

Cooling Technology for Large Space Telescopes

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Abstract - NASA's New Millennium Program funded an effort to develop a system cooling technology, which is applicable to all future infrared, sub-millimeter and millimeter cryogenic space telescopes. In particular, this technology is necessary for the proposed large space telescope Single Aperture Far-Infrared Telescope (SAFIR) mission. This technology will also enhance the performance and lower the risk and cost for other cryogenic missions. The new paradigm for cooling to low temperatures will involve passive cooling using lightweight deployable membranes that serve both as sunshields and V-groove radiators, in combination with active cooling using mechanical coolers operating down to 4 K.

The Cooling Technology for Large Space Telescopes (LST) mission planned to develop and demonstrate a multi-layered sunshield, which is actively cooled by a multi-stage mechanical cryocooler, and further the models and analyses critical to scaling to future missions. The outer four layers of the sunshield cool passively by radiation, while the innermost layer is actively cooled to enable the sunshield to decrease the incident solar irradiance by a factor of more than one million. The cryocooler cools the inner layer of the sunshield to 20 K, and provides cooling to 6 K at a telescope mounting plate. The technology readiness level (TRL) of 7 will be achieved by the active cooling technology following the technology validation flight in Low Earth Orbit.

In accordance with the New Millennium charter, tests and modeling are tightly integrated to advance the technology and the flight design for "ST-class" missions. Commercial off-the-shelf engineering analysis products are used to develop validated modeling capabilities to allow the techniques and results from LST to apply to a wide variety of future missions. The LST mission plans to "rewrite the book" on cryo-thermal testing and modeling techniques, and validate modeling techniques to scale to future space telescopes such as SAFIR.

I. MISSION OVERVIEW

Space provides a unique vantage point for telescopes used in infrared astrophysics. To take full advantage of the space environment, it is necessary to suppress the self-emission of the telescope by cooling it to 4-6 Kelvin (K). In the past, these low temperatures were achieved using stored cryogenics, such as helium or hydrogen. Stored cryogenic systems are

incompatible with the design and lifetime requirements of large far-infrared (IR) observatories: they are large, cumbersome to incorporate into an observatory, require special launch and early operations procedures, and ultimately limit the useful lifetime of the instruments. The new paradigm for cooling to low temperatures will be cryogen free. It will involve passive cooling using light-weight deployable membranes that serve both as sunshields and V-groove radiators, in combination with active cryogenic coolers providing temperatures down to 4 K. The sunshield inner membrane layer must reach ~15 K and exhibit low surface emissivity. Passive cooling alone cannot reach these temperatures under the conditions required for far-IR observatories so a new technological solution is required, Fig. 1.

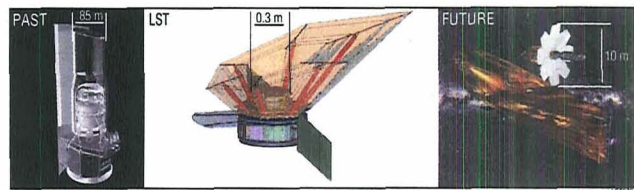


Fig. 1 LST is a bridge for cryogenic technology for future space missions

The science goals for SAFIR and similar far-IR missions require that the telescope be cooled to 4-6 K. The exact temperature requirement depends upon the detailed science goals, and on assumptions of instrument design, but a 4-6 K temperature range is generally accepted [1]. Cooling the telescope to this temperature range permits improved performance in two ways: (1) smaller telescopes or shorter integrations can be employed, Fig. 2, and (2) decreased background noise allows detection of weaker signals, Fig. 3. [DMM1]

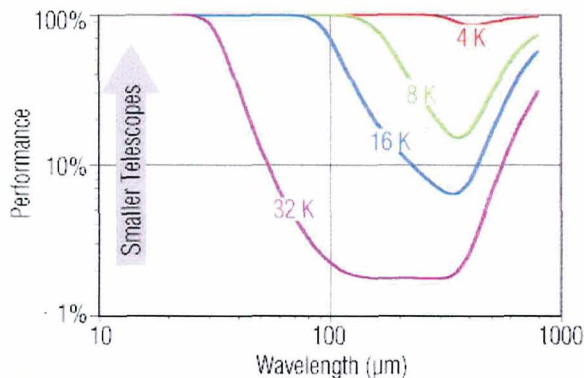


Fig. 2 4K telescopes can be much smaller for non-photon-limited objects.

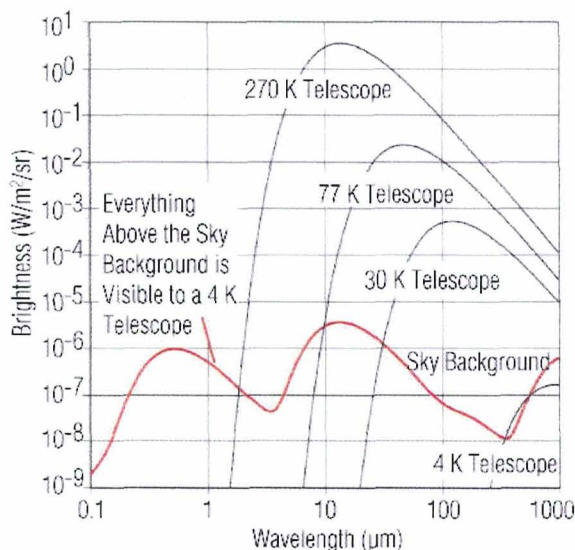


Fig. 3 4K is necessary to see the faintest objects.

A number of very successful astronomical missions have employed stored cryogenics to directly cool telescopes, among them the InfraRed Astronomy Satellite (IRAS, 1983), the Cosmic Background Explorer (COBE, 1989), the Infra-Red Telescope in Space (IRTS, 1994), and the Infrared Space Observatory (ISO, 1995). The Spitzer Infrared Observatory (2003), the first to cool a mirror located outside the main cryogen dewar to save mass, is an exquisitely engineered liquid helium cooled telescope. Yet, for a 4 to 5 year projected on-orbit life, it requires a 360 liter dewar and 237 kg of cold mass to cool a 0.85 meter diameter telescope to 5.5 K. Cooling by the helium vapor provides only 6 mW at this temperature and only 26 mW at the next warmer stage (24 K). This type of system cannot be reasonably scaled up to the much larger 3.5 m Japanese mission, SPICA, 10 m SAFIR, the two 4 m Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), or to the telescopes for the Space Infrared Interferometric Telescope (SPIRIT), Survey of Infrared Cosmic Evolution (SIRCE), and Cosmic Microwave Background Polarization (CMB-Pol) missions. Two technologies, alone or in combination as required, are envisioned

as substitutes for stored cryogen systems in the future: passive cooling and mechanical cryocoolers. The power of the new technology proposed by LST is reflected in cost and mass savings; for example, using lightweight passive shields and a cryocooler rather than rigid metal shields and a helium dewar, Spitzer's mass could have been reduced by at least 25%.

The New Millennium Program (NMP), managed by the Jet Propulsion Laboratory/California Institute of Technology (JPL), selected actively cooled sunshields as a system-level technology to be matured through a Phase A study under Space Technology 9 (ST9). The LST team, comprised of industry and government team members, was chartered to advance the technology from a minimum of Technology Readiness Level 3 through TRL 4 and prepare a system-level flight validation concept to fly in LEO. The government study team consisted of members from the NASA Goddard Space Flight Center (GSFC) and JPL. For the active cooling technology, Lockheed Martin was selected to provide a high performance deployable sunshield with one or more actively-cooled layers that will significantly reduce the thermal emissions impinging on the payload. Northrop Grumman was selected to provide a mechanical two-stage cryocooler with the capability to generate greater than 150 mW of continuous active cooling at less than 25 K to cool the cold-side layer of the sunshade, and greater than 20 mW of continuous active cooling at less than 15 K for cooling of a telescope mount plate. The LST ST9 flight concept experiment is shown in Fig. 4. LST will be the first flight of this two-stage pulse-tube/Joule-Thompson 6 K mechanical cryocooler and a lightweight membrane sunshield/V-groove radiator.

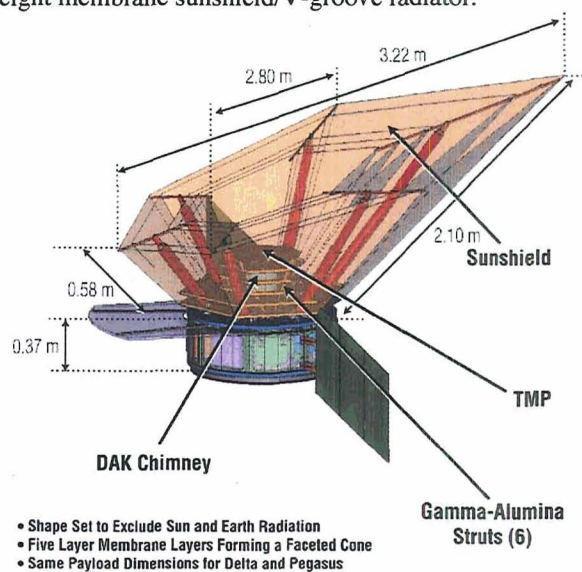


Fig. 4 LST ST9 Flight Configuration.

Technology readiness levels describe increasing levels of technological maturity as an advanced technology progresses from an initial idea to a flight-quality device. The NMP assigned Technology Review Board members to provide an

independent assessment of the technology status through credible metrics for the TRLs of the actively cooled sunshield. These TRLs ranged from 3 for an “analytical and experimental critical function proof-of concept achieved in a laboratory environment” through 7 for a “system prototype demonstrated in a space environment” through a LEO flight validation. The NMP-defined TRL levels are augmented from the standard NASA TRL levels to include predicting performance of the technology via physics-based analysis to the next TRL level. The sunshield was assessed by the TRB to be at TRL 3 at the beginning of the study, while the mechanical cryocooler components had been previously validated in a laboratory environment to a TRL 4, through the ACTDP program [2], [3].

Current and future large space telescope missions are so large, cold, and lightweight that they cannot be verified by a single system-level end-to-end test. Instead, performance will be anchored by an end-to-end integrated model verified by a complex series of tests, and models of smaller components, subassemblies, subsystems and subscale systems. LST will pioneer this verification method for actively cooled sunshields. Studies were performed with models of a SAFIR design, to ascertain what characteristics and environmental inputs that affect SAFIR’s performance could be validated with the LST active cooling system. The LST team then designed the ground tests, modeling and flight operations to capture the relevant physics, needed test data, and conditions for model and scaling validation with LST.

Verifying the thermal design is a challenge in the new cryogenic cooling architecture. Spitzer’s attempt at verifying the expected 5-6 mW heat leak resulted in a 50 mW test value [DMM2]. On-orbit measurements indicate that 6 mW was the correct value, and that the test conditions were at fault. The LST program includes new methods to verify the cryo-thermal design of a system using subscale testing, and new processes for modeling at cryogenic temperatures. LST also plans to check the ability of an 80 K test to be used in the future for workmanship verification on the flight item. Finally, LST spaceflight data validates modeling and ground test correlation efforts and scales the analytical techniques to the SAFIR-class scaling target. This combination of test and predictive power yields a more robust, lower cost, lower risk system for the very large telescopes of the future.

Despite well-designed ground tests and modeling, the technology and models cannot be validated until the payload flies. The [DMM3] LST team has designed the mission operations and instrumentation suite to gather the on-orbit engineering data required to quantify the models’ predictive capabilities. LST will launch into a sun-synchronous, low Earth orbit along the terminator to economically achieve a low thermal background. This enables testing of passive cooling techniques and extends LST technology to a future deep space mission. For small thermal perturbations, thermometers sensitive enough to test the limits of LST’s modeling ability will be strategically located. Heaters will be used to perturb the system, which will aid in model valida-

tion. Video cameras with fiber optic inputs will provide periodic updates about the state of the shields. The structural/mechanical state of the system and its interactions with the thermal system will be measured with load cells and accelerometers.

II. TECHNOLOGY ADVANCEMENT

By the end of the NMP funded study phase, the independent TRB agreed that the LST team had advanced the active cooling system technology to a TRL 4 with significant progress to validate the components in a relevant environment and achieve TRL 5.

The activities required to achieve TRL 4 included:

- perform coupon tests of material properties of the sunshield material at 15-30 K including emissivity, conductivity, coefficient of thermal expansion, modulus and strength
- test the mechanical performance of the membrane joints
- demonstrate the effectiveness of the actively cooled sunshield to achieve a nominal 25K through an actively cooling test
- demonstrate deployment of sunshield segment of three bays at room temperature
- demonstrate thermal performance of a subscale passively and actively cooled sunshield
- demonstrate a breadboard pulse-tube compressor/cold head unit operating at a nominal design temperature of 18K and transferring a nominal 75 mW heat load [2], [3]
- demonstrate a breadboard JT compressor/cold heat unit operating at a nominal design temperature of 6K and transferring a nominal 15 mW heat load [2], [3].
- incorporate results of the tests listed above into a model to predict the system-level performance in the relevant thermal environment for TRL 5, as well as the performance of the flight validation article in LEO including parasitic loads required as a TRL 6 gate.

Significant progress was made toward reaching TRL 5 as the following activities also were completed:

- conduct deployed sunshield tests of six panels and three layers at room temperature
- conduct thermal breadboard sunshield test at 6 K and 80 K
- characterize the effect of thermal parasitic loads internal to the pre-cooler assembly
- characterize functional breadboard pulse tube cryocooler-JT recuperator support structure through launch vibration tests.

Finally, a technical non-advocate review determined that the prototype mechanical cryocooler achieved TRL 6 through a development activity funded by James Webb Space Telescope (JWST) Project.

A. Coupon Tests

There are several material properties of the Double Aluminized Kapton (DAK) that are not currently well known at low temperatures. First, the thermal conductivity of the aluminum layer, which dominates the kapton at low temperature, is generally assumed to be that of an equivalent thickness of nominally pure aluminum, and the bulk properties are used. The LST team measured the electrical resistivity and thermal conductivity of samples of DAK material with a nominal 100 nm aluminum coating on each side. DAK with 500 nm thick aluminum on each side was also measured to anchor the technology extension to thicker layers for larger shields. Results are shown in Fig. 5. Analysis using the established Wiedemann-Franz relation ($K=LoT/\rho$) between thermal conductivity (K), and electrical resistivity (ρ), gives agreement to within 10%, with the electrical resistance, predicting a somewhat lower value of thermal conductance than measured. This level of agreement is excellent since the Lorenz value (Lo) is only known to approximately 10%, and can vary with temperature. For the emittance values, data exist to 50 K [5] and further unpublished data down to 35 K were made available [6]. These data have been extrapolated to lower temperatures; however, simple extrapolation may not be warranted [7] because there is a wavelength dependence to the emissivity, and the electrical skin depth of the material approaches the thickness of the material for wavelengths of greater than 200 μ m, which is the peak of the black body spectrum at 15 K. Therefore, the LST team also measured the total hemispheric emittance (ϵ) and the absorptance of the same sample by reversing the temperatures of the sample and chamber. As seen in Fig. 6, the absorptance matches the emittance within 10% when plotted versus the emitter temperature. The temperature-dependent emissivity was calculated from the Hagen-Rubens relationship [7] using electrical resistivity measured at room temperature and 4 K, and then calculated at intermediate temperatures through the Weidemann-Franz relationship. Skin depth and transmissivity effects were considered in the analysis, and were found to be important below about 40 K. Data on a smooth sample [6] show the sort of emissivity that was expected, especially at temperatures above 50 K.

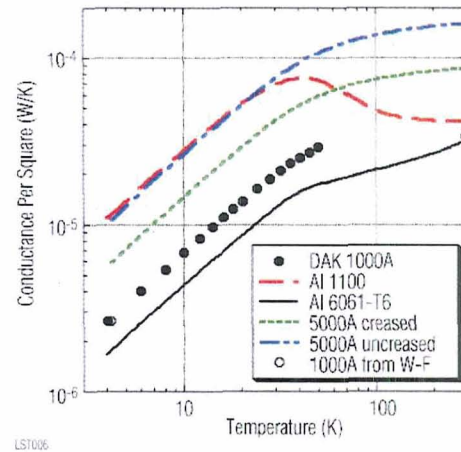


Fig. 5 The thermal conductance of DAK has been measured at low temperature extending existing data.

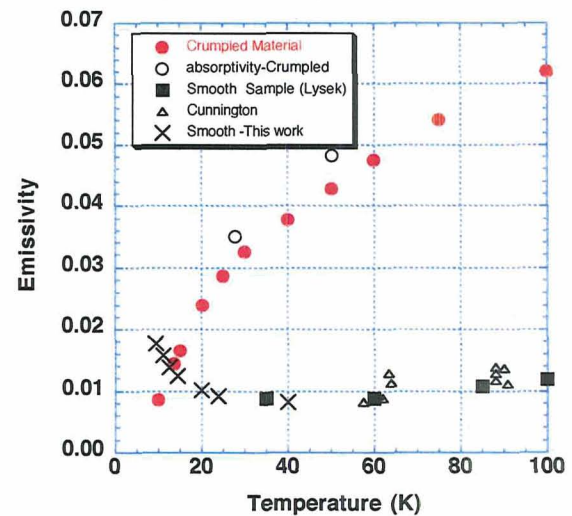


Fig. 6 The emissivity of DAK has been measured to much lower temperatures and has been shown to be sensitive to creasing.

B. Active Cooling Test

A testbed was created to characterize the thermal aspects of an actively cooled sunshield layer. The testbed consists of two 1.2 m square LHe cooled panels and close-outs mounted in a 2 m diameter thermal vacuum chamber. An approximately 1 m square DAK membrane, instrumented with Cernox temperature sensors and supported from a separate LHe manifold and tabs at the sides and bottom corners, is placed between the LHe panels. DAK films with different metallization thicknesses can be used; however, standard DAK with 100 nm metallization was studied here. A stainless steel panel, covered with aluminum tape in order to simulate the sunshield optical properties, is suspended adjacent to the DAK test article. The DAK panel is attached to the LHe manifold along the top using the same technique planned for membrane attachment on the flight sunshield, sketched in Fig. 7.

Heater tape along this edge simulates the active cooling boundary condition of the coldest, innermost sunshield layer.

The adjacent steel panel has a separate LHe manifold along the bottom edge and heaters at both top and bottom, to simulate the spatially variable radiation environment due to the next warmer sunshield layer. The LHe enclosure, adjacent shield, and temperature controlled edge simulate the on-orbit thermal environment of the actively cooled sunshield layer.

Thermal balance data were obtained for five adjacent shield temperatures. A thermal finite-difference/finite-element model of the actively cooled membrane was developed using Thermal Desktop (TD) to successfully correlate results with the test data [7]. Conductivity and emittance data from coupon measurements are included in the thermal model, which also accounts for the effects of specularity, wavelength dependence of emissivity, and residual gas conduction. Fig. 8 shows some of the results of an initial correlation of this thermal model of the ACT with test data. The measured interface conductance at the clamped epoxy hard shield/DAK interface was approximately $0.45 \text{ W/m}^2\text{K}$.

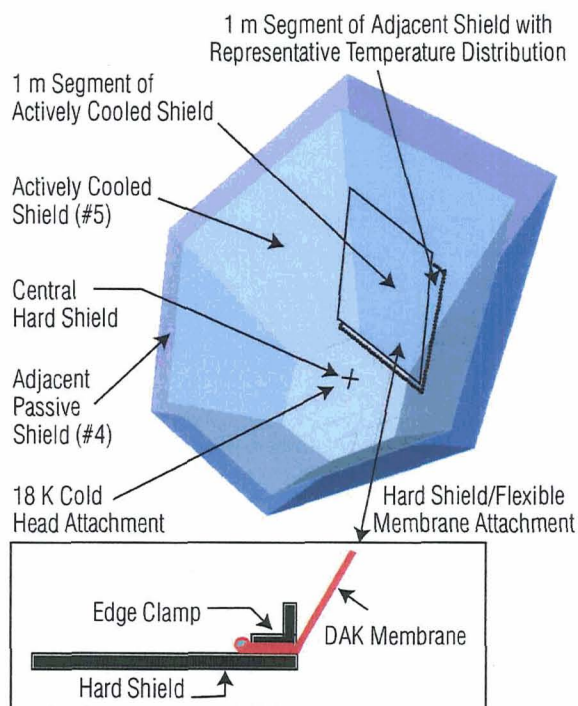


Fig.7 ACT test article captures the essential physics of t actively cooled sunshields.

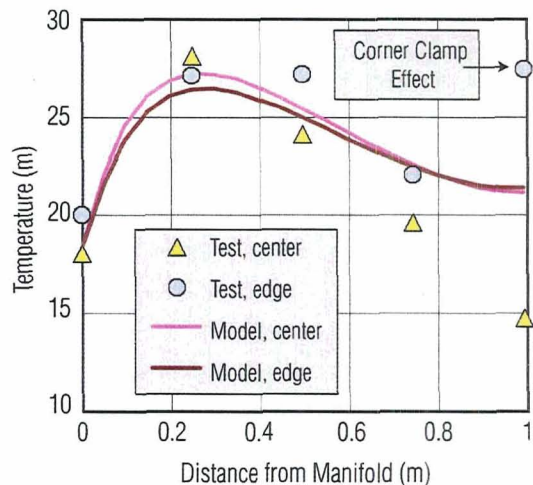


Fig. 8 Comparison of membrane predicted temperature distribution with test data. Adjacent shield temperature gradient is 22 K to 60 K.

C. Sunshield Deployment Test and Analysis

To characterize the deployed sunshield, the LST team developed a room temperature deployment sunshield testbed. The testbed, shown in Fig. 9, was used to examine the interlayer mechanical interactions, representative views for a potential camera system, wrinkling, and forces through deployment of the membrane. Deployed testbed models at room temperature were used to successfully predict the shape of the sunshield, as well as to confirm the tension-level in the test, and identify any potential design issues as the number of layers to deploy is increased.

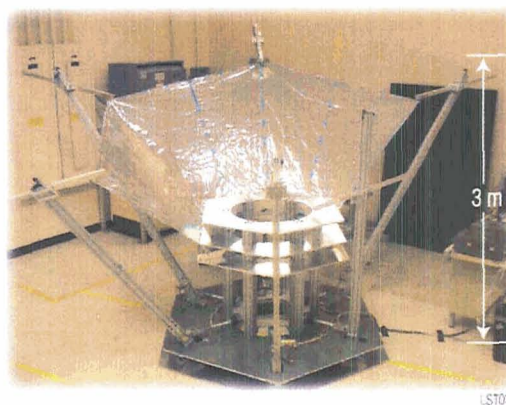


Fig. 9 The deployment testbed is flexible and expandable, and usable for further advancement of the TRL.

Shape measurements for the deployment testbed were made using the three bay/one layer shield configuration with a total of four booms in a gravity field. There were approximately 100 photogrammetry targets on the central bay. A surface fitting routine indicated a peak surface distortion of approximately 30 mm peak to valley (including gravity) and about 9 mm rms.

The LST team developed a physics-based mechanical finite element models to assess the surface distortion of gravity

and load introduction on representative sunshield membrane models. Both LM and GSFC performed surface distortion analyses using two different geometrically nonlinear solution procedures within MSC/NASTRAN [8]. The shape of the deployed sunshield under gravity was measured. The full tension load was input to a finite element model and a geometrically nonlinear analysis to predict the gravity sag. This shape was subtracted from the photogrammetry data to yield a surface distortion of 4 mm rms. Wrinkles were also measured.

D. Subscale Cryo-thermal Test

To prove the LST capability to accurately measure and model a multilayer sunshield with a cooled layer in the range of 20 K, the team performed a subscale test of a preliminary SPIRIT [9] telescope design shown in Fig. 10. Cryocooling was simulated by calibrated thermal straps with heaters and thermometers. The 4 K shroud covered only the lowest temperature surfaces (<120 K). Radiation close outs between the 4 K shroud and the outer 80 K environment were designed to have minimal thermal impact to the test article. Experimental artifacts, common to previous tests of the type, such as radiation reflected into the cold areas from the chamber and inadvertent thermal shorts, were negligible as a result of the design of this test. While the geometry of the subscale SPIRIT model is different because SPIRIT is designed for an L2 orbit, the 20 K SPIRIT shield is used in exactly the same way as the LST actively cooled layer. The test fixturing including a very high emissivity (0.98) 4 K shroud and low conduction thermal radiation closeouts were also in place for this test. Thermal Desktop finite-difference/finite-element models were used to successfully correlate results with the data from the subscale testbed.

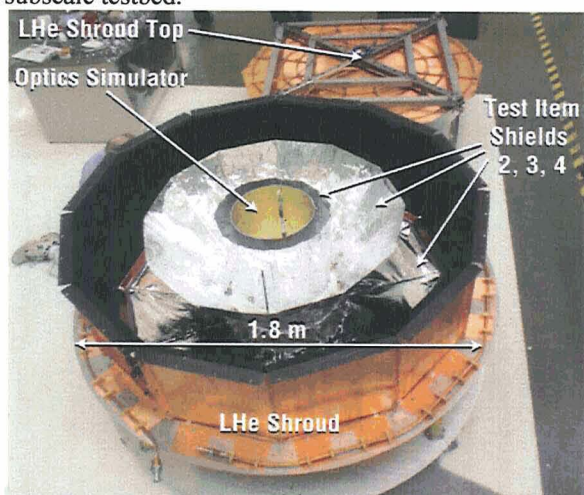


Fig. 10 LST has tested its TRL 5 thermal breadboard test methods during the Study phase by performing a subscale test.

E. Cryocooler testing and analysis

The LST cryocooler approach minimizes cost, schedule, and risk by adapting the design developed for JWST's MIRI (Mid-InfraRed Instrument) to meet LST mission require-

ments. This NGST ACTDP cryocooler provides remote cooling at two temperatures: 15-20 K, and 4-8 K. Cooling at 4-8 K is achieved by a 4He Joule-Thomson (JT) cooler. A Pulse Tube cryocooler (PT) pre-cools the He gas to 18 K for use by the JT stage and provides additional cooling at 18 K for parasitic and explicit loads, if any. A cryocooler performance model also takes into account the level of parasitic heat loads from conductive and radiative sources. The cryocooler performance model was built from a mixture of test data and physics-based analyses to provide an interface for the thermal engineer to determine heat removal capacity at the two heat-lift locations as a function of temperature and compressor input power-

III. MODELING AND SCALING

The LST modeling effort connects the activities that mature the actively cooled technology and the flight design, and demonstrates scaling/extension to future telescopes. Sources of "missing physics" in the standard cryo-thermal modeling and testing practices were identified: including the effects of wavelength-dependent emissivity and absorptivity, thermal distortion of sunshield membranes, contamination, and basic investigations into the generation of wrinkles in the deployed shields and the effects of wrinkles on heat transfer.

Cooling the Telescope Mounting Plate (TMP) on the LST flight vehicle in LE0 to 6 K is predicted to require 10.3 mW of cooling power, and cooling the hard shield to 5-18 K requires 86 mW. Predictions were made with a system-level thermal model integrated with the cryocooler performance model. The thermal model of the actively cooled inner shield is shown in Fig. 11.

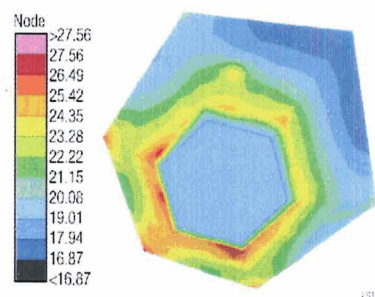


Fig. 11 Modeling predicts that the LST on-orbit performance will meet the temperature and heat load requirements.

The thermal model was used to predict the response of the LST flight concept on-orbit, and to confirm design studies for components such as the cryocooler chimney shown in Fig. 4. The cryocooler "chimney" provides a known radiative environment for the cryocooler. The chimney also protects the cryocooler from potential contamination sources. Trade studies of different external chimneys were performed using the integrated system-level thermal model. The current chimney design is a 50 μ m DAK sleeve. A heat map showing the temperatures and the heat flows between components

is shown in Fig. 12. Because these heat loads are dominated by conduction in the support struts and are not dependent on the cold end temperature very little modeling extrapolation is needed to scale the temperatures to a future large telescope.

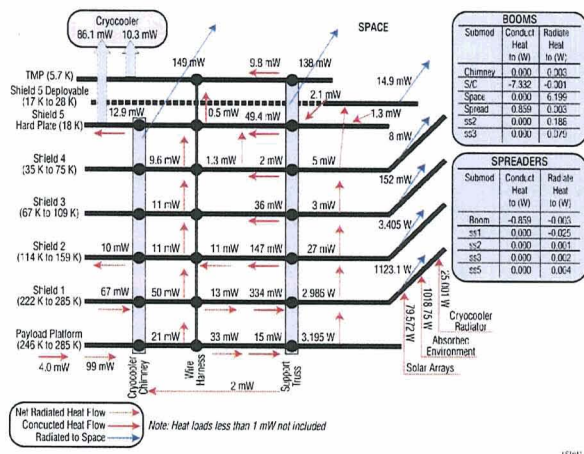


Fig. 12 LST heat flow map shows that the cryocooler heat loads are mostly due to conduction.

A. Wavelength Dependency

The wavelength dependence of thermal radiation exchange is well-understood, but has previously been neglected in the design of passive radiators. It is known that the emissivity and absorptivity, for a given surface, temperature, and wavelength, are equal. The emission of thermal radiation is centered at a wavelength which varies inversely with temperature, so that as the temperature of a surface decreases, the emission (absorption) is dominated by longer wavelengths, for which the emissivity (absorptivity) decreases inversely with the square-root of the temperature.

Neglecting wavelength dependence severely underestimates the radiative transfer from the warmer to the colder shield layer. As the temperature of the coldest, actively-cooled, sunshield layer is approximately 20 K, and the adjacent passively-cooled sunshield layer is at 60 K, the absorptivity of the 20 K shield, for radiation from the 60 K shield, is ~1.7 times as large as would be predicted if the wavelength dependence were not considered. The temperatures predicted with system-level thermal flight model with wavelength-dependent properties are 6 K higher than those which assume temperature-dependence but ignore the wavelength-dependence. Fig. 13 shows the cumulative effect on the temperatures for the coldest, warmest, and one intermediate layer of the five-layer sunshield. Inclusion of the wavelength dependence is anticipated to benefit a wider spectrum of cryogenic applications, including, but not limited to, LST and future large telescopes.

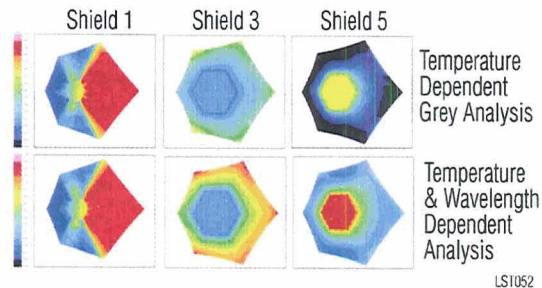


Fig. 13 Models show that wavelength-dependent analysis is necessary to achieve accuracy in predictions.

A systems-levels approach to modeling has revealed many of the system maturation issues. The LST team is focused on the structural interactions that influence the thermal performance. The thermal distortion of the sunshield on a larger scale was studied by performing an analysis on a pre-tensioned sunshield to assess its distorted shape and to assess the LST design robustness to thermal distortion. The thermal distortion, analyzed with hand-calculations and confirmed with detailed analysis, revealed that the edges of the LST sunshields are properly oriented to minimize stray thermal radiation. The tension level of the flight article is selected such that thermal distortions do not adversely affect the sunshield and the shield avoids going "slack." At a smaller distortion scale, the forces on the membrane are anticipated to induce wrinkles as the shape of the sunshield precludes a uniform tension field. These wrinkles, if large and extensive enough, were shown via parametric modeling to affect the heat exchange between layers. LST will reduce thermal distortions so they do not affect thermal performance and performance predictions. Papers on wavelength-dependent modeling and the model correlation activities have already been presented [10 - 12].

B. Scaling Analysis

Model validation is demonstrated by the correlation of model predictions with test data. Results from the ground and flight validation tests and analyses must be extrapolated to predict with confidence the behavior of different sized sunshields operating in different environments. Scaling analyses, or the extrapolation of model results beyond the demonstrated range of validity, must have a set of target conditions to design with confidence and effectively meet modeling requirements. The scaling target defined for LST is a SAFIR-class far-IR mission operating at L2. The LEO environment is significantly warmer (due to Earth proximity) and much more variable (due to orbit variation, lunar position, and Earth-sourced heating) than the environment at L2. To design the lightest, simplest, least-expensive sunshield that will meet requirements at L2, the LST team first predicted the response to inputs at those lower levels. The correlation of LST data from LEO with models will validate the models for response to the combined inputs. However, this is not sufficient for predicting performance at L2. To make that step, the response of the LST spacecraft to the multiple contribut-

ing inputs must be separated and determined to the greatest degree possible. This approach is illustrated by example in Figure 14. To demonstrate scaling of performance to the smaller inputs, it is necessary to model separately the responses to various inputs. The model is validated by showing that the individual responses are as expected when compared with the flight data. The inputs are then combined to give the observed total response. The different timescales of the inputs provide the means to distinguish the components of the combined payload response.

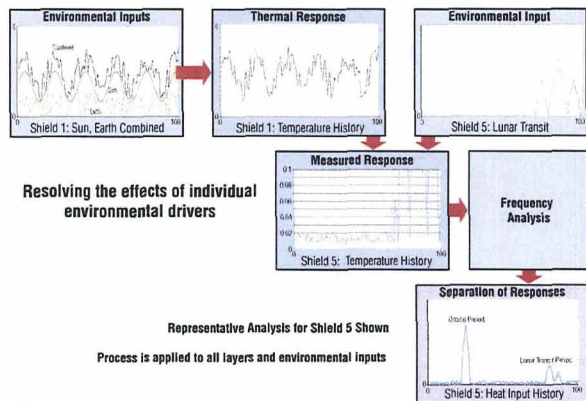


Fig. 14 LST will sort out the heat input contributions to be able to scale the predictions to L2.

IV. MISSION DESIGN

The LST was designed to be placed in a sun-synchronous low-Earth orbit, 500-600 km altitude, passing over the day-night terminator with declination approximately 7 degrees, as shown in Fig. 15. The LST mission was designed to be compatible and had sufficient mass margin with either a Pegasus-XL or the lower half of the payload fairing of a Delta-II 7320-10 launch vehicle. The spacecraft is maintained with axis nadir-pointing, and with the same outer sunshield panels always toward the Sun. Orbital precession keeps the spacecraft sun-synchronous, while the orbit declination varies slowly with mission duration. Heat inputs to the spacecraft are primarily from the Sun, incident on the two panels of the sunshield outer layer that face the Sun, and from the Earth, incident from below onto the spacecraft bus and all six panels of the sunshield outer layer. The coldest, inner layer of the sunshield always faces toward zenith, while rotating through the ecliptic plane twice each orbit. The inner portions of the multilayer sunshield will routinely view lunar transits.

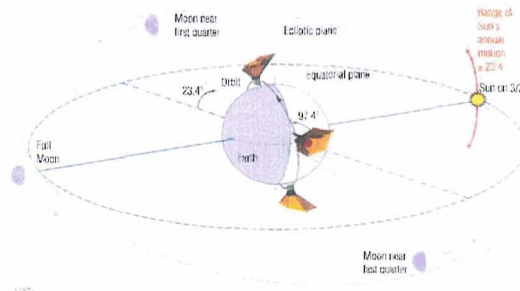


Fig. 15 LST is launched into a sun-synchronous terminator orbit to have the best thermal environment in LEO.

Fig. 16 shows a preliminary experiment time line for the flight validation mission activities. Launch will be followed by a standard suite of timed operations, including signal acquisition, health and safety checks, and solar array deployment. The expected time for this activity is between several hours and several days, during which the sunshield remains stowed and the cryocooler inactive. Tip-off conditions will prevent unacceptable sunward pointing, and stabilization to nadir-pointing will occur rapidly, thus providing a safe environment for the sunshield during checkout. The sunshield inner layers will cool little prior to deployment, even over several days of checkout, so deployment of the sunshield begins with the components relatively warm.

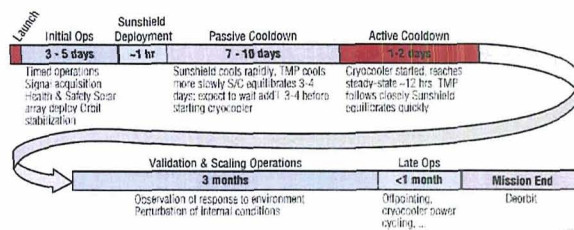


Fig. 16 Mission Sequence Timeline.

Sunshield deployment initiation will be commanded, and then run to completion in less than 1 hour. The sunshield cools more rapidly once deployment begins, but not appreciably during the deployment interval. Sunshield deployment is timed for maximum real-time downlinking of deployment imagery. The deployment will be recorded by eight "video" cameras viewing internal, external, and intermediate sunshield bays.

Once deployed, the sunshield will cool more rapidly; while the TMP cooling will lag due to its higher specific heat and thermal isolation. Preliminary modeling indicates that after approximately 3-4 days through passive cooling, the sunshield assembly will approach steady-state conditions at a higher temperature than when the mechanical cryocooler is operational. The LST team planned to observe the performance of the sunshield for several more days before activating the mechanical cryocooler. During this time, visual imagery will be collected to determine the surface figure of the as-deployed membranes, which is of significance to the thermal radiative cooling performance of the sun shield assembly.

Once activated, the mechanical cryocooler will very rapidly cool the actively-cooled sunshield to 18 K, and the TMP to 6 K.

Validation operations occupy most of the mission duration, and consist of observing the response of the LST experiment to the environment and to controlled stimuli. Concurrent modeling of the sunshield behavior under passive conditions is a key part of the model validation effort to correlate both the passive and actively cooled response of the innermost sunshield layer. The understanding gained from intensively investigating both conditions will be invaluable in demonstrating the range of model validation. It is known that the LEO environment, which determines the LST thermal performance, will vary significantly on several timescales: solar heating will vary regularly with Sun-spacecraft orientation during each orbit and more slowly during seasonal progression; Earth reflection and emission will vary irregularly; and lunar heating of the colder segments will be brief but unavoidable.

The continuously changing environment will be reflected in the spacecraft temperatures and mechanical configuration; measurement of these conditions will provide the test data for correlation with model predictions. Payload temperatures will be monitored at over 100 locations, selected as the best indicators of the thermal performance and of the factors that influence that performance. Mechanical loads used to tension the deployed membranes are also monitored at 30 locations, to confirm the level of tensioning in the sunshield and its nominal configuration. Visual imagery of the deployed shields will be available to determine the degree of surface distortion.

Following the validation operations, the LST team may elect to exercise the LST experiment with additional stimuli late in the mission. Cycling the cryocooler off and on to observe transients, pointing the spacecraft significantly off-nadir to increase heating rates, illuminating different parts of the deployment structure, or inducing decontamination of cold surfaces, are examples of activities which would only be undertaken near mission end. The motivation is to extend the range of validation and predictive capability of the models. The decision to undertake such operations will be based on the state of model validation. Detailed plans for all reasonably foreseen activities will have been reviewed well before the decision is required. The mission will end with the usual operation of passivation. The entire flight mission duration, including the checkout phase, is not expected to exceed 4 months.

V. SUMMARY

A critical juncture has been reached in the state of cryocoolers and sunshields. The proposed technology builds on recently-developed state-of-the-art cryocooler and sunshield technologies. The recently-completed advanced cryocooler technology development program brought 4-6 K mechanical cryocoolers to TRL 4, and JWST has advanced it to TRL 6 in

early 2007. JWST deployable, light weight, passive cooling sunshields have passed TRL 6. LST will take the JWST pulse-tube/Joule-Thompson mechanical cryocooler, integrate it into a system, and fly it. LST planned to extend this technology to lower temperatures by actively cooling an inner layer of a multilayer shield to 30 K (or lower), and by providing direct 6 K cooling to a telescope mounting plate.

The goal of the LST team was to explore the cryo-thermal-mechanical analyses fully, and devise a test program that is effective and affordable for future large space cryogenic systems. A successful flight validation by LST will lower the risk and cost for smaller missions and will enable SAFIR, plus a whole class of future missions that can now credibly move onto NASA's road maps.

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REFERENCES

- [1] Lester D, Benford D, Blain A, Bradford CM, Dragovan M, Langer W, Lawrence C, Leisawitz D, Mather J, Moseley SH, Mundy L, Rieke G, Stacey G, Yorke H, Young E, The science case and mission concept for the single aperture far-infrared (SAFIR) observatory, in *Proceedings Of The Society Of Photo-Optical Instrumentation Engineers (SPIE)*, Mather JC (editor), Optical, Infrared, And Millimeter Space Telescopes, Parts 1-3 5487: 1507-1521, Part 1-3, 2004.
- [2] R.G. Ross, Jr. and D. L. Johnson, "NASA's Advanced Cryocooler Technology Development Program," Adv. In *Cryogenic Engin.*, Vol. 1A, Amer. Inst. Of Physics, NY, 2006.
- [3] R.G. Ross, Jr. and D.L. Johnson, "NASA's Advanced Cryocooler Technology Development Program, (ACTDP)," Jet Propulsion Laboratory, Presented at the Cryogenic Engineering Conference, Keystone, Colorado, August 30-September 2, 2005.
- [4] Kittel, Charles, *Introduction to Solid State Physics*, John Wiley and Sons, New York (1976).
- [5] Robert Seigel and John Howell, *Thermal Radiative Heat Transfer*, Taylor and Francis, New York, 1992.
- [6] Lysek, M. private communication.
- [7] C & R Technologies, 9 Red Fox Lane, Littleton, CO 80127-5110, <http://www.crtech.com>.
- [8] MSC/NASTRAN, MCS Software Corporation, 2 MacArthur Place, Santa Ana, CA 92707, <http://www.mssoftware.com>.
- [9] The Space Infrared Interferometric Telescope (SPIRIT): mission study results, David Leisawitz, Charles Baker, Amy Barger, Dominic Benford, Andrew Blain, Rob Boyle, Rich-

ard Broderick, Jason Budinoff, John Carpenter, Richard Caverly, Phil Chen, Steve Cooley, Christine Cottingham, Julie Crooke, Dave DiPietro, Mike DiPirro, Michael Femi-
 ano, Art Ferrer, Jackie Fischer, Jonathan Gardner, Lou Hal-
 lock, Kenny Harris, Kate Hartman, Martin Harwit, Lynne
 Hillenbrand, Tupper Hyde, Drew Jones, Jim Kellogg, Alan
 Kogut, Marc Kuchner, Bill Lawson, Javier Lecha, Maria Le-
 cha, Amy Mainzer, Jim Mannion, Anthony Martino, Paul
 Mason, John Mather, Gibran McDonald, Rick Mills, Lee
 Mundy, Stan Ollendorf, Joe Pellicciotti, Dave Quinn, Kirk
 Rhee, Stephen Rinehart, Tim Sauerwine, Robert Silverberg,
 Terry Smith, Gordon Stacey, H. Philip Stahl, Johannes Sta-
 guhn, Steve Tompkins, June Tveekrem, Sheila Wall, Mark
 Wilson; *Proc. SPIE* Vol. 6265, 626540, Space Telescopes
 and Instrumentation I: Optical, Infrared, and Millimeter; John

C. Mather, Howard A. MacEwen, Mattheus W. de Graauw;
 Eds.; Jul 2006.

[10] M. DiPirro, et al., Subscale cryo-thermal tests of a large
 4 K space telescope, *Proc. SPIE* Vol. 6275, P. 62750F
 (2006).

[11] C.G. Paine, C.M. Bradford, M.C. Dragovan, H.W.
 Yorks, A parametric design tool for large space telescope
 sunshields, *Proc. SPIE* Vol. 6265, p. 62652R (2006).

[12] M. DiPirro, J. Tuttle, A. Mattern, S. Ollendorf, D. Lei-
 sawitz, M. Jackson, J. Francis, J. Bichell, and T. Hait, 2006,
 Subscale Cryo-thermal Tests of a Large 4 K Telescope,
Thermal and Fluids Analysis Workshop, 7-11 August 2006,
 TFAWS06-1023, College Park, MD.