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Surface Water Ocean Topography Ka-band Radar Interferometer Payload Thermal Design Challenges

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The proposed Surface Water Ocean Topography mission would be a joint NASA/CNES mission with a launch baseline in 2020. This would be the first mission capable of precise measurements of continental water levels (lakes, rivers) as well as improving knowledge of ocean topography which ultimately would aid in climate modeling and predictions. The primary instrument, the Ka-band Radar Interferometer, includes stringent requirements in order to meet the primary mission science goals. Two features that would drive the thermal design are large electronics dissipation (1 kW range) that would need to be co-located and tight temporal stability requirements (<0.05°C/min) in a low earth orbit environment. This has led to a thermal architecture involving high-conductance thermal pallets and loop heat pipes in order to transport the waste heat as well as working closely with Systems and Mechanical engineering teams to ensure both flight attitudes and strategic placement of radiators would be able to help meet the thermal stability requirements. Design trades are being conducted to optimize the thermal architecture given the flight system resource constraints. Risks have also been identified along with mitigation plans, one of which is a testbed developed to validate that the requirements could be met.

Nomenclature

CCHP	=	constant conductance heat pipe
CNES	=	French National Space Studies Center (Centre National D'Etudes Spatiales)
DAQ	=	data acquisition system
ERBS	=	Earth Radiation Budget Satellite
IR	=	infrared radiation
KaRIn	=	Ka-band Radar Interferometer Instrument
K-PLM	=	KaRIn Payload Module
K	=	Kelvin
Km	=	kilometers
kW	=	kilowatt
LHP	=	loop heat pipe
min	=	minute
mK	=	mili-Kelvin
NASA	=	National Aeronautics and Space Administration
PID	=	proportional-integral-derivative
PRT	=	platinum resistance thermometer
STEM	=	Simple Thermal Environment Model
SWOT	=	Surface Water Ocean Topography mission
TC	=	thermocouple
TES	=	Tropospheric Emission Spectrometer
TESTSTEM	=	Simple Time Series Test Program
WCC	=	worst case cold
WCH	=	worst case hot
WG	=	waveguide

I. Introduction

THE proposed Surface Water Ocean Topography (SWOT) project would be a joint National Aeronautics and Space Administration (NASA) and French National Space Studies Center (CNES) mission with a launch

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baseline for 2020. The primary focus would be to produce precise measurements of land hydrology and ocean circulation at spatial resolutions between 15 and 200 km. These measurements would aid the determination of the global continental surface water inventory (lakes, reservoirs, wetlands, and large rivers) and provide oceanic circulation measurements at a scale that is currently not available. The combined data set would be used to generate a global assessment of surface water resources and detailed ocean process mapping, all of which ultimately could be used for climate modeling.

There are six proposed payloads including an altimeter, microwave radiometer, global positioning systems, and a laser retroreflector. The primary payload would be the Ka-band Radar Interferometer (KaRIn) which would make swath measurements to measure the surface elevations of water bodies. In order to achieve the primary science proposed for SWOT, there are many design challenges for the engineering team to accommodate in the KaRIn design. Thermally, the main drivers would be large electronics dissipation (1kW range) that must be co-located while also maintaining tight temporal stability requirements (<50 mK/min) in a low-earth environment.

II. KaRIn Requirements

KaRIn would have three major components in its hardware chain, the reflectarray, the feeds, and the electronics package. The reflectarrays on KaRIn would be sets of panels with elements that direct the radar waves to/from the feeds. Due to this interaction they must be precisely aligned with their respective feeds. The feeds, which transmit and receive the radar signal, would be connected to the receive and transmit electronics via waveguides (WGs). There would be ten electronic boxes connected with a multitude of coaxial cables and WGs that all need to have their length minimized to reduce signal quality loss in order to achieve the primary science goals. Therefore, all the electronics must be co-located in a compact design and in-line with the feeds and reflectarrays as depicted in Figure 1.

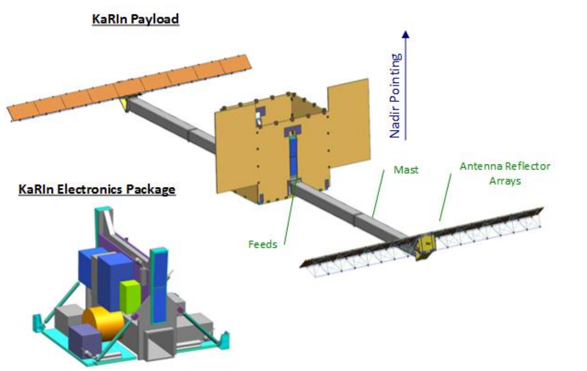

Figure 1. Proposed KaRIn hardware configuration.

The co-location requirement of the hardware had two major configuration impacts. The first was that in order to spatially fit all of the electronics into a compact arrangement, the boxes would have to be distributed among four separate pallets so that they would not have to be spread out in-plane with each other. The second was that the electronics would have to be in-line with the feeds and antenna arrays and therefore would have to be located in the middle of the KaRIn Payload Module (K-PLM), as opposed to mounted directly to a radiator panel.

The thermal stability requirement is based on a decomposition of the overall phase error the instrument can tolerate in order to meet the primary science objectives. KaRIn surface water height measurement accuracy is directly proportional to phase. However, instrument electronics-based phase shift can be induced by thermal fluctuations and therefore affect the measurement quality. In order to determine a thermal requirement, an integrated phase error that could be tolerated over all frequencies of interest were calculated and then normalized over a one minute period, leading to the <50mK/min requirement.

III. KaRIn Thermal Design

The most challenging thermal design requirement would be meeting the temporal stability requirement of <50 mK/min coupled with the additional constraints of co-location and high electronics waste dissipation (>1kW). Typical spacecraft have stability requirements on the order of 1 K and basic approaches to meet temporal stability requirements are to isolate the components requiring the tight stability from environmental changes as much as possible and then use thermal capacitance and conductance to meet the stability requirement[1]. While a total dissipation of approximately 1kW for a single payload is large, it is not uncommon for terrestrial based spacecraft. Individually, these three design constraints (temporal stability, co-location, large dissipation) have all been successfully achieved by many previous projects; KaRIn's thermal architecture would have the challenge of accounting for them simultaneously.

A. Thermal Architecture

The basic thermal architecture for KaRIn would involve four thermal zones controlled by dedicated loop heat pipes (LHPs). The four zones are a direct result of the electronics' hardware configuration being split into four separate pallets but it has the advantage of breaking the total power into separate zones. Each pallet would be an individual zone with a dedicated LHP. The LHPs would transport the heat from the thermal pallets to the space facing radiators. Alternative methods were investigated to transport the heat, but the large distances and heat transport needs made simple methods such as conductive links impractical. Another factor that made LHPs an attractive heat transfer method was the ability to shut down the thermal transport capability with minimal heat input for survival and off conditions. Figure 2 is a representation of the hardware configuration within the K-PLM.

With each thermal zone (thermal pallet) on the order of 1 m in length and the only heat sink for the thermal pallet at the end with the LHP evaporator, it was determined that a simple plate could not transport the necessary heat loads efficiently enough due to the thermal resistance of the plate. Simple metal plates, high conductivity carbon fiber composites, and k-Core™ (encapsulated annealed pyrolytic graphite system) were considered, but they all were mass and/or cost intensive/prohibitive in order to achieve the desired performance. During this trade, it was determined that the best configuration was to use embedded constant conductance heat pipes (CCHPs) within the thermal pallet which provided a moderate cost solution with relatively low mass. A first-order study was done to compare using an aluminum honeycomb pallet versus a light-weighted aluminum pallet, both with embedded CCHPs. It was determined that the thermal conductance of the light-weighted aluminum pallet was about a factor of two better when comparing approximately mass equivalent configurations, primarily due to the added thermal resistance of the honeycomb core. Additionally, there would be less adhesive paths between the heat source (electronics box) and heat sink (CCHP). Figure 3 is a cross section of the thermal pallet configuration.

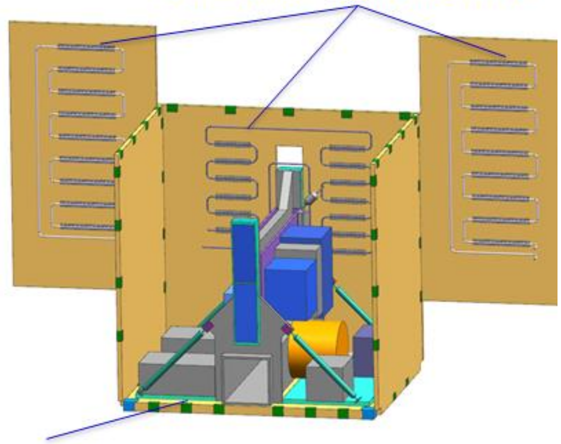

Figure 2. K-PLM layout with representative thermal hardware configuration.

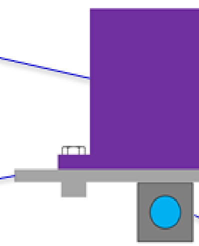

Figure 3. Cross section of thermal pallet showing representative configuration.

The system-level thermal architecture is shown in Figure 4 for the K-PLM. The architecture could be summed as electronics mounted to a light-weighted aluminum pallet with embedded CCHPs that would transport the electronics waste heat to a LHP evaporator. The LHP would transport the electronics waste heat from the evaporator to the condenser lines which would then be bonded to a radiator panel on the K-PLM structure. The radiator panel would be coated with a thermal control surface and the remainder of the K-PLM structure would be covered with MLI.

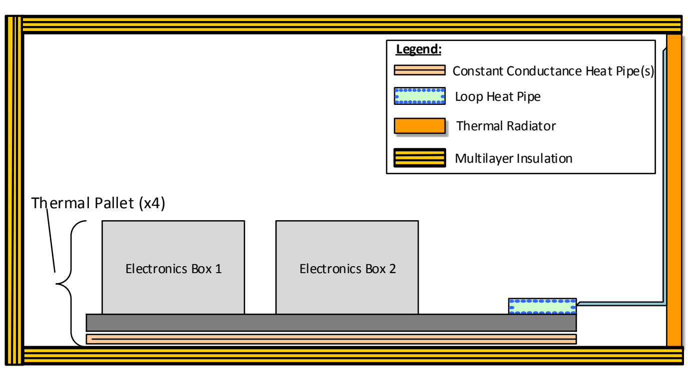

Figure 4. KaRIn system-level thermal block diagram.

B. Verifying Requirements and Key Challenges

The primary requirements are to ensure the hardware would remain within their respective temperature limits for a 1 kW payload and maintain a temporal stability of <50 mK/min. Meeting the absolute temperature requirements is a standard design problem involving sizing the radiators appropriately for the heat load and given environment extremes. The non-standard temporal stability requirement would require careful attention and analysis to validate the thermal architecture does indeed meet the requirements.

Although hundreds of LHPs have been flown and proven their capability to transport large heat loads long distances, there are no documented cases of using LHPs in a configuration where stability to less than a few degrees Celsius would be a primary concern. Furthermore, there are studies showing oscillatory temperature performance of LHPs when subjected to various conditions[2,3]. This led the SWOT project to invest in a LHP testbed to validate whether the proposed SWOT specific conditions could result in LHP performance that could violate the <50 mK/min stability requirement.

IV. Thermal Environment

Understanding the thermal environmental factors is key to verifying the requirements could be met. The nominal orbit of the SWOT mission is currently proposed at 77.6° inclination with an orbital altitude of 891 km and precesses through the full range of beta angles (-90° to +90°). This results in the spacecraft going through periods of eclipse which could be a large environmental factor that causes temporal swings. To provide the most stable environment possible, the mission orbital design would execute a yaw flip at Beta 0° in order to maintain an anti-sun orientation at all times on a preferred surface. With an anti-sun orientation for the radiators, the major influence on thermal stability would be Earth effects, namely Earth infrared radiation (IR) and albedo.

Typical design approaches utilize worst case parameters for Earth IR and albedo for hot and cold case analysis. Oftentimes a detailed thermal analysis will specify an Earth IR value for the light and dark side of the earth at the subsolar and anti-subsolar points and then integrate the value over the orbital positions and specifying albedo versus latitude to account for increases due to snow/ice coverage, cloud cover and decreasing solar-elevation angle[1]. While this approach works for capturing worst case hot (WCH) and worst case cold (WCC) environments, it does not necessarily capture the worst case transient thermal environment due to Earth affects. Both Earth IR and albedo can be highly variable factors since they are based on ever changing and coupled variables such as cloud cover and local surface temperature.

Using WCH/WCC analysis is standard practice for sizing radiators and the overall thermal subsystem. However, because the proposed SWOT mission would have tight temporal stability requirements and because there have been studies showing LHPs can have instabilities in certain operating regimes, it was deemed important to make a focused effort to determine a worst case disturbance scenario (based on current best estimates of mass, dissipations, and maximum environmental disturbance) and how it would apply to the SWOT thermal architecture.

Ideally, a large set of flight data with the exact orbital conditions would be the best resource to determine the worst case transient loads due to Earth environmental effects. Unfortunately, this type of data is not readily available. However, the Earth Radiation Budget Experiment collected a series of data specifically to collect regional and global measurements of Earth IR and albedo energy. This data was later analyzed, compiled, and used as the dataset for two developed programs called “Simple Thermal Environment Model” (STEM) and “Simple Time Series Test Program” (TESTSTEM) by the Environments Group of the NASA Marshall Space Flight Center[4,5].

For the proposed KaRIn instrument, the primary concern is the largest transient pulse of the thermal environment with respect to managing the temporal stability requirement. One of the output selections in the TESTSTEM program is to output the post-processed flight data. Using an available sample of 13 profiles included with STEM/TESTSTEM from the Earth Radiation Budget Satellite (ERBS; 57° inclination, 610 km altitude) outputs of time-series Earth IR and albedo were generated. This data was manipulated to generate a time-series effective sink temperature for the KaRIn radiators and interpolated to get uniformly spaced data points at 1 min intervals (raw data time intervals were approximately 0.3 min). A sink temperature rate of change per 1 min time period was then generated for each series and the maximum value for the entire data set was extracted. One observation was that the maximum rate of change did not change when comparing sink temperatures based on Earth IR only versus Earth IR and albedo combined. This is reasonable given the thermal-optical properties for the SWOT thermal radiators were chosen to maximize long wave radiation over short wave since direct solar was not a concern due to the optimized radiator pointing. For modeling purposes, this lends to a strategy that focuses on including higher resolution Earth IR values over albedo where stability is concerned. The maximum instantaneous sink temperature rate of change over a 1 min period from the sampled ERBS data was 7.9 K. This is almost a factor of two larger than what was originally calculated when specifying an Earth IR value for the light and dark side of the earth and then integrating the value over the orbital positions.

The next step was to quantify appropriate pulse duration. Figure 5 shows a snapshot of the analyzed ERBS data focusing on the three largest rate-of-change pulses. The largest temperature rate-of-change generally lasts no longer than three minutes. A conservative bounding testing/analysis value is 8 K/min over a 3 min period.

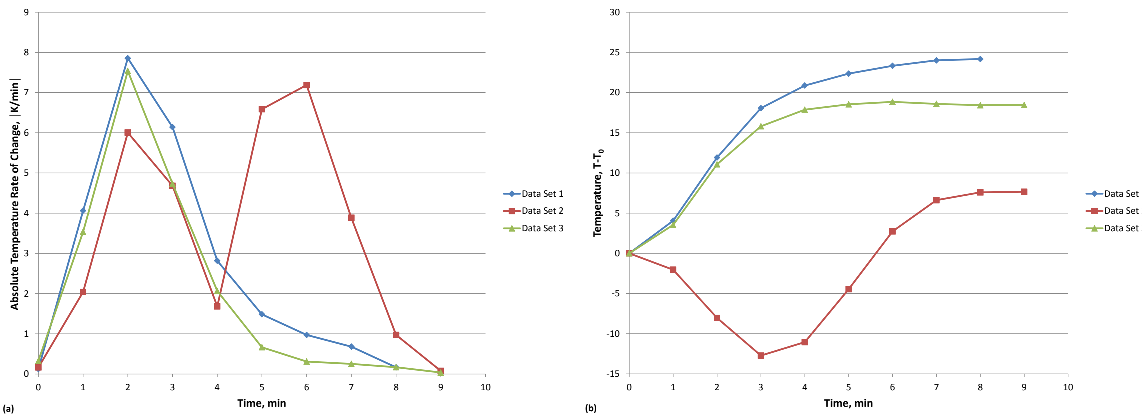

Figure 5. (a) Absolute maximum effective sink temperature rate of change per one minute period pulses for three different data sets and their respective (b) temperature profiles.

V. Testing and Analysis

A. Preliminary Studies and Lessons Learned

During the conceptual design, the main focus has been verifying that the proposed KaRIn instrument would have the proper architecture to meet the performance requirements, particularly the temporal stability. In the conceptual studies phase of the project, the assumption was that the thermal design should be able to withstand a transient thermal environmental pulse of 4 K/min over a 3 min duration. This was based on model results using an integrated dark/light side Earth IR and latitude based albedo profiles as discussed in section IV. Thermal modeling showed the thermal mass of the system would be sufficient to damp the electronics transient response to maintain the <50 mK/min requirement. Even with the updated worst case transient of 8 K/min over a 3 min duration, analysis still showed that the thermal mass of the system would be sufficient to meet the temporal stability requirement. The only threat remaining is whether the two-phase hardware between the thermal sink and the electronics could cause instability due to their performance nature[2,3]. Careful design reviews with experts regarding proposed KaRIn configuration and thermal environment concluded that LHP induced instability would be low-risk. To verify, a test campaign was formulated. A multi-phase test approach was taken with a contingency third phase. The first phase (Step 1) was primarily a discovery phase to determine the best test setup, become familiar with LHP operation, and get the proper infrastructure in place. The second phase (Step 2, current) is the primary test that will be used to verify the requirements. The third phase (Step 3, contingency) is reserved in the event that further modification of the baseline architecture is required to meet the stability requirement.

The hardware basis for the Step 1 setup was an engineering model (Figure 6) from the Tropospheric Emissions Spectrometer (TES) instrument which was launched in 2004. Although the Step 1 LHP differs from the proposed SWOT LHP significantly with respect to size (max load of 45 W), it was deemed adequate to get introductory experience with LHPs and to get the necessary components in place for the testbed. This included a heat exchanger, thermocouples, a platinum resistance thermometer (PRT), heaters, an instrumentation rack, data acquisition (DAQ) system, recirculation bath, and a purge system, as shown in Figure 7.

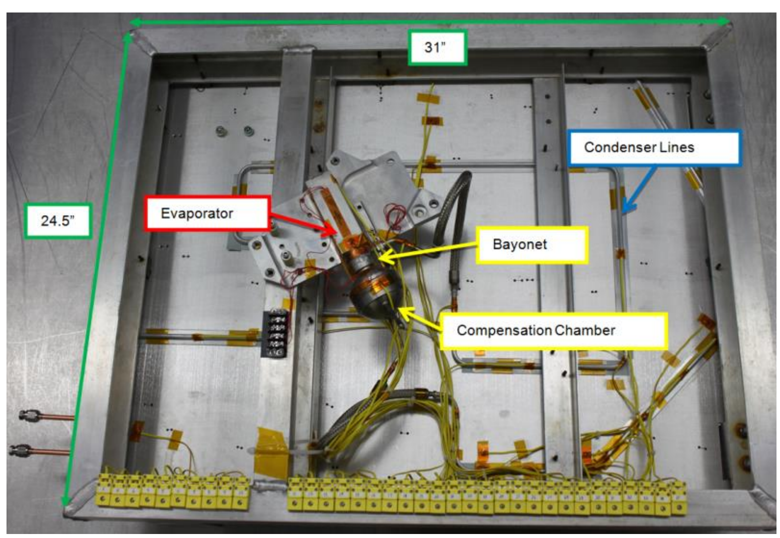

Figure 6. TES LHP Engineering Model modified for SWOT LHP Step 1 testbed.

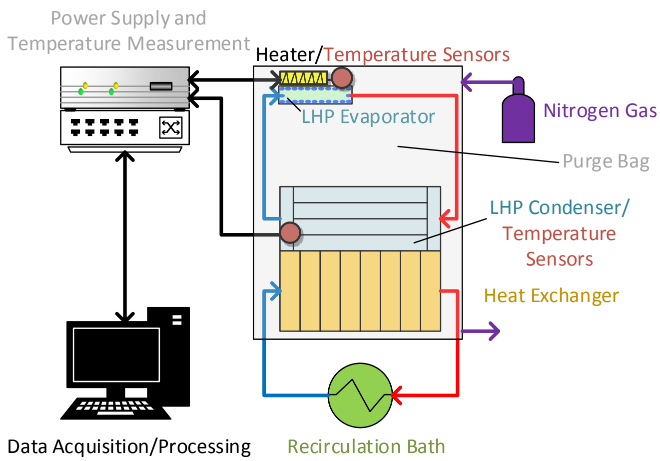

Figure 7. Step 1 testbed configuration.

The heat exchanger was a simple bonded copper tube to aluminum plate. The heat exchanger was then bolted to the condenser lines with interface filler between the condenser line flanges and the heat exchanger. While simple in design and performance, it was sufficient for the intended purposes. The entire setup was well instrumented with thermocouples (TC). Particular clustering was focused on the LHP compensation chamber, evaporator, and the condenser with a dense clustering on the end of the condenser line in order to try to visualize the vapor front during testing. A reference PRT was included as a comparison against the TC noise in the measurement system. The LHP already contained heaters on the compensation chamber and evaporator. The instrumentation rack consisted of two power supplies, one for the evaporator and one for the compensation chamber, and a data logger. The DAQ was built in LabVIEW that interfaced with the data logger and had the capability of plotting and displaying any combination of temperature and heater power channels. With the baseline test approach of controlling the condenser temperature profile with the heat exchanger, a precision recirculation bath with a resolution of ±0.01 K was hooked up to the Step 1 heat exchanger. Finally, a purge bag was built around the hardware and connected to a regulated gaseous nitrogen line in order to minimize condensation during testing dwells below ambient.

The primary results and lessons learned from the Step 1 testbed were the setup of the DAQ, recirculation bath/heat exchanger setup/operation, determination of sensor accuracy, environmental profile of testbed ambient environment, and a preliminary look at LHP stability in response to a transient condenser sink.

1. DAQ

The DAQ configuration and design went through a number of iterations to determine an efficient, user-friendly setup. The primary features included a graphical display for ease of temperature spatial distribution and performance, ability to plot and/or display any combination of sensors, and output a data file in a format that easily imports to spreadsheets with time stamped comments for test documentation.

The DAQ will be updated to interface with the new setup. This includes expanding the sensor input capacity and displays. A feature is planned to output real-time temporal stability results for a quick-look understanding of performance.

2. Recirculation Bath/Heat Exchanger

The original intent of the recirculation bath/heat exchanger configuration was to use the built-in proportional-integral-derivative (PID) controller of the chiller to precisely control the LHP condenser. Upon operation, it was realized that the thermal mass of the system was incompatible with the control authority of the recirculation bath and proper PID tuning was not achievable in order to impart desired transient profiles. To overcome this deficiency, maximum rates-of-change tests were performed by running the heating or cooling component of the recirculation bath at maximum performance. It was determined that the current setup could be ramped a maximum of 0.3 K/min (with a 45 W load) in a conductively coupled configuration to the LHP condenser. This was one third the target ramp rate of 1 K/min which was determined to be an equivalent test conductive coupling to the flight radiative transient sink temperature. Note that at the time of Step 1 operations, the assumed maximum rate of change of the sink temperature was a radiatively coupled 4 K/min.

The Step 1 testbed highlighted the deficiencies of both the planned approach and hardware. It is assumed that while the recirculation bath was capable of maintaining an internal fluid reservoir temperature, it did not have sufficient capability to control a large external system. This was despite the heat load ratings advertised by the manufacturer which did not specify configuration conditions for the rating.

The baseline Step 2 configuration has been reformulated to use a much larger recirculation bath controlling a heat exchanger to a constant cold-biased set-point of the fluid temperature. A custom, aluminum brazed, heat exchanger that can handle a wide range of temperatures (77 to 360 K) and cooling fluids is in fabrication. An interface plate between the heat exchanger and the LHP condenser will be used to control the sink temperature transient profiles using precision controlled heaters. However, further planning and investigation on how best to drive the thermal transients onto the LHP to mimic flight conditions is underway and may yield a different testing method and architecture. Careful consideration is being placed on ensuring all the differences between flight and test are considered and accounted for. This includes differences between LHP condenser thermal mass, evaporator side thermal mass, condenser line liquid length, total heat load transported, and thermal resistance between heat source, LHP fluid, and thermal sink.

3. Temperature Sensors

While TCs are not known for low noise operation, their low cost and ease of installation and integration made them an attractive choice for the Step 1 testbed. With a requirement of <50 mK/min on a timescale of one minute, a measurement stability period of 30 sec was chosen as the measurement resolution minimum. A stability study was conducted for the Step 1 setup by comparing a TC output against an adjacent PRT output. The two sensors were bonded to the LHP condenser and the recirculation bath was set to a constant 298 K. The results of the study showed that the raw TC data was too noisy (0.06 K/min), with both high frequency and low frequency fluctuations, for requirements verification. The period of the low frequency fluctuations was on the order of 500-800 seconds which was much larger than the desired 30 sec measurement stability criteria established, eliminating data smoothing as an option. The raw PRT sensor fluctuations were 0.006 K/min, almost an order of magnitude smaller than the 50 mK/min stability requirement to be verified. For Step 2, PRTs are planned for any critical measurement area with regards to requirements verification. However, TCs would supplement in non-critical areas to compliment the instrumentation due to their low-cost and ease of implementation and data acquisition.

4. Ambient Environment

During a long term quiescent ambient test, it was determined that the overall environmental variation was 0.002 K/min as determined by the smoothed data of both the PRT and TC data. The observed environmental variation is negligible in comparison to the much larger transient pulses planned (8 K/min) and therefore is an acceptable ambient environment to test the LHP stability. However, access to a high precision environment (0.01 K) is available and if necessary can be utilized.

5. Initial Stability of LHP Evaporator

While the Step 1 configuration did not have the fidelity to accurately test stability in a flight-like manner due to the many variables needing reconciliation (heat load, mass, thermal sink coupling, liquid-phase condenser line length) a test was conducted for operational experience. The results showed that a 0.3 K/min conductively coupled sink temperature ramp rate on the LHP condenser produced a 0.1 K/min ramp rate at the LHP evaporator. While this clearly does not meet the stability requirement, it was an expected result primarily due to the LHP evaporator temperature measurement being taken directly on the evaporator which was not connected to any additional thermal mass. More importantly, this sink temperature pulse did not cause any unexpected instability on the LHP performance which this essentially massless configuration is more susceptible to. As discussed in Section V.A., analytical calculations show the thermal mass of the system is sufficient to damp the worst case transient pulse and that the primary threat is inherent LHP performance instabilities. While the worst case pulse has yet to be tested, these results are leading in the correct direction.

The final Step 2 setup will have a flight-like thermal mass and conductive path between the control point and the thermal sink and the initial presumption is this would be sufficient to dampen the worst case disturbance scenario. As indicated in section V.A.2., a comprehensive study is currently underway to determine the best test approach to represent the planned flight architecture using the Step 2 testbed hardware and configuration.

B. Current/Future Studies

In order to verify the proposed KaRIn temporal stability requirement, the Step 2 testbed will undergo extensive testing and development of the testbed is currently underway. A LHP capable of transporting 450 W has already been procured and delivered to the project. An integration frame has been built and configured to the Step 2 LHP so that it can be supported on a gear driven tilt/rotate cart. This would allow for adverse tilt/elevation testing which is important characterization data for SWOT given there would be multiple testing orientations on the ground at system level.

A breadboard thermal pallet with embedded CCHPs would be integrated to the LHP evaporator in order to get a representative end-to-end configuration similar to flight. Detailed testing would be conducted in ambient to characterize responses to adverse orientations, transient sink temperatures, and varying power levels. The test campaign would end with performance verification in a vacuum environment. In the event that the temporal stability requirement cannot be met with the baseline architecture, the Step 3 contingency testbed would be used to determine what other technologies could and should be leveraged to help meet these requirements. This could lead to the addition of thermal mass, active thermal control of the LHP, addition of phase change material, or other to-be-determined techniques.

VI. Conclusion

Although there is significant work to be done for a successful thermal subsystem design for the proposed SWOT project, the progress to date is in-line with the development schedule. The baseline configuration and architecture would be able to meet the absolute temperature requirements. Initial analysis shows that the system has enough mass to handle peak thermal sink fluctuations. The Step 1 testbed results, while not conclusive, show that no additional LHP instability characteristics were observed when a disturbance was applied to the LHP condenser connected to a low mass LHP evaporator system. Of key importance would be the verification of the temporal stability requirement which should come from the Step 2 testbed results which is scheduled to complete in 2015.

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