of the radiator has been cut off. The 5-cm strip could have served as a blocker to the sunlight, because the sun comes from that direction. Another possible cause is that there is a difference between the Landsat-4 and -5 spacecraft bus, and the Landsat-7 spacecraft bus. So, the shielding from the sunlight for the cooler by the spacecraft bus is different. When the cooler door is fully open, solar radiation impinges on the polished aluminum side of the cooler door, and is reflected away from the cooler and into space. It has no significant impact on the cooler thermal performance.

IMAGING DUTY CYCLE

The 15-orbit mission design profile was used by the Landsat-7 Project to design and test the spacecraft bus and ETM+. The 15-orbit profile in the summer solstice was used for the worst hot case design and analysis of the different subsystems, such as thermal, power, etc. The instrument-level thermal vacuum qualification test of the ETM+ in summer of 1998 was also based on the 15-orbit profile in the summer solstice. What makes the thermal analysis, thermal vacuum testing, and mission operation difficult is that there is no flight temperature telemetry of the internal components, particularly the switching diodes, of MEM power supplies. Therefore, instead of using the flight temperature telemetry of the diodes as a maximum limit of imaging, the imaging time in the 15-orbit profile in the summer solstice is used. Operating the ETM+ at imaging duty cycles beyond what it was qualified in the instrument thermal vacuum test could potentially cause overheating and thermal overstress, which could subsequently lead to a mission failure. This is the reason why the Landsat-7 Project has been very careful in dealing with the safety of the ETM+. Operating the ETM+ at imaging duty cycles within what it was qualified in the instrument thermal vacuum test is a safe approach.

Figure 18. Flight Temperatures of Cooler Door.



15-Orbit Mission Design Profile

Table 3 presents the 15-orbit mission design profile in the ETM+ Interface Control Document (ICD).[4] The average ETM+ duty cycle is 16.7% in the summer solstice, and is 13.5% in the winter solstice. Figure 19 shows the duty cycle versus days of the year. It is assumed to be sinusoidal.

Duty Cycle in Flight

From mid-July 1999 through April 2000, the average duty cycle in flight reported by the Landsat-7 Mission Operation team is 14%.[5] It is somewhat less than the design average duty cycle of 15%. Figure 20 presents the imaging time versus the orbit number during that period.

Table 3. ETM+ Imaging Time in 15-Orbit Design Profile (Minute).

Orbit #	Summer Solstice	Winter Solstice
1	12	8
2	7	3
3	10	6
4	11	18
5	14	13
6	24	20
7	17	13
8	10	10
9	31	29
10	19	17
11	16	15
12	17	9
13	20	15
14	22	15
15	18	9
Total	248	200
Average	16.53	13.333
Average Duty Cycle	16.7%	13.5%

Figure 19. ETM+ Design Duty Cycle vs. Days of

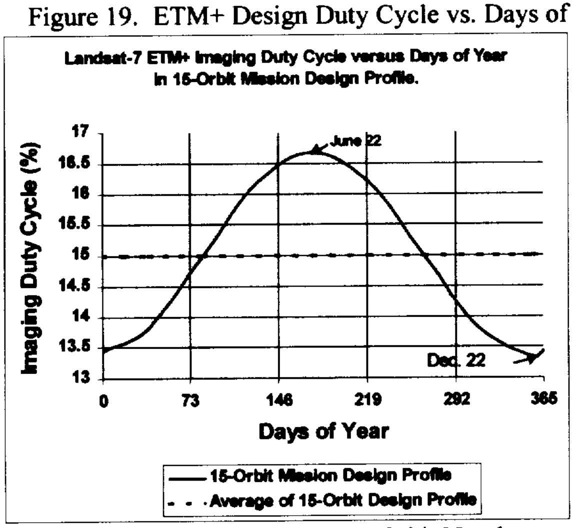
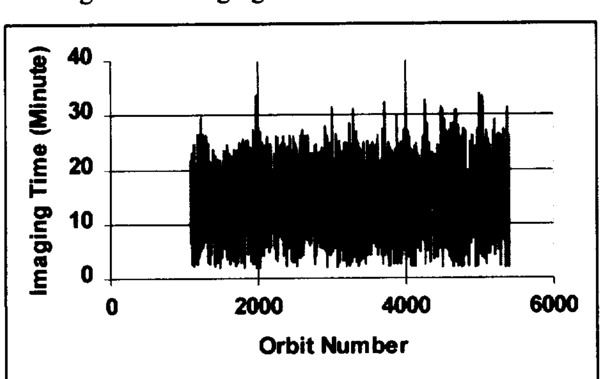


Figure 20. Imaging Time vs. Orbit Number.



Constraints on Imaging Time

Currently, the limits of the imaging duty cycles in the ETM+ ICD[4], based on a 100-minute orbit period, are as follows:

- Short-Term: 34 minutes in any 100-minute window,
- Mid-Term (Near-Term): 52 minutes in any 200-minute window,
- Mid/Long Term (Medium-Term): 131 minutes in any 600-minute window,
- Long-Term: 230 minutes in any 1,380-minute window.

These limits are intended to prevent the MEM power supplies from overheating and thermal overstress. They were added to the ICD in June 1999 after launch. They were derived from the 15-orbit design profile in Table 3. The actual orbit period is 98.75 minutes. But, in the above limits, it was rounded off to 100 minutes.

The 15-orbit design profile in the summer solstice was used in the ETM+ instrument-level thermal vacuum qualification test in 1998. The orbit period used in the test was 99 minutes. The imaging time was 248 minutes in a 1,485 minute window, and the average imaging duty cycle in this window was 16.7%. In addition to the 15-orbit design profile, the ETM+ was also tested with 34 minutes of imaging in a 99-minute window in the instrument thermal vacuum test. This explains why the Short-Term imaging time limit in the ICD is 34 minutes, despite that the longest imaging time in the 15-orbit design profile is 31 minutes. The Mid-Term limit was derived from orbits 9 and 10, which have the longest total imaging time of any 2 consecutive orbits. It is 2 minutes higher than the total imaging time of orbits 9 and 10. An explanation is that an imaging time of 34 minutes for orbit 9 was used in deriving the Mid-Term limit. The Mid/Long Term limit was derived from orbits 9 through 14, which have the longest total imaging time of any 6 consecutive orbits. The Long-Term limit was derived from the 15 orbits. The percent duty cycle is 16.7%. But, the window is 1.2 orbits less than the 15-orbits. The Mission Operation Team reported that some of these constraints have caused interruptions during imaging.[5]

Based on the 15-orbit design profile and orbit period used in the ETM+ instrument-level thermal vacuum test, the limits of the imaging times in the ICD should be:

- Short-Term: 34 minutes in any 99-minute window,
- Mid-Term (Near-Term): 50 minutes in any 198 minute window,
- Mid/Long Term (Medium-Term): 125 minutes in any 594-minute window,

• Long-Term: 248 minutes in any 1,485-minute window.

Proposed Changes to Constraints on Imaging Time

In the 15-orbit design profile used in the ETM+ thermal-level vacuum test to qualify the instrument, orbit 9 has a 31-minute imaging, and orbit 10 has a 19-minute imaging. The Mid-Term limit was derived from these two orbits. It protects the MEM power supplies from overheating in the second orbit. Currently, the Mid-Term limit does not depend on the imaging time of the first orbit over a 2-orbit window. If the imaging time in the first orbit is less than 31 minutes, not only less thermal energy is stored in the MEM power supplies, but also the cooling time is longer. So, the total imaging time over the 198-minute window can be increased. If the imaging time in the first orbit is more than 31 minutes, not only more thermal energy is stored in the MEM power supplies, and but also the cooling time is shorter. So, the total imaging time over the 198-minute window should be decreased. Table 4 presents the proposed Mid-Term limit to increase the duty cycle and to relieve the problem of imaging interruptions experienced by the Mission Operation Team.

Also, the Mission Operation Team desires to extend the window of the Long-Term imaging limit to the daily stored command load of 40 hours. Suppose consecutive 15-orbits were run in the ETM+ thermal vacuum test, the lowest total imaging time in any 24 consecutive orbits (39.6 hours) is 384 minutes, and it is thermally acceptable to change the Long-Term limit to 384 minutes of imaging in a 39.6-hour window. The ETM+ duty cycle is 16.2% in this Long-Term limit. Therefore, the imaging limit should be 388.8 minutes in any 40-hour window. However, to maintain the ICD limit of 16.7% over 40 hours, the imaging time needs to be 400.8 minutes. After the Short-Term, Mid-Term, and Medium Term imaging limits are already satisfied, the risk of overheating the MEM power supplies by adding 12 minutes of imaging over 40 hours (24 orbits) is low. Therefore, a Long-Term imaging limit of 400.8 minutes in any 40-hour window should not be a problem thermally.

SUMMARY AND CONCLUSIONS

The Landsat-7 ETM+ instrument began the normal imaging phase of the mission in mid-July 1999. The thermal performance of the ETM+ from mid-July 1999 to mid-May 2000 is nominal. The yellow temperature limits were derived from the flight temperature predictions by a thermal model correlated to the observatory thermal balance test, plus some margins. The yellow limits work well in flight, so that only several minor changes to them were needed. Overall, the flight temperatures and flight temperature predictions have good agreement. Imaging time limits were added to the ICD after launch to protect the MEM power supplies from overheating. The Mid-Term limit was derived from orbits 9 and 10 of the 15-orbit mission design profile. Currently, the Mid-Term limit does not depend on the imaging time of the first orbit over a 2-orbit window. If the imaging time in the first orbit is less than 31 minutes, not only less thermal energy is stored in the MEM power supplies, but also the cooling time is longer. So, the total imaging time over the 198-minute window can be increased. If the imaging time in the first orbit is more than 31 minutes, not only more thermal energy is stored in the MEM power supplies, but also the cooling time is shorter. So, the total imaging time over the 198-minute window should be decreased.

Also, the Mission Operation Team desires to extend the window of the Long-Term imaging limit to the daily stored command load of 40 hours. Based on the 15-orbit mission design profile used in the ETM+ instrument-level thermal vacuum test, a new Long-Term imaging limit of 400.8 minutes in any 40-hour window should not be a problem thermally.

Table 4. Proposed Mid-Term Limit (Minutes).

First Orbit	Second Orbit	Total
34	13	47
33	15	48
32	17	49
31	19	50
30	21	51
29	23	52
28	25	53
27	27	54
26	29	55
≤25	31	≤56

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2. Landsat-7 Mission Operation Center, Landsat-7 Flight Telemetry Temperature Data, July 1999-May 2000, Goddard Space Flight Center, Greenbelt, MD.

3. Choi, M. K., "Solution for Direct Solar Impingement Problem on Landsat-7 ETM+ Cooler Door During Cooler Outgas in Flight ", SAE Paper Series 1999-01-2677, 34th IECEC, Vancouver, B.C., Aug. 1999.

4. ETM+ ICD, Landsat-7 Document 430-L-0002-J, Goddard Space Flight Center, Greenbelt, MD.

5. Guit, W., Re: Notes from ETM+ Duty Cycle Meeting, e-mail to M. Choi, Mar. 16, 2000.