Lessons Learned from the Wide Field Camera 3 TV1 Test Campaign and Correlation Effort

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Abstract

In January 2004, shortly after the Columbia accident, future servicing missions to the Hubble Space Telescope (HST) were cancelled. In response to this, further work on the Wide Field Camera 3 instrument was ceased. Given the maturity level of the design, a characterization thermal test (TV1) was completed in case the mission was re-instated or an alternate mission found on which to fly the instrument. This thermal test yielded some valuable lessons learned with respect to testing configurations and modeling/correlation practices, including:

1. Ensure that the thermal design can be tested
2. Ensure that the model has sufficient detail for accurate predictions
3. Ensure that the power associated with all active control devices is predicted
4. Avoid unit changes for existing models

This paper documents the difficulties presented when these recommendations were not followed.

Introduction

The Wide Field Camera 3 (WFC3) is an instrument to replace the Wide Field Planetary Camera II instrument (WF/PC-II) on the Hubble Space Telescope. The instrument consists of two channels: UV/Visible (UVIS) and Infrared (IR). A pickoff mirror reflects the incoming light to a channel select mechanism, which then directs the light through either the UVIS path or the IR path to the corresponding detector unit. Both the UVIS and IR detector subsystems utilize a multi stage Thermo Electric Cooler to cool the detectors to the required temperatures, as well as to radiatively isolate the detectors from the surrounding surfaces by way of actively controlled shields. The instrument has two main radiators, one to reject the majority of the electronics heat and one to reject the detector heat. Furthermore, some of the lower dissipating electronics boxes reject their heat directly to the internal surfaces of HST.

Shortly after the Columbia accident, further missions to support HST were cancelled after being deemed high risk. The WFC3 program had reached a level of maturity and had sufficient funding to complete a characterization test of the instrument, should any future HST missions be reinstated or if the instrument were to fly on another mission. This test campaign was deemed TV1 and provided the first opportunity to validate the thermal model against test behavior. The test provided many lessons learned both from test configuration as well as modeling/correlation standpoints.

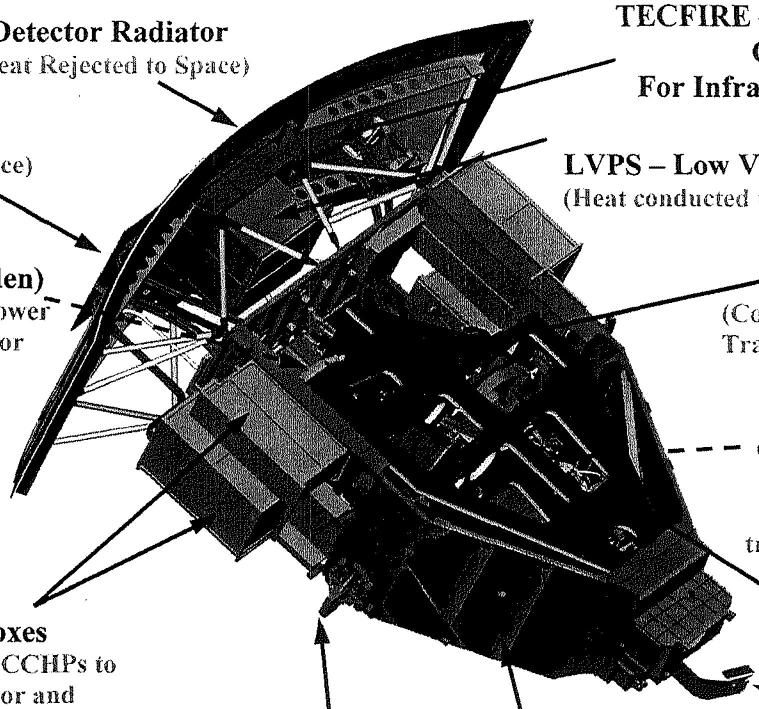

Figure 1 – Overview of WFC3 Thermal Design

WFC3 Thermal Design

WFC3 consists of two actively cooled detectors (UVIS and IR), housed inside of actively controlled uints. The detector units themselves are mounted inside a thermally controlled optical bench. The bench is structurally tied to the HST frame via low conductivity struts connected to three thermally controlled latch points. The bench itself is thermally controlled by a cold plate mounted below the bench, which is maintained at temperature by a combination of heaters and a Variable Conductance Heat Pipe (VCHP). The entire optical bench/cold plate subsystems are radiatively isolated from the surroundings by multi-layer insulation (MLI). Furthermore, the surrounding MLI is enclosed in an exoskeleton panel configuration to which the external electronics boxes are mounted. Two radiators are employed to reject the majority of the power dissipation to space: the Detector Radiator and the Electronics Radiator.

The Detector Radiator includes a network of six spreader heat pipes perpendicular to two header heat pipes to help isothermalize the radiator and increase its efficiency. Throughout the design a number of other heat pipes are used to move the heat from dissipation location to the dedicated radiators. Four major heat paths to the radiators exist: UVIS Detector, IR Detector, Optical Bench/Cold Plate, and Electronics Boxes.

The UVIS detector is a Charge Coupled Device (CCD) which is actively cooled by a 4-stage Thermo-Electric Cooler (TEC) to -83°C. Surrounding the UVIS detector is a radiative isolation shield which is cooled by 4 constant current, 2-stage TECs. The heat from these TECs is deposited on the UVIS detector baseplate, which is conductively coupled to the evaporator end of a Gas Charged Heat Pipe (GCHP). The condenser end of the GCHP is coupled directly to the Detector Radiator and rejects its heat to space.

Similarly, the IR detector consists of a Focal Plane Assembly (FPA) which is actively cooled by a 6-stage TEC to -128°C. The IR detector is housed inside a Cold Enclosure which provides a layer of isolation between the detector and the surrounding instrument surfaces. The heat from the 6-stage TEC is deposited on the baseplate of the Cold Enclosure, which is conductively coupled to the evaporator end of a flexible heat pipe. Furthermore, the top of the cold enclosure is also coupled to the evaporator end of a second flexible heat pipe. The condenser ends of these two pipes are regulated by a subsystem called TECFIRE: Thermo-Electric Cooling For Infra-Red Electronics. TECFIRE consists of 3 assemblies of six 1-stage TECs in parallel (2 for the detector baseplate: DB, and 1 for the Cold Enclosure: CE). TECFIRE provides a thermally stable interface to the condenser ends of the flex pipes and maintains -53°C for the DB and -45°C for the CE. The heat removed by the TECs as well as the power generated by the TECs to remove the heat is deposited directly on the Detector Radiator and rejected to space.

Both detectors reside inside an optical bench whose bulk temperature is maintained at 0°C nominally by a cold pate below the optical bench. The cold plate contains a constant conductance heat pipe (CCHP) embedded in the panel and a heater to help provide an isothermal, warm sink to regulate the optical bench temperature. Furthermore, the condenser end of the cold plate CCHP is coupled to the evaporator end of a VCHP, with the VCHP condenser coupled directly to the detector radiator.

Lastly, four major electronics boxes reject their heat to the Electronics Radiator or directly to the internal HST surfaces. The Main Electronic Boxes (MEB, nominally 32 W) are coupled to the Electronics Radiator via a CCHP and are coated with a low emissivity coating to minimize its radiative heat loss/gain from the internal surfaces. The Low Voltage Power Supply (LVPS) is mounted directly to the back side of the Electronics Radiator, and rejects its heat to space through the Electronics Radiator. The Detector Electronics Box (DEB, nominally 11 W) and the CCD Electronic Box (CEB, nominally 21 W) are coated with high emissivity coatings and are intended to reject their heat directly to HST.

All of the heatpipes used in the design are planar and may be ground tested if level, with the exception of the six vertical spreader heat pipes in the Detector Radiator

Test Configuration and Overview

The test was conducted in late August through mid October in 2004 in the Space Environment Simulator TV chamber at Goddard Space Flight Center. The instrument was surrounded by cryo panels on each side (top, bottom, sides, and the radiator). Separate cryopanels were maintained for the Electronics Radiator and the Detector Radiator. Furthermore, two ground cooling loops were used to compensate for the lack of functioning spreader heat pipes, with one cooling loop used to control the TECFIRE side of the radiator, and the other used to control the UVIS side of the radiator. The chamber shrouds were kept at ambient thermal conditions. An optical stimulus system was used to characterize the science performance of the camera. Three balance points were achieved: Cold Operate, Hot Operate, and Cold Safe.

After the test, an initial correlation was performed using the values measured in test. Unfortunately, due to the cancellation of the mission, the thermal team who had supported much of the modeling and test efforts up to and through the test were no longer available.

Lessons Learned

After the initial correlation effort, the model was handed off to another organization and a new team was responsible for upgrading and maintaining the model. The baseline model as received was suitable for the TV configuration only, including constant powers as measured in test. After a thorough review of the model, some major shortcomings of the test and analysis were revealed, yielding the following lessons learned:

1. Ensure that the thermal design can be tested
2. Ensure that the model has sufficient detail for accurate predictions
3. Ensure that the power associated with all active control devices is predicted
4. Avoid unit changes for existing models

Ability to Test

The use of the ground cooling loops to compensate for the non-functioning vertical spreaders masked the increase/decrease of the TECFIRE power necessary to maintain the desired setpoints. By controlling the temperature of the radiator (i.e. the hot side of the TEC), the radiator temperature was not allowed to respond to changes in the power dissipation by TECFIRE as it would in flight. Therefore, in essence, the design was tested upsteam of the radiator, but not end to end. A future test (TV2) is planned, which will not use the cooling loops but will instead allow the radiator to respond to changes in TECFIRE power.

Sufficient Modeling Detail

The model as received was also lacking in detail in the detector region, with only the outer shielding (Cold Enclosure and UVIS Housing) being represented. This made it impossible to predict the TEC power needed to cool the CCD or the IR FPA, with no thermal representation. The model was upgraded to include the detailed detector models as well as the detailed IR Cold Enclosure model and provided better representation to align with flight telemetry, where previously no representation existed. Furthermore, the inclusion of the detectors themselves allowed for the use of a SINDA routine to be developed[1] to model the response of a TEC to input boundary conditions from a thermal model. The WFC3 model was upgraded to include this capability for the UVIS 4-stage, UVIS 2-stage (constant current), IR 6-stage, and TECFIRE TECs. The actual performance curves were scaled to match the power output and performance as seen in test.

Also, the model included some artifacts of Hot/Cold biasing that were not removed during the initial correlation. These included the use of degraded optical properties for the internal optical bench coating and the use of different gas charges in the GCHP for hot and cold. The hot case included twice as much gas charge as the cold case. Consequently, the hot case predicted a warmer UVIS (more of the pipe shut down) and the cold case predicted a colder UVIS (less of the pipe shut down). Assuming the actual gas charge was the average of these two values yielded good agreement with the test data.

The use of constant power heaters also neglected important changes in the thermal control system when the input voltage was not regulated. Two heaters, one on the UVIS Window (often referred to at the 25 W heater) and one on the IR Cold Enclosure (often referred to at the 40 W heater) were both powered off of unregulated voltage. In reality, both heaters had very similar resistances with the 25 W heater measuring 25 W at 24 V, and the 40 W measuring heater being 40 W at 28 V. Therefore, the use of constant heater power in the thermal model should be avoided unless the power feed is coming from a regulated supply. The WFC3 model was upgraded to provide power based on a V^2/R relation.

Ability to Predict Power

The inability of the original model to predict TECFIRE power also masked possible controllability problems. The flight model only estimated a steady state TECFIRE power based on the hot side temperature, control setpoint, input heat load, and characteristic TEC performance curves. This was done in an external model and the results imported simply as a constant power for flight predictions. This completely neglected the dynamically changing flight environment and the radiator responding both to environmental loading changes and TECFIRE power to maintain control.

The TEC performance curves should also be compared to measured data, as it was found that many of the vendor TEC performance curves were very conservative, predicting the maximum amount of power needed to achieve a particular temperature. While this is good for bounding a problem, the realistic values should be used in a correlated model. For the UVIS 4-stage TEC, and improvement of about 5% was needed, and for the IR 6-stage, an improvement of about 8% was needed. Conversely, the TECFIRE performance curves actually needed to be degraded by 5% (to 95% of nominal) to match test data. Further subsystem testing for the requalification of the unit to lower operating temperatures showed that the actual voltage needed by the TEC was higher than the vendor supplied data and confirmed the necessary degradation.

Furthermore, the actual LVPS dissipation is based on the power dissipated by the numerous components for which it provides a constant voltage and the device dependent efficiency for the voltage conversion. Using the test values for flight instead of dynamically predicting the LVPS power as a function of the power dissipations of its components neglected the dynamic response of the system to changing thermal environments.

The LVPS dissipation from test is not a directly measured value, but rather a spreadsheet derived value based on the hold power and the sum of component associated losses due to the efficiency of the converter. The loss for each component is based on ($P/\varepsilon - P$), with the sum of these terms being the LVPS dissipation. This value was compared back to the total power coming in to the LVPS (I*V) minus the power dissipated by each of the devices. Some of the derived efficiencies for the heaters, which were not characterized at a subsystem level, were incorrectly derived. This occurred because the predicted power was based on an average but the actual measured component from test data was the full heater power. This led to incorrect powers being calculated in the spreadsheet for the LVPS dissipation in the Cold Safe case, and consequently poor correlation for the affected components.

A relation was also identified between efficiency and voltage, which was not previously characterized. Under similar conditions, the power dissipation estimated for the LVPS was 55.9 W at 28V and 61.7 W at 32 V, even though the component dissipations of all connected devices were nearly identical. This led to a correction factor of 94% begin applied to the all efficiency terms under the assumption that power losses (i.e heat dissipation) would be greater when going from 32 V to a constant voltage than from 28 V to the same constant voltage. This factor produced good agreement between temperatures and powers at the two different points in the test. Furthermore, a special dedicated portion of the future TV2 test is planned to gather data to characterize the efficiency of each device independently at three different voltages.

Unit Changes

With the cancellation of HST missions, the HRSDM (Hubble Robotic Servicing and Deorbit Mission) was proposed. This new mission levied new requirements on the models in terms of the acceptable units to be used. Unfortunately, these did not coincide with the current legacy models and significant manual effort was spent to convert the model to be compliant. Unfortunately, while the only affected unit was time (hours to seconds), the sheer number of capacitance locations that needed to be updated, made this effort prone to human error. Further exacerbating the situation was the use of the original model under steady state, constant environment test conditions. Once the model was updated for flight, unexpected behavior (extremely stable) was predicted. Further debugging efforts revealed an incorrect 3600 factor applied to the radiator, making it 3600 times heavier than in actuality. This resulted in a very slow response to any changes in environment. This error could have easily been avoided by the newer mission conforming to the existing set of units rather than vice versa.

Conclusions

Some significant shortcomings of the WFC3 model were eliminated resulting in the ability of the model to predict and respond to a dynamically changing thermal environment. These updates allowed for design modifications to be made where previously the model would have been incapable of predicting the effect of the changes. The inability of the design to be ground tested will likely continue to be a challenge during TV2, but at a minimum the system will be able to respond to the environment and the design can be tested end to end. The improvements in the model fidelity and the ability to predict the power of the various active control devices also provides a better understanding of the power consumption needs and thermal behavior once in flight to ensure mission success.

Acronyms

HST	Hubble Space Telescope
WF/PC-II	Wide Field Planetary Camera II
WFC3	Wide Field Camera 3
TV	Thermal Vacuum
TEC	Thermo Electric Cooler
GCHP	Gas Charged Heat Pipe
CCHP	Constant Conductance Heat Pipe
VCHP	Variable Conductance Heat Pipe
UVIS	UltraViolet Visible
CCD	Charge Coupled Device
IR	InfraRed
FPA	Focal Plane Assembly
TECFIRE	Thermo Electric Cooling for InfraRed Electronics
DB	Detector Baseplate
CE	Cold Enclosure
LVPS	Low Voltage Power Supply
MEB	Main Electronics Box
DEB	Detector Electronics Box
CEB	CCD Electronics Box
SINDA	Systems Improved Numerical Difference Analyzer

References

1. "Development of a Thermo-Electric Cooler Simulation Routine for the Wide Field Camera 3 Thermal Model", H. Peabody, R. Stavely, and D. Maidt, SAE Paper 2006-01-2114 from International Conference on Environmental Systems

2. "Lessons Learned from Wide Field Camera 3 Correlation Effort for TV1 Test" presentation, H. Peabody, R. Stavely, B. Bast, Spacecraft Thermal Control Workshop 2007

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