Thermal Design Considerations of the Hubble Space Telescope (HST) Science Instrument Control and Data Handler (SI C&DH-2)

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Following a failure in side 1 of the HST SI C&DH in September 2008, HST Servicing Mission 4 (SM-4) was delayed so that a SI C&DH Orbital Replacement Unit (ORU) could be qualified for flight. This second generation SI C&DH (SI C&DH-2) included several enhancements which increased its thermal dissipation near critical components. In order to maintain the SI C&DH-2 within its operational temperature limits, several thermal modifications were installed prior to its final qualification testing. This paper presents the thermal modifications performed on the SI C&DH-2, as well as the thermal ground test results and a correlation of the SI C&DH-2 thermal design to flight telemetry.

I. Introduction

In September 2008, side 1 of the Science Instrument Control and Data Handling (SI C&DH) subsystem of the Hubble Space Telescope (HST) failed. Since the SI C&DH had fully redundant electronics, the SI C&DH and HST were converted to Side 2 operation and the science mission continued.

However, the SI C&DH side 1 failure left the HST with zero fault tolerance to another similar failure in that subsystem. Without the SI C&DH subsystem, the HST would have no way to control the operation of the science instruments on board the observatory and no way to get science and engineering data from the instruments to the ground. An additional failure in the SI C&DH could effectively end the useful scientific life of the telescope. In order to restore redundancy in this critical subsystem, the National Aeronautics and Space Administration (NASA) delayed the launch of the HST Servicing Mission 4 (SM-4) from October 2008 to May 2009. During this launch delay, a SI C&DH (SI C&DH-2) Orbital Replacement Unit (ORU) was qualified for flight and installation onto HST during SM-4.

The SI C&DH-2 design included several enhancements, including additional memory and several electrical design improvements, which increased thermal dissipation near critical components. Prior to performing the final SI C&DH-2 qualification testing, thermal modifications were installed onto SI C&DH-2 to reduce electronics temperatures during hot attitudes and environments. This paper presents the thermal modifications performed on SI C&DH-2, as well as the thermal ground test results and a correlation of the SI C&DH-2 thermal design to flight telemetry.

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II. Overview

The SI C&DH-2 is the second generation Science Instrument Command and Data Handler subsystem for the HST. The SI C&DH-2 handles the transfer of commands from the ground to the HST science instruments and provides both science and engineering data from the instruments to the ground.

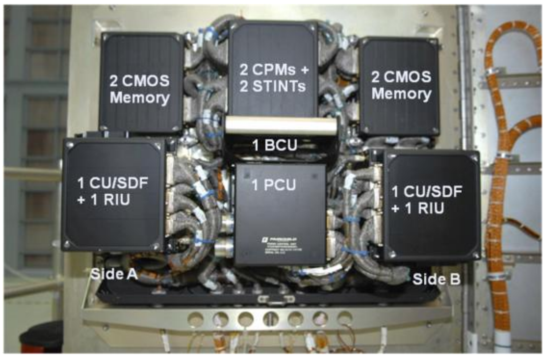

Figure 1. SI C&DH-2 Mounted on a HST Door Mockup.

For redundancy, the SI C&DH-2 has two sides with a full complement of electronics on each side. The SI C&DH-2 subsystem consists of 14 individual electronics boxes mounted to one common baseplate. As shown in Fig. 1, these electronics include: 4 Complementary metal-oxide-semiconductor (CMOS) Memories, 2 Central Processor Modules (CPMs), 2 Standard Interface for Computer (STINT) boxes, 2 Remote Interface Units (RIUs), 2 Control Unit/Science Data Formatters (CU/SDFs), 1 Power Control Unit (PCU), and 1 Bus Coupler Unit (BCU). Both sides of the redundant PCU and BCU are contained within their single electronics box.

III. SI C&DH-2 Background and Thermal Modifications

A. Pre- HST Launch Subsystem Development and Environmental Testing

During HST development, the SI C&DH vendor conducted environmental testing at the component and the subsystem level. Temperature requirements for the SI C&DH mounting interface (the ORU tray) were generated by the spacecraft thermal control engineers using an integrated thermal model. This analysis used the expected power dissipation and mounting interface conductance and was confirmed during HST system-level thermal vacuum testing.

In a near parallel design effort, the vendor also developed the flight spare, designated SI C&DH-2. This design incorporated several electrical design enhancements to subsystem components resulting in an increase of the power dissipation in the CU/SDF by 5 W.

To counter the rise in CU/SDF dissipation, the vendor increased heat paths from critical components to the box chassis, as well as paths through the chassis to the CU/SDF base plate. Subsequent CU/SDF environmental testing was successful; however the base plate temperature specification was not increased to reflect the increased power dissipation and no system-level thermal analysis was performed. The SI C&DH-2 subsystem environmental qualification tests were cancelled due to budget and programmatic constraints with the understanding that the environmental tests would be performed in the event that the flight spare SI C&DH-2 was called up for installation on the telescope. Prior to SM-4, the SI C&DH-2 flight spare was used in air for various ground test activities.

B. SM-4 SI C&DH-2 Commissioning

Following the on-orbit failure of the SI C&DH and the subsequent addition of SI C&DH-2 to the SM-4 manifest, the HST Flight Servicing team began to qualify the SI C&DH-2 for launch. With years of flight telemetry showing that the original SI C&DH was already operating near maximum temperature limits and the increased power dissipation in SI C&DH-2, HST thermal engineers began searching for design solutions to maintain SI C&DH-2 within its operate limits under the extremely tight schedule constraints of the launch delay.

Spacecraft thermal radiator temperatures would necessarily increase with the additional SI C&DH-2 thermal dissipation; however there was not hardware or servicing mission time available to address this problem and lower the radiator temperature. Therefore, the thermal design solution would have to overcome the increased radiator temperatures with a significantly improved thermal path from the hot electronics components to the spacecraft radiator. To that end, the thermal design modifications focused in two main areas:

- Lowering the temperature gradients between critical components within the CU/SDF and the SI C&DH-2 tray, and
- Lowering the temperature gradient at the SI C&DH-2 / HST mounting interface

C. Initial Thermal Design Enhancements and Thermal Vacuum Test #1

The original SI C&DH CU/SDF was formed from a magnesium alloy to reduce weight; however this created a dissimilar metals concern when the components were mated to the aluminum ORU tray. The original designers overcame this obstacle by using a Choseal pad and slightly thinner metal spacers at the CU/SDF interface to provide a thermal path while providing some mechanical compliance. The SI C&DH-2 CU/SDF was formed of aluminum and did not pose similar concerns. Therefore, to reduce temperature gradients between the CU/SDF and the ORU tray, the metal spacers were eliminated and eGraf® interstitial material from GrafTech was used at the CU/SDF interface to increase contact area and conductivity.

However, the first SI C&DH-2 thermal vacuum test showed that the heat rejection path from the CU/SDF to the ORU tray and from the tray to the cold plate simulating the HST bay door were not sufficient to maintain the CU/SDF temperatures with the increased power dissipation. Under this configuration, the appropriate acceptance test environmental levels could not be achieved without hitting hot operate temperature limits on the CU/SDF. These results would mean that the SI C&DH-2 would not be fully qualified for flight. Clearly, this condition was not acceptable so additional thermal design improvements were required.

D. Final SI C&DH-2 Thermal Design and Thermal Vacuum Test #2

Following Thermal Vacuum test #1, additional thermal modifications were designed, built and installed onto SI C&DH-2 to lower the temperature gradient from the CU/SDF to the simulated HST bay door. The first modification consisted of adding a thermal link from the CU/SDF to the ORU tray.

Since the microprocessor inside the CU/SDF was the hottest component, the thermal link was designed to attach to the side of the CU/SDF box close to the microprocessor and provide a direct thermal path to the ORU tray. Figure 2 shows the design of the thermal link and the implementation of the actual thermal link onto the CU/SDF. Note that the thermal link was later covered with black Kapton tape to provide more radiation to the environment. The link is shown here during a fit check without the black Kapton tape for clarity. Thermal testing showed that the thermal link provided an additional 1.3W/°C effective end to end conductance from the CU/SDF to the ORU tray.

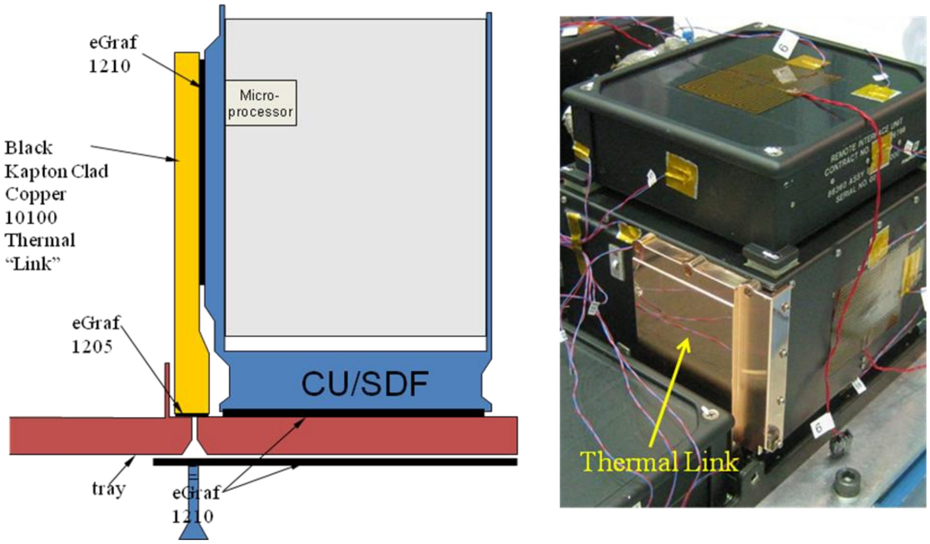

Figure 2. CU/SDF Thermal Link Design and Implementation.

The second thermal modification consisted of adding eGraf® between the SI C&DH-2 tray and the cold plate simulating the HST bay door to provide better contact area and conductance. During the pre-launch HST observatory thermal vacuum test, engineers discovered that the bay door to which the SI C&DH is attached was not flat. In addition, the SI C&DH-2 tray was not perfectly flat. As such, there was minimal contact area between the SI C&DH tray and the bay door except around the bolts.

In order to improve the thermal contact area and conductance between the SI C&DH-2 tray and the HST bay door, eGraf® strips were added under the ORU tray. During the SI C&DH-2 thermal vacuum test, two configurations of eGraf® strips were tested to determine the optimum contact area. The tray under Side A of the SI

C&DH-2 was lined with eGraf® pads corresponding only the area directly under the electronics boxes. On Side B of the tray, a long strip of eGraf® was applied over the length of the tray.

The SI C&DH-2 thermal vacuum test #2 temperatures showed similar results between the two sides of the tray. Therefore, the longer single pads of eGraf® were chosen for the flight configuration due to easier implementation and reduced risk of eGraf® edge lifting during astronaut Extra Vehicular Activity (EVA) installation of the SI C&DH-2.

In order to determine the contact area gained by the eGraf®, contact area tests were performed using contact pressure sensitive film. The film is designed to discolor at any areas with a minimum contact pressure of 15psi or greater. Figure 3 shows the contact pressure test results for the thermal vacuum test configuration and the final flight configuration. Figure 4 shows the flight eGraf® installed on the bottom of the SI C&DH-2 tray.

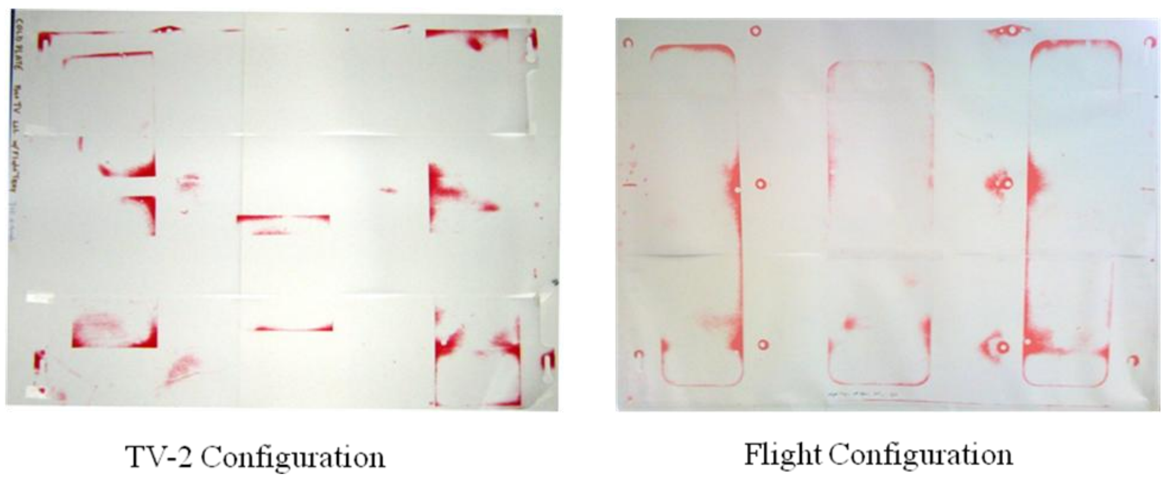

Figure 3. Contact Pressure results for eGraf® in TV and Flight Configuration .

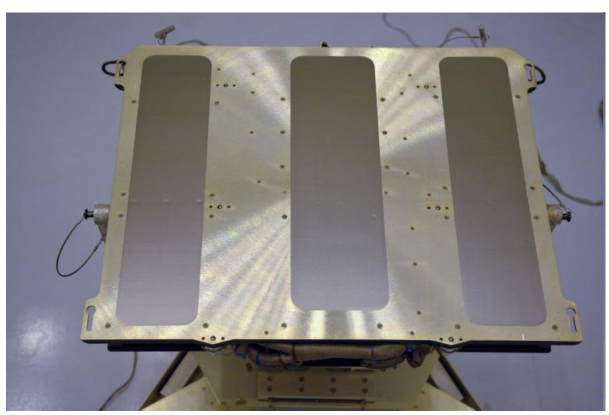

Figure 4. Flight eGraf® installed on the SI C&DH-2 tray.

Following the addition of the thermal link onto the CU/SDF and the eGraf® under the SI C&DH-2 tray, a second thermal vacuum test was conducted to verify the thermal design and performance of the modifications. With these thermal modifications, the SI C&DH-2 subsystem was successfully tested to their full defined acceptance test levels without hitting any hot operate temperature limits.

IV. On Orbit Thermal Performance

The combined performance of the thermal link and eGraf® interface between the CU/SDF and the tray was assessed again using onboard HST flight temperature telemetry. Temperature sensors are available within the

CU/SDF and on the SI C&DH-2 tray. The temperature difference between these sensors, along with power telemetry for the SI C&DH-2 subsystem, was used to assess the thermal conductance before and after SM-4 as shown in Fig. 5. Based on this rough analysis, the modifications to the thermal path between the CU/SDF components and the tray (a combination of affects from the addition of the thermal link and from the installation of eGraf® under the CU/SDF box) increased conductance more than 600% over the original unit.

Figure 5. Temperature Gradient as a function of SI C&DH power.

The performance of the eGraf® interface between the SI C&DH-2 tray and HST was inferred by comparing temperature telemetry at the SI C&DH tray before and after SM-4. Because no temperature sensor exists on the HST radiator beneath the SI C&DH-2, tray temperature telemetry was normalized for differences in equipment duty cycle and HST attitude by computing the total orbit average heat load on the thermal radiator. Figure 6 demonstrates the noticeable improvement in the interface thermal performance.

The increased thermal conduction allows the SI C&DH-2 tray to run 8.5°C cooler than its predecessor under similar conditions (or equivalently, to dissipate an additional 8W with the same tray temperature). This was a very significant improvement, although pre-flight predictions estimated the tray would run 12.5°C cooler for an underperformance of 4°C.

The reasons that the SI C&DH-2 tray/HST interface did not perform as expected may never be fully known, however some possible explanations include:

- The topography of the on-orbit door may have produced gaps under high dissipating components since door flatness is unknown within a loose specification and due to the poor flatness of the SI C&DH-2 tray.

* Temperature differences between the SI C&DH-2 tray and HST door during on-orbit installation may have resulted in a loss of contact pressure as temperatures equilibrated, although this concern was addressed prior to SM-4 and should have been mitigated by fastener design.
* Creep in the eGraf® material may have reduced contact pressure. Although eGraf® is very stiff, for a typical application the fasteners would be retightened after a period of time to ensure contact pressure was maintained. EVA time constraints during SM-4 did not allow time for the fasteners to be retightened after temperature equilibrium and any eGraf relaxation.

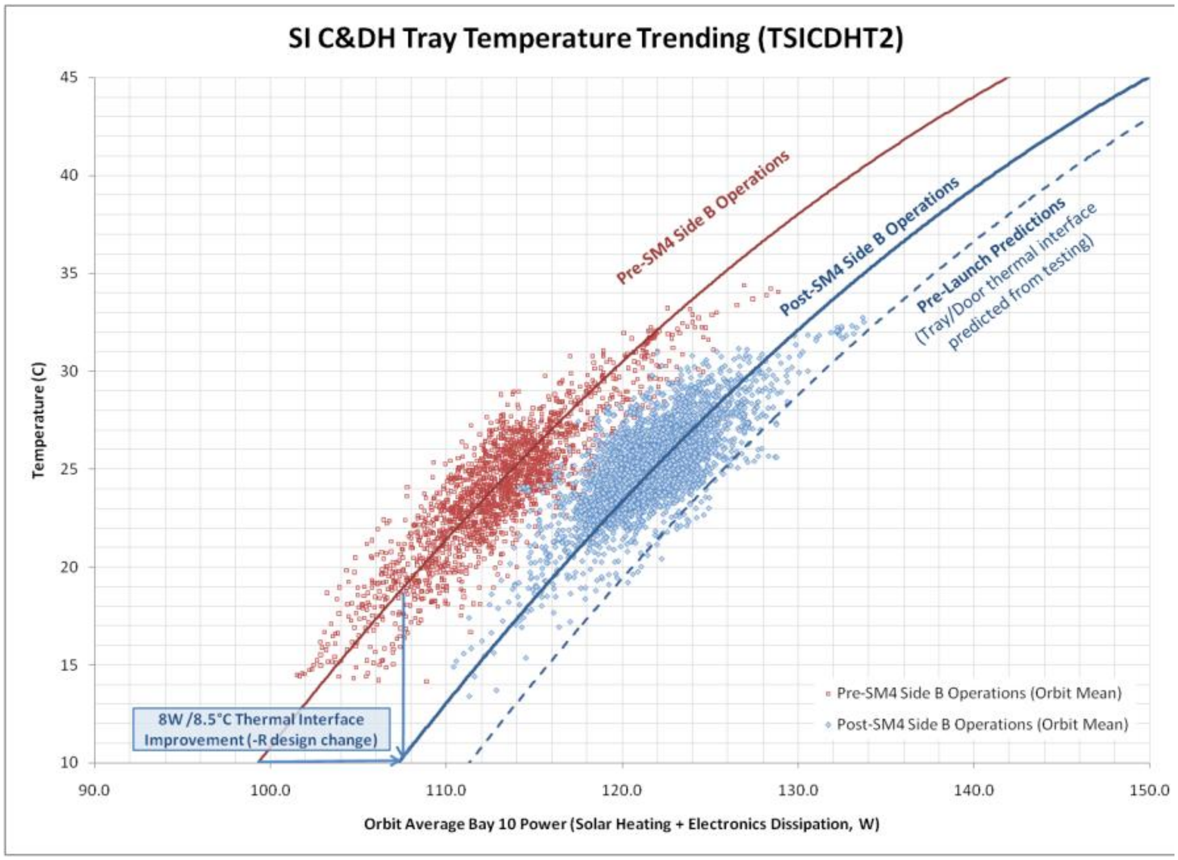

Figure 6. SI C&DH-2 Tray Temperature as a function of Bay 19 power.

V. Thermal Model Correlation

Following HST SM-4, a flight correlation of the SI C&DH-2 Thermal Math Model (TMM) was performed to determine the accuracy of the model. Several thermally stable HST attitudes were chosen as correlation periods and the HST TMM, including the detailed SI C&DH-2 model, was configured to reflect these attitudes. Figure 7 shows the detailed SI C&DH-2 geometric thermal math model.

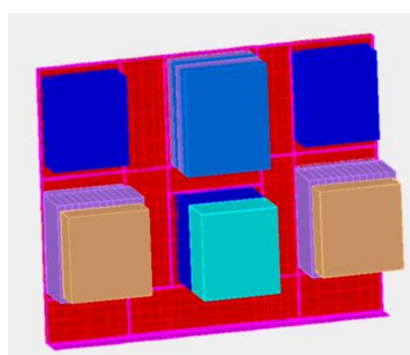

Figure 7. SI C&DH-2 Thermal Math model.

Initial results indicated that the SI C&DH-2 TMM did not correlate well to flight telemetry with the SI C&DH-2 model predictions generally several degrees colder than the on-orbit telemetry values. The predicted CU/SDF temperatures were approximately 7°C colder than their corresponding telemetry value. Under predicting the CU/SDF temperature was a concern since pre-flight predictions for the CU/SDF indicated it would approach its 70°C hot operate limit in the typical hot operate case and would exceed its limit in the worst hot design case. The typical hot operate case assumed worst case seasonal orbit and beta angle parameters, as well as the maximum predicted power profile in the SI C&DH-2 split between sides A and B on the tray. In addition to those hot conditions, the hot design case assumed a worst case off nominal roll of the telescope towards the SI C&DH-2 bay and the maximum predicted power located on only one side of the tray. Under these conditions, the pre-flight model predicted +64°C and +78°C for the typical and design hot operate cases, respectively. Operational constraints were implemented prior to launch to ensure that all of the hot design case parameters will not be realized simultaneously resulting in an over temperature on the CU/SDF.

To improve the SI C&DH-2 TMM correlation, several refinements were made to reflect the intricacies of the flight environment. The conduction between the SI C&DH-2 tray and the HST bay door was an area of the TMM that could be refined. The flatness of the HST bay door and the torque on the SI C&DH-2 tray fasteners are both unknown and could impact the SI C&DH-2 flight correlation significantly. With this in mind, the conduction value from the SI C&DH-2 tray to the HST bay door was reduced to 25% of its initial value based on pressure tests conducted during SI C&DH-2 ground testing. This change resulted in a general increase in predicted SI C&DH-2 temperatures, with the CU/SDF temperature increasing by 4.7°C.

In addition, the CU/SDF baseplate nodalization was refined from one node to 36 nodes in an attempt to better account for possible gradients in the baseplate. Also, the CU/SDF box was refined to account for additional conduction through a component mounting tray. It was thought that the flight thermal environment may introduce subtleties not captured by the thermal vacuum correlation and that these subtleties may be better captured with a refined CU/SDF baseplate and box. Unfortunately, the predicted CU/SDF temperature change was negligible when the CU/SDF baseplate and box were refined.

A careful audit of the detailed SI C&DH-2 TMM revealed two offsetting errors in the code. An error around the modeling of the CU/SDF thermistor increased the predicted temperature at the CU/SDF thermistor by 4.2°C. However, an error in the telemetry power calculation was also identified which reduced the power to the SI C&DH-2 by 4W causing the CU/SDF temperature to decrease by -3.5°C.

After all the flight correlation refinements and corrections had been implemented, the SI C&DH-2 TMM predicts the CU/SDF temperature within 1°C of flight telemetry. Table 1 shows the initial and final model correlation results for the SI C&DH-2 TMM.

Table 1. SI C&DH-2 Thermal Math Model Correlation Results

	Initial Model			Correlated Model		
	2009 Day 193 Average			2009 Day 193 Average		
SI C&DH-2 Component	Telemetry (°C)	Model (°C)	ΔT	Telemetry (°C)	Model (°C)	ΔT
RIU A Temp	22.3	20	-2	22.3	21	-1
CU/SDF A Logic A210	12.0	8	-4	12.0	11	-1
CU/SDF A Power	12.1	8	-4	12.1	11	-1
STINT A Temp	20.1	18	-2	20.1	20	0
RIU B Temp	24.8	20	-4	24.8	21	-3
CU/SDF B Logic A211	54.5	47	-7	54.5	53	-1
CU/SDF B Power	48.5	43	-6	48.5	47	-1
STINT B Temp	28.5	27	-1	28.5	29	1
Regulator A/B Temp	22.3	21	-1	22.3	24	1
SICDH Tray Temp 1	17.4	13	-4	17.4	16	-2
SICDH Tray Temp 2	24.1	20	-4	24.1	23	-1
Bay 10 Door Temp	0.9	2	1	0.9	1	0
CDH 2 Memory 0 Temp	18.6	18	-1	18.6	20	2
CDH 2 Memory 0 Temp	13.7	16	3	13.7	19	5
CDH 2 Memory 0 Temp	18.4	18	-1	18.4	20	1
CDH 2 Memory 0 Temp	10.8	14	3	10.8	16	5
SIC&DH Power [W]	79.5W	83.3W		79.5W	79.3W	

VI. Conclusions and Lessons Learned

The conclusions of this paper are best demonstrated as Lessons Learned for future hardware development. During the process of qualifying the SI C&DH-2 prior to flight and of operating the SI C&DH-2 onboard the HST, several Lessons Learned have been identified. The Lessons Learned include the following:

Lessons Learned 1: Changes in component dissipation (or equivalently, contact area, finish, etc.) must be evaluated at the system level. In the case of the HST SI C&DH-2, the component power increase caused a bulk temperature rise of approximately 5°C at the system level that could not be mitigated by vendor thermal design enhancements within the subsystem. Without the appropriate system level analyses and tests, this temperature increase was not accounted for sufficiently.

Lessons Learned 2: Environmental testing at the subsystem level, even for seemingly minor design changes, can be critical in catching unforeseen thermal control problems. In the case of the HST SI C&DH-2, the affect of the increased component power for the flight spare would have been seen during subsystem testing as a significant increase in CU/SDF chassis temperature from the previous model. Even without an increase in the tray conductive sink driven by system-level analysis, the increase in CU/SDF chassis temperature due to interface resistance at the tray may have resulted in CU/SDF internal temperatures 8°C higher than the flight unit. This would have prompted earlier action to make the spare unit flight-worthy.

Lessons Learned 3: For repeatable dry thermal interfaces between flexible surfaces with few fasteners, flatness requirements and/or a known topology of the two surfaces is critical. If a dry bolted interface is a critical thermal path which must be exercised via an EVA or any other application (such as launch pad installation) where schedule or logistics do not allow for test and verification, several methods can be used to enhance the predictability and repeatability of the interface. These methods include: (1) specifying the flatness and surface roughness of each side of the mating interface to tight tolerances, (2) adding fasteners to force the surfaces to conform mechanically, and (3) recording the as-built surface topology of the spacecraft side of the interface using contact pressure mapping film and/or laser topology techniques. In the case of the HST SI C&DH-2, without knowledge of the interface contact pressure profile, it is not possible to determine the cause of the reduced thermal performance seen on orbit.

Appendix

Acronyms used in this report are defined as follows:

CMOS	Complementary metal-oxide-semiconductor
CPM	Central Processor Module
CU/SDF	Control Unit/Science Data Formatter
EVA	Extra Vehicular Activity
HST	Hubble Space Telescope
NASA	National Aeronautics and Space Administration
ORU	Orbital Replacement Unit
SI C&DH-2	Science Instrument Command and Data Handler-2
SM-4	Servicing Mission 4
STINT	Standard Interface for Computer
TMM	Thermal Math Model

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