In flight the orbital parameters and attitude of spacecraft is perturbed by small forces and torques. Over time, the forces deorbit the spacecraft and the torques repoint the spacecraft. The pointing disturbance is compensated by onboard reaction wheels. Eventually reaction wheels saturate at their maximum angular momentum design specification. In relatively low ambient magnetic fields where angular momentum magnetic torque desaturation is not practical, from a spacecraft beam constellation of jets, onboard compressed reaction fluid is vented to space. At the Spitzer outer shell temperature of 40 kelvin, a 50 kilogram mass of science instrument detector cooling super fluid He is vented to space. To achieve long lifetime reaction gas supply He is vented in precisely known directions. Presented here are the qualification results for the Spitzer Low Thrust Vent System (LTV) nozzles gas vent plume thrust directions.

* Background and Introduction:

[WE SHOULD HAVE A GENERAL DISCUSSION HERE OF WHY THIS TOPIC IS OF GENERAL INTEREST FOR CRYOGENIC MISSIONS, REFERRING SPECIFICALLY TO THE FAILURE OF WIRE AND THE LESSONS LEARNE D, AND SAYING WHY WE WERE CONCERNED ABOUT THIS ISSUE FOR THE SIRTF MISSION..... ]

The venting of gas resulting from the evaporation of the super fluid helium that cools the cryogenic science payload of Spitzer Observatory can exert undesirable body forces and torques on the spacecraft. To minimize these forces and torques, the He boil off gas is vented to space through equalized low thrust vent (LTV) nozzles that are in opposite directions along a line that intersects the observatory center of mass and is perpendicular to the sun direction line.

The LTV design is shown schematically in figure [figure number]

One component of the design error budget for the observatory external torques exerted by venting science instrument cryogen mass through a LTV assumes that the LTV He gas venting force points in a direction that is known to within a cone half angle of 0.5°. To maximize the likelihood of successful in orbit performance, it was decided to verify the gas vent force direction experimentally. We describe here the method used to measure this quantity, and we report here the results of the force direction measurements for all 4 Spitzer flight candidate LTV assemblies. The 2 best matched LTV assemblies were chosen for flight.

* The Force Measurement Apparatus:

The Jet Propulsion Laboratory Pendulum Force Balance (PFB) [reference number] is a sensitive force measurement instrument. The PFB is a modified Lehman pendulum, a pendulum design that is sometimes referred to as the garden gate pendulum, or tilt seismometer, see figure [figure number].
The PFB Lehman pendulum consists of two cross flexures that define the pendulum fulcrum axis line. From the fulcrum axis, a rigid beam of length $L$ supports a mass $M$. The pendulum plane of oscillation is defined by the trajectory of $M$. The fulcrum axis line is perpendicular (normal) to the plane of oscillation. In the Lehman pendulum the fulcrum axis direction is held close to the direction of gravity vector $\vec{g}$ by a small angle $\gamma$. In the conventional timepiece clock pendulum, the fulcrum axis is horizontal, perpendicular to $\vec{g}$, at angle $\gamma = 90^\circ$. As in the Galileo's incline plane, on the plane of oscillation, the apparent gravitational acceleration $\ddot{a}$ is given by

$$\ddot{a} = \vec{g} \sin(\gamma)$$

To characterize the LTV thrust force, the LTV is attached to the pendulum mass $M$ and gas is made to flow through the LTV. The resulting gas plume produces a thrust force vector. The projected component of that force onto the plane of oscillation defines the line of action. For the line of action and the fulcrum axis, the shortest distance between these two lines defines the torque moment arm. [A DIAGRAM LABELING THESE THINGS WOULD BE WORTH A THOUSAND WORDS] The product of the moment arm and the projected thrust force magnitude is the applied pendulum disturbance torque. The disturbance torque is reacted by the pendulum mass $M$ which, after some time, comes to rest at an angle $\Theta$ which is measured from a fiducial mean undisturbed rest angle $\Theta_0$.

To measure the LTV thrust direction, the LTV is attached to the pendulum mass $M$ in different orientation directions with respect to the pendulum arm $L$. At specific LTV gas mass flows and directions, the corresponding pendulum displacement angles $\Theta_{\text{net}}$ are measured and recorded. From these data, the net LTV gas plume thrust directions are calculated.

In the ideal simple pendulum the force on mass $M$ is

$$F = MgL \sin(\Theta - \Theta_0)$$

where:

$M$ = mass
$g$ = gravitational acceleration magnitude
$L$ = the length of the pendulum arm
$\Theta$ = resulting mass displacement angle
$\Theta_0$ = Mass mean rest position angle

In the Lehman pendulum, the force equation is:

$$F = MgL \sin(\gamma) \sin(\Theta)$$

In the limit, when angle $\gamma$ becomes sufficiently small, an instability in $\Theta$ arises. This instability
precludes meaningful definition of the pendulum datum angle $\theta_0$. The threshold of instability determines the PFB force measurement sensitivity. In the PFB instrument, the angle $\gamma$ is not measured. Instead the PFB calibration procedure establishes the pendulum applied force $F$ with respect to the pendulum displacement angle $\theta$. The instrumented calibration procedure consists of a collision between a small test mass and the pendulum mass. For the 2 masses momentum before and after collision is measured.

To minimize atmospheric gas windage disturbances on the PFB pendulum, the PFB is enclosed in a vacuum chamber. Because the PFB chamber cryogenic vacuum pump does not pump Helium (He) gas, all LTV characterization measurements were performed using Argon (Ar). through a compliant The Ar mass flow (mass per unit time) was scaled by gas species properties to produce a thrust equivalent to the mission He gas mass flow. The thrust direction tests were conducted at gas mass flow rates that bracket the range of He mass flow rates expected to be encountered during the Spitzer mission. This flow range included the high mass flow rate expected following launch during the cooling of the cryogenic telescope assembly (CTA) from 300K to the low mass flow rate expected at the science instrument operating temperature of 5.5K.

The PFB LTV gas supply presented a design challenge. One configuration would have the gas supply and control manifold on board the pendulum mass $M$. The other configuration has the gas supply and control manifold external to the FPB vacuum chamber. We opted for external gas supply and control. A chamber tube gas feed through brings gas in to the chamber, a torsionally compliant flexible tube crosses the fulcrum axis, a tube runs the length of the pendulum arm $L$ and supplies gas to the LTV on mass $M$. For different gas supply test pressures changes in volume of the flexible tube that crosses the fulcrum axis lead to a Bourdon Tube effect that introduce pendulum disturbing torques. After few trials, we chose a suitably thin wall tube flexible tube in a well defined catenary suspension to cross the fulcrum axis. The following calibration data correction procedure was adopted: On mass $M$ the LTV gas supply is capped perverting mass flow. The manifold is pressurized and the disturbance torque is measured. This is repeated for all test pressures. The disturbance toques are subtracted from the LTV characterization test data at each mass flow. The Bourdon tube effect was found to be an acceptably small component of the LTV trust direction characterization.

* Definition of the thrust direction angles

The LTV gas thrust directions are defined with respect to the LTV assembly mechanical attachment plane. The attachment plane bolt circle and circle center define the LTV thrust fiducial reference point. The LTV thrust direction angles are in spherical coordinates. The objective of the thrust direction characterization is to determine the thrust direction angles $(\alpha, \beta)$. The ideal LTV has cone half angle equal to zero $(\alpha = 0)$.

At the time of LTV manufacture, the gas exhaust tube bore directions are also determined with respect to the LTV fiducial reference points. In what follows, the manufactured bore directions are not required, all PFB LTV trust direction measurements are with respect to the LTV assembly attachment fiducial reference point.

* The LTV to the pendulum mass $M$ attachment orientations
See figure [figure number]. Reference surfaces are machined on the pendulum mass for LTV assembly attachment. The two basic LTV attachment orientations are the radial and the tangent directions with respect to the pendulum mass \( M \) trajectory arc. In addition, in each radial and tangent directions, there are 4 LTV attachment axial rotations designated with index \( j = 1, 2, 3, 4 \).

1-Tangent Force measurements \( \bar{F}_{T,j} \)

In general, typical FPB force measurements are conducted with the force applied in the pendulum tangent direction. In this geometry the moment arm is equal to the pendulum arm length \( L \) and the entire force is applied perpendicular to \( L \). It can be shown that, with in or specification of some half angle of less than 0.5 degree, all tangent thrust force measurements are essentially the same. For small angles the force projected on the plane of oscillation is proportional to \( \cos(\alpha) \). For example for a cone half angle \( \alpha = 0.0^\circ \) the normalized thrust magnitude is 0.99996. Accordingly we average all measured \( \bar{F}_{T,j} \) over \( j \) and set the average equal to the tangent force \( \bar{F}_T \). From \( \bar{F}_T \), at the gas exit temperature we calculate the gas Specific Impulse (ISP). ISP is the impulse (force*time) developed per unit mass of propellant consumed. In the Metric system ISP is called apparent velocity in (meter/second).

2- Radial Force measurements \( \bar{F}_{R,j} \)

Radial direction force measurements are in the “nulling” PFB force measurement configuration. A radial direction force has a line of action that is parallel to the pendulum arm \( L \) and intersects the fulcrum axis. A radial force has moment arm equal zero and produce no torque. For the LTV attached to the radial direction facet of the pendulum mass \( M \), the PFB is only sensitive to the off axis force components which are due to cone half angles that are not zero or \( \alpha \neq 0.0^\circ \) . In the radial direction the PFB measured force is proportional to cone half angle \( \alpha \). In the radial direction the axial rotations \( j \) can not be ignored and in some cases even cage the sign of the applied torque. In the radial direction we retain the force index \( j \) in the radial force notation \( \bar{F}_{R,j} \).

* Practical considerations and the LTV direction angle equations.
Because the fulcrum axis is obscured by mechanical hardware, we are unable to precisely determine the location of fulcrum axis. This limitation leads to intractable errors which prevent determination of the LTV thrust direction characterization angles. To overcome this limitation, we gather a geometrically over constrained data set and we eliminate the unknown fulcrum axis coordinates from the from LTV thrust angle equations. location variables. Using all 4 radial direction force measurements, the fulcrum axis coordinate free LTV direction equations are:

\[
\alpha = \frac{1}{2\bar{F}_T} \sqrt{(\bar{F}_{R,1} - \bar{F}_{R,2})^2 + (\bar{F}_{R,3} - \bar{F}_{R,4})^2}
\]

\[
\beta = \arctan \left( \frac{(\bar{F}_{R,1} - \bar{F}_{R,2})}{(\bar{F}_{R,3} - \bar{F}_{R,4})} \right)
\]
Where:

\((\alpha, \beta)\) are the thrust direction angles, in spherical coordinates (radian).

\(F_T\) is the magnitude of the total thrust, defined above.

\(\left( F_{x_1}, F_{x_2}, F_{x_3}, F_{x_4} \right)\) Radial forces at 4 LTV axial rotations.

* Additional LTV requirements:

In the Spitzer dewar He exhaust gas exchanges heat with the observatory 37 Kelvin Outer Shell (OS). The exhaust gas is essentially isothermal with the OS. The LTV supply He gas tube direction is confined to the OS surface. Therefore the gas supply tube must be at a right angles to the LTV vent bore. Also at all times, the LTV must be remain in the Observatory Sun shield shadow. Any Sun exposure brings parasitic heat to the 37 Kelvin OS. Therefore the LTV axial dimension must therefore be kept short. This means the LTV must produce a well pointed trust after a right angle gas flow in a reasonably short diameter to length exit bore ratio.

* Brief LTV design concept description. [THIS PARAGRAPH NEEDS D.ELLIOT AND B.QUEEN REVIEW.]

For the LTV gas mass operating range, the LTV gas supply manifold design is of sufficient cross section area such that the supply gas has low convection velocity and is near gas stagnation conditions. At the LTV exit, the gas tube bore section area is minimum. There against the vacuum of space, LTV gas pressure at a minimum and the gas velocity at a maximum near the velocity of sound. At all times the LTV operates in the mass choke flow regime. The LTV gas impedance (mass_flow / pressure) has been carefully characterized. [ reference #: December 27, 2005, JPL SIRTF document, “SIRTF_LTV_mass_flow_vs_pressure_report.pdf” by Dave Elliott]

* [Conclusion paragraph]
[ REFERENCES ]


(2) This Test Chamber is now part of JPL division 3530 under the management of James E Polk.
(3) The Pendulum calibration concept.
Procedure. details are described in reference (1).

[figure caption needs review from JPL Robert Shotwell and or John Blandino ]

Detail of a typical pendulum calibration trace at the time of test mass collision. On the vertical axis is plotted is pendulum angular velocity, time is plotted along the the horizontal axis. At time of collision momentum is exchanged . The observed oscillation is a structural mode that is not related to the pendulum period.
(4) The original optical interferometer used to measure the pendulum angular displacement described in reference (1) above has been replaced by an LVDT.

(5) The Spitzer LTV design was proposed in "Method to Straighten Out The Flow Entering The Nozzle" by David G Elliott, JPL. memorandum of February 11 1999.

(6) The Spitzer LTV mechanical design was completed by Bradley Queen, Ball Aerospace. "Nozzle Assembly LTV" Ball Drawing 545354, September 01
[FIGURE NUMBER]

[NEED A BETTER FIGURE DRAWING, ALSO THE FIGURE NEEDS TO SHOW THE AXIAL ROTATIONS]
Figure 2

[HERE THE FIGURE VERTICAL AND HORIZONTAL AXIS ARE IN UNITS OF RADIANS, THE FIGURE AND CAPTION NOTATION NEEDS TO BE CHANGED. SUBSCRIPTED CAPITAL F HAS BEEN USED TO DESIGNATE FORCES]

is a schematic plot of 4 radial direction forces. In the radial direction the projected plane of oscillation.. The coordinate axis of the figure point in the tangent and fulcrum axis directions in units of angle (Radian) designated $X_T$ and $X_F$ [THAT] are drawn along the horizontal and vertical direction respectively. In this view the radial axis $X_R$ is out of the page. The measured LTV axial forces are $(F_{E1}, F_{E2}, F_{E3}, F_{E4})$ are expressed in units of angle (Radian) by taking the arctangent of the radial and tangent force magnitudes, or simply dividing them since the resulting angles are small. The pendulum surface misalignment angle $\varepsilon_T$ leads to a systematic force measurement error. Angle $\varepsilon_F$ has no plane of oscillation projection and is not a component of the measured force. Data precessing removes influence of angle $\varepsilon_R$. In radian units, the LTV measured cone half angle is equal to the radius of the circle in the figure.
Figure 3. The Pendulum force balance in the vacuum chamber. The pendulum arm is the upper horizontal bar, which in this view appears diagonal. The pendulum fulcrum is located in the vertical beam assembly, which is in middle of the left hand side view. The fulcrum consist of a pair of cross flexures [THAT] are located above and below the pendulum arm, the cross flexures are not visible in this view. The LTV attachment cube with the tangent and radial faces visible is in the foreground center view. The 4 point LTV attachment is discernible. In this picture the cube is shown supporting LTV simulator hardware. Above the pendulum arm between the vertical beam assembly and the cube are the flexible gas supply and gas pressure sense lines.

*Setting angles $\gamma$ and $\theta_0$ [needs review by Robert Shotwell, John Blandino]*

The pendulum fulcrum axis beam assembly is attached to a triangular beam base, which is partially visible in the lower left view. The tip tilt orientation angles of the triangular beam base are adjusted with 2 motorized lead screw jacks. One lead screw jack is visible on the right hand view. The triangular beam base tip and tilt angles in turn determine the pendulum angles $\gamma$ and $\theta_0$, defined above. Partly visible in the lower right hand view is the position sensing LVDT (4).
Figure 4. [this figure caption needs review from Dave Elliott and Brad Queen] The Spitzer Low Thrust Vent (LTV)(6) At the center of the isometric view on the left is visible the gas exit aperture which is the circular opening at the center of the cylinder top face. There is no conventional expansion nozzle, the expansion ratio of the throat to exit area is one. At right angles to the exit bore and in the plane of the 4 point attachment spider is visible the upstream gas supply tubing connector. In the right hand side section view the cylindrical exit bore with its pronounced its elliptical entrance taper is clearly visible. To the right preceding the exit bore entrance is a plate with many holes with rounded entrances so that the total pressure drop though this plate is approximately 15% of the upstream supply pressure $P_0$ (5).
Summary of thrust direction testing of the 4 flight candidate LTV hardware units. The vertical and horizontal axis are the direction cosines of the thrust unit vector. Since the direction of the thrust vector is very nearly out of the page the direction cosines are also small and the units of vertical and horizontal axis are in units of (Radian). In this plane the ideal LTV would have coordinates (0,0) at all flows. The are 4 parametric lines, one for each LTV unit. Each point in this parametric line is for a different mass flow. Also plotted as individual points is the mechanical direction of the LTV gas venting cylinder bore. The axis of the vent bore was measured by conventional metrology.

Figure 4
Figure 5

((8 mg/s and 40 mg/s of what Ar or He ))

Detail from Figure 4 for LTV SN1. The bore axis was in fact measured twice once at Ball during manufacture, and once at JPL as a confirmation of the coordinate axis definition.
Figure 6
Detail from Figure 4 for LTV SN2. [do we need to present results for all 4 LTV?]
Figure 7
Detail from Figure 4 for LTV SN3-5.