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COMPARATIVE IN-FLIGHT THRUST MEASUREMENTS OF THE SERT II ION THRUSTER

by William C. Nieberding, Daniel J. Lesco, and Frank D. Berkopec
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at
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Abstract

A description and an analysis of the three methods used to measure the thrust of the SERT II (Space Electric Rocket Test) ion thrusters in flight are given. The first is the use of the MESA accelerometer to measure the 2 μg's resulting from the radial component of the thrust. The second is the use of telemetered beam electrical parameters to calculate thrust. The third is the measurement of orbit change resulting from the thrust. It is shown that the three methods yield values of thrust which agree with each other within the error bands of the methods. It is concluded that the thrust was measured to within ± 1% by the MESA, to within ± 2.2% by beam electrical parameters, and to within about ± 5% by orbit changing.

Introduction

The successful operation of the SERT II (Space Electric Rocket Test) spacecraft[1], developed and built at the Lewis Research Center, represents the first successful life test of an ion thruster in space. The primary goal of the SERT II mission is to achieve at least six months of ion thruster operation in a space environment. A secondary goal is to measure the thrust to an accuracy commensurate with the requirements of postulated, deep space, ion propelled vehicles.

The purpose of this paper is to describe the means available on SERT II for measuring thrust, to compare them, and to present the available results. The thrust of an ion thruster very similar to that on SERT II was measured on the SERT I spacecraft to within an error of about 5%[2]. The goal on SERT II is to substantially reduce this error. It will be shown in this report that an error of about ± 1% of the 28 mN (6.3 mlb) thrust was achieved.

Many of the contemplated uses of electric propulsion are for deep space missions. The primary advantage obtained by using this type of propulsion is the large specific impulse delivered by it. This large impulse, though, is delivered in the form of low thrust for a long time contrasted with other propulsion means which deliver large thrust for a short time. As a result, accurate navigation during such an electrically propelled mission requires that the thrust be known precisely.

The thrust of an ion thruster can be most easily, but not necessarily most accurately, determined by measuring the ion beam current and the potential through which the ions are accelerated. These electrical measurements can be readily made in the thruster power supply with little error. Calculation of thrust from these measurements, however, requires corrections for such things as lack of beam collimation and doubly and triply charged ions. The uncertainty in these corrections may result in an error in thrust larger than desired.

Direct measurement of thrust is difficult on an ion propelled vehicle because of the inevitably low thrust-to-weight ratio or acceleration which results. One can measure the change of flight path caused by the thrust, but this change is so gradual that very long averaging times are required. The direct approach of measuring vehicle acceleration with an accelerometer is better if a sufficiently sensitive instrument exists. The radial component of thrust-induced acceleration on SERT II is about two micro g's which must be measured to the order of one percent error. This requires an instrument with an error band no greater than a few tens of nano g's. The MESA (Miniature Electrostatic Accelerometer)[3] theoretically meets these requirements and was flown on SERT II.

This report discusses the three thrust measurement methods on SERT II and presents and compares the results obtained from them. These three methods are (1) MESA measured acceleration, (2) beam electrical parameters, and (3) flight path or orbit change.

Spacecraft and Orbit

The SERT II spacecraft was launched on February 3, 1970 into a nearly sun-synchronous, nearly polar, circular orbit of about 1000 km altitude. An artist's conception of the spacecraft in orbit is shown in figure 1. It consists of an expended Agena stage permanently affixed to the spacecraft support and experiments section. A large solar array, attached as shown, supplies electrical power for the ion thruster, for housekeeping, and for the other experiments.

The spacecraft is stabilized in orbit such that the Agena long axis always lies along the earth radius line and such that the solar panels and thrusters always lie in the orbit plane. The earth oriented stabilization is achieved by means of gravity gradient torque coupled with control moment gyros. The desired solar panel to sun orientation is achieved by inclining the orbit such that it precesses at the rate required[1].

There are two ion thrusters aboard, only one of which operates at any time. Each thrust vector is aligned by means of gimbals to pass through the spacecraft center of mass and form a 10° angle with the spacecraft long or yaw axis. Thus, there is a component of thrust directed along the orbit radius which is proportional to the cosine of 10° and another component which is directed along the orbit tangent and is proportional to the sine of 10°. The MESA accelerometer is oriented with its

sensitive axis parallel to the yaw axis so that it senses the radial component of thrust. The tangential component causes the orbit altitude to change with time and is the basis for the orbit raising thrust measurement method.

It should be mentioned at this point that a fourth means of measuring thrust exists aboard SERT II. This consists of purposely gimbaling the thruster so that the thrust vector does not pass through the center of mass. The resulting torque will be balanced by the torque from gravity gradient at some attitude offset angle. Measurement of this offset yields a measure of thrust. Error analysis of this method shows that a measurement with no less than ± 10% error would be achieved due primarily to angle uncertainties. Therefore, it will not be treated further in this paper.

Thrust Measurement Methods

MESA Accelerometer

The electrostatic accelerometer is a single axis instrument designed for measurement of extremely low accelerations in a low-gravity environment. State-of-the-art techniques in machining are required to produce a successful instrument based on the principle of electrostatic force. A detailed description of the basic MESA structure and operating principles is found in references 3 and 4.

Electrostatic forces are used both for the support of the acceleration sensing element (the proof mass) and for the measurement of external acceleration. The proof mass is suspended orthogonal to the accelerometer sensitive axis by means of a.c. voltages via series tuned LC circuits. The magnitude of this voltage is selected to support the proof mass against the expected level of cross axis acceleration forces. The lower the cross-axis g environment, the lower the required cross-axis voltages. It is advantageous to reduce the support voltages as low as practical, commensurate with the expected environment, to reduce the instrument null bias. This null bias represents the instrument output with zero input acceleration. In general, the null bias term is proportional to the cross-axis support forces. The cross-axis suspension capability for the SERT II MESA was 100 μg.

The MESA uses an electrostatic force rebalance method in the sensitive axis to measure acceleration. The frequency of voltage pulses required to maintain the proof mass at its balance point is proportional to the external acceleration. The voltage pulse amplitude, width, and maximum frequency determine the full scale sensitive axis acceleration capability of the instrument. For SERT II, the MESA full scale was set for 100 μg even though only about 2 μg were to be measured. This full scale was chosen as the minimum which would allow accurate calibration on earth. Unlike most instruments, the MESA measurement error is a percentage of reading, plus null uncertainty, rather than the usual percentage of full scale, plus null uncertainty. Thus, in space the 2% of full scale can be measured with the same accuracy as 100% of full scale except for the null uncertainty[3]. The internal data conditioning provides 100 second averages of the measured frequency. Because the MESA output is based on frequency averaging and because of large internal damping, the MESA is a steady state instrument.

MESA calibration. The only presently practical method of on-earth calibration of the MESA uses accurate small angle deflection and measurement to produce low magnitude input accelerations derived from earth's g vector.

Figure 2 illustrates the MESA dividing head calibration method. With the sensitive axis perpendicular to the earth g vector, the mounting surface is varied to obtain an instrument null. The angle θ is then varied to provide input accelerations of g sin θ, or g θ for the small full scale angles of 20 arcseconds required for the SERT II MESA. Use of autocollimator angle measuring techniques for small angles results in an angle measurement accurate to within ± 0.05 arcseconds, with a corresponding calibration error of ± 0.25 percent.

Of course, on-earth calibration requires a 1g cross-axis suspension capability for the MESA and results in the accompanying increase in null bias due to cross-coupling. Measurement of null bias under these conditions was 50 μg. Theoretically, the null bias scales down with the reduction of cross-axis voltages. The expected null bias for the SERT II level of 100 μg suspension is therefore 0.005 μg.

SERT II accelerations. Figure 3 shows the SERT II spacecraft configuration details pertinent to the MESA. The MESA is located at a distance d = 2.39 ± 0.015m from the vehicle center of mass with the sensitive axis aligned with the spacecraft yaw axis. The thrust vector is $\varphi = 10^{\circ}$ from the MESA sensitive axis. Equation (1) is the expected sensitive axis acceleration at the MESA location, consisting of the thrust-produced term F cos φ divided by the spacecraft mass, and two simplified orbital components.

$$a = \left(\frac{F \cos \varphi}{m_s} + d\omega^2 + \frac{2d\mu}{r^3}\right)\frac{1}{g} \qquad (1)$$

where

- a = MESA sensitive axis acceleration (g's)
- F = thrust (N)
- φ = angle between MESA sensitive axis and thrust vector ($^{\circ}$)
- m_s = spacecraft mass (kg)
- d = spacecraft center of mass to MESA proof mass distance (m)
- ω = orbital rate (rad/sec)
- μ = universal gravitational constant times mass of earth (m^3/sec^2)
- r = distance from center of earth to spacecraft center of mass (m)
- g = free fall standard acceleration (9.807 m/sec^2)

Since the spacecraft is gravity gradient stabilized, it has a pitch rate of one revolution per orbit. The MESA thus revolves about the spacecraft center of mass at a once per orbit rate and senses a centripetal acceleration $d\omega^2$. The third term in equation (1) is the gravity gradient component which is due to the MESA being closer to the earth than the spacecraft center of mass.

The orbital accelerations for SERT II were calculated to be 0.73 μg. Other sensitive axis accelerations due to vehicle attitude and accelerometer misalignment contribute terms two orders of magnitude less than these and are considered insignificant.

The orbital acceleration reading of the MESA prior to thruster turn-on can be considered a secondary calibration source for the MESA, although it is impossible to separate null bias from scale factor, since only one data point is available. However, assuming that the MESA scale factor does not change with cross-axis voltage changes, this orbital acceleration measurement can be used to determine the null bias scaling of the MESA with respect to the 1-g calibration value.

The expected ion thrust for SERT II was about 28 mN (6.3 mlbs). For $\varphi = 10^\circ$ and $m_s = 1434$ kg (3162 lbs) the thrust-produced acceleration was calculated to be 1.9 μg.

Beam Electrical Parameters

A measurement of thrust can be made by using the following equation:

$$F = I_B \sqrt{2 \frac{m}{q}} \sqrt{V_{net}} \qquad (2)$$

where

I_B = ion beam current (A)
V_{net} = net accelerating potential (V)
m/q = mass-to-charge ratio of a singly ionized propellant molecule (kg/C)

In this equation, I_B and V_{net} are measured values telemetered from the spacecraft. This equation is the result of a one-dimensional analysis of the ion thruster[5]. (Additional treatment of the thrust equation is presented in reference 6.)

The one-dimensional equation is used to determine an ideal thrust for the SERT II thruster. Corrections for significant real effects such as doubly ionized propellant atoms, ion beam divergence, and uncertainty in the thrust vector direction are treated in the section of this report titled "Errors".

Orbit Changing

Another method of obtaining the thrust is to measure the change in orbit radius over a period of time. The equation governing this measurement is obtained by solving the equations of motion and integrating over the averaging time.

$$\frac{dr}{dt} = \frac{2F \sin \varphi}{m_s \sqrt{\mu}} r^{3/2} \quad \text{(see ref. 7)} \qquad (3)$$

$$F = \frac{m_s \mu^{1/2}}{t \sin \varphi} \left(r_o^{-1/2} - r^{-1/2}\right) \qquad (4)$$

where

t = time (sec)
r_o = orbit radius at time t=0 (m)(about 7400 km)

With the expected thrust level of 28 mN (6.3 mlb) the orbit will increase radius by about 570m per day. Measuring the rate of orbit radius change thus yields a measure of thrust.

Errors

MESA Accelerometer

The engine thrust determined from the MESA acceleration measurements is given by

$$F = \frac{m_s}{\cos \varphi} (a_{on} - a_{off}) \qquad (5)$$

$$F = \frac{m_s}{\cos \varphi} \left[(a_T + a_o + a_{N.B.}) - (a_o + a_{N.B.}) \right] \qquad (6)$$

$$F = \frac{m_s}{\cos \varphi} a_T \qquad (7)$$

where

a_{on} = acceleration with thruster on
a_{off} = acceleration with thruster off
a_T = acceleration due to thruster
a_o = orbital acceleration
$a_{N.B.}$ = null bias

Therefore, the thrust measurement (eq. 7) is independent of orbital acceleration and null bias (if null bias is constant).

The error in F, dF, is a function of errors in the mass of the spacecraft, errors in determination of the angle φ, and accelerometer errors. These errors will be discussed and root sum squared to provide a total error in the measurement of F.

$$\left(\frac{dF}{F}\right)_{m_s} = \frac{dm_s}{m_s}$$

$$\left(\frac{dF}{F}\right)_{\varphi} = \tan \varphi d\varphi$$

$$\left(\frac{dF}{F}\right)_{a} = \frac{da}{a}$$

$$\frac{dm_s}{m_s} = \pm 0.22\% \text{ (ref. 1)}$$

φ is known to within ±0.5 deg. = ±0.0087 rad. Therefore, for $\varphi = 10^\circ$, $\tan \varphi d\varphi = \pm 0.15\%$. The error da/a is composed of several possible errors:

1. Scale factor calibration error.
2. Scale factor stability and repeatability.
3. Null bias drift.
4. Readout system error.
5. Basic instrument linearity.

As mentioned previously in this report, the final on-earth scale factor calibration is considered known to within $\pm 0.25\%$. However, the measured scale factor was found to vary by as much as 0.8% between calibration tests following the vibration, shock, and thermal-vacuum qualification tests. (It is possible that other calibration errors, such as test base stability, are contributing to this variation rather than actual physical changes in the MESA.) Assuming that no added change in scale factor occurs with 10^{-4}g cross-axis suspension, the final in-orbit scale factor is known to

$$\pm \sqrt{(0.25)^2 + (0.8)^2} = \pm 0.84\%.$$

The null bias drift was studied using the average drift in orbital acceleration data prior to thruster turn-on and was determined to be less than 0.5% over a short (500 second) time period.

The readout system error is a maximum of $\pm 0.2\%$ for a 100 second reading and decreases proportionately with time averaging over longer periods.

The basic instrument linearity is $\pm 0.1\%$ of reading[4].

Using root sum square totaling for the independent percentage errors in a:

$$\frac{da}{a} = \pm\sqrt{(0.84)^2 + (0.2)^2 + (0.1)^2 + (0.5)^2}$$

$$= \pm 1.00\%$$

Therefore, to determine the rss error for thrust, F:

$$\frac{dF}{F} = \pm\sqrt{(0.22)^2 + (0.16)^2 + (1.00)^2}$$

$$\frac{dF}{F} = \pm 1.03\%$$

Hereafter in this report, we will consider the error in thrust as determined by the MESA to be $\pm 1\%$.

Beam Electrical Parameters

Measurement accuracy. Determination of thrust using equation (2) for the SERT II thruster is made by substituting flight data as received. Equation (2) becomes

$$F = (I_5 - I_6 + \Delta I_6)\sqrt{2\frac{m}{q}}\sqrt{V_5 + V_4 - V_{SP}} \qquad (8)$$

where[1,6]

I_5 = screen current, A

I_6 = accelerator current, A

ΔI_6 = accelerator current due to neutralizer ions[8], A

V_5 = positive high voltage, V

V_4 = anode voltage, V

V_{SP} = space probe voltage, V

The relation of these parameters is shown in figure 4 which is a plot of the potential seen by an ion on its way out of the thruster.

The thrust determined by using equation (8) is subject to errors in the measured quantities. An error analysis of this method yields the following errors:

$$\left(\frac{dF}{F}\right)_{I_5} = \frac{dI_5}{I_5 - I_6 + \Delta I_6} \qquad (9a)$$

$$\left(\frac{dF}{F}\right)_{I_6} = \frac{dI_6}{I_5 - I_6 + \Delta I_6} \qquad (9b)$$

$$\left(\frac{dF}{F}\right)_{\Delta I_6} = \frac{d\Delta I_6}{I_5 - I_6 + \Delta I_6} \qquad (9c)$$

$$\left(\frac{dF}{F}\right)_{V_5} = \frac{1}{2}\frac{dV_5}{V_5 + V_4 - V_{SP}} \qquad (9d)$$

$$\left(\frac{dF}{F}\right)_{V_4} = \frac{1}{2}\frac{dV_4}{V_5 + V_4 - V_{SP}} \qquad (9e)$$

$$\left(\frac{dF}{F}\right)_{V_{SP}} = \frac{1}{2}\frac{dV_{SP}}{V_5 + V_4 - V_{SP}} \qquad (9f)$$

The root-sum-square error in the SERT II analog flight data is (including the quantizing error of the digital telemetry system) 1.59 percent of the full scale value of the parameter measured. This was applied to the parameters for each thruster. It was determined that the contributions of the terms in equations (9b), (9c), (9e), and (9f) to the error are negligible.

The root-sum-square errors in thrust, as determined by equation (8), for each SERT II thruster at each nominal operating condition during the SERT II mission are given in Table I. Variations in error and thrust with time arise from two sources: V_5 decreases as the solar array degrades; V_4 decreases as the thruster wears with operating time.

Table I
ROOT-SUM-SQUARE ERROR IN THRUST
AS DETERMINED BY EQUATION 8

Nominal thrust level, percent	Thruster 1	Thruster 2
	Root-sum-square error, percent	
30	5.5	5.7
80	2.7	2.6
100 (10 hours)[a]	2.2	2.2
100 (100 hours)[a]	2.3	
100 (4400 hours)[a]	2.3[b]	

[a]Time from thruster beam turn-on.

[b]Estimated from projected operation.

Nonideal effects. Effects of thruster construction and operation are now considered. Not all the propellant in the SERT II thruster is ionized; approximately 15% is expelled as neutral particles[9]. The net momentum contribution of this efflux to the total thrust is less than one part in 10^5. This contribution will be neglected.

Some of the propellant in a mercury electron-bombardment ion thruster is doubly or triply ionized. Studies of the ionization process to determine the extent of these phenomena have been undertaken[10,11]. The net result of these studies is that, for nominal SERT II thruster operating conditions, a reduction in thrust of 0 to 2.5 percent can be applied. This paper will assume 0 percent reduction.

The problem of unwanted thrust vector deflection in mercury electron-bombardment ion thrusters due to electrode (grid system) misalignments has been treated in reference 12. The analysis used a digital computer program and was applied to the SERT II thruster configuration. Misalignment types were considered as translational, rotational, and skew.

The limits of the fabrication and assembly tolerances of the SERT II thruster can be applied to the results of the analyses in reference 12. Thrust vector deflection due to translational misalignment can be 1.46° or less. Skew misalignment can produce a thrust vector deflection of 0.04° or less. (Additional, and potentially the most unpredictable and damaging, skew misalignment can result from thermal-mechanical warping of the electrodes during thruster operation. However, the bulk of experience with SERT II thrusters leads to the conclusion that, for the SERT II thruster configuration, thermal-mechanical warping occurs primarily in the screen grid, and this warping is radially near-symmetrical. Any skew contribution to thrust vector misalignment from this source is deemed negligible.) Rotational misalignment produces an azimuthal component of thrust which results in a couple about the longitudinal axis of the thruster. SERT II spacecraft attitude data lead to the conclusion that rotational misalignment is negligible.

Each SERT II thruster system is mounted to a gimbal system capable of moving the thrust vector plus or minus 10°, in two orthogonal axes, from the preflight geometric alignment through the spacecraft center of mass. The anticipated in-flight corrections to the thrust vector of an operating thruster have been unnecessary for SERT II. Nine opportunities for a change in thrust vector direction with a commanded change in thruster operating conditions occurred: thruster 2 (backup) startup through three discrete thrust levels and two thruster 1 (primary) startups through three discrete thrust levels. (Thruster 1 was shut off during the solar eclipse of March 7, 1970.) SERT II spacecraft attitude data show that the thrust vector of each thruster is misaligned by less than 0.63° under all operating conditions. (In addition, results obtained in ground testing of a flight-configuration SERT II thruster have shown the thrust vector to be misaligned by less than 0.5°.) The correction in thrust due to thrust vector misalignment which can be applied to the thrust determined by using equation (8) is then cos 0.63°, or a reduction of 0.002 percent; this will be neglected. (As the electrodes wear during the mission, the thrust vector direction may change, gimballing may become necessary, and the correction may become significant.)

The remaining real effect to be quantitatively considered is the divergence of the ion beam. The ion current density distribution is a function of the operating characteristics, mechanical design, and fabrication and assembly tolerances of the particular thruster under consideration.

The divergence of the ion beam and the ion current density distribution have not been determined for the SERT II thruster configuration. Experience leads to an estimate of a 1 to 3 percent reduction in the magnitude of the thrust vector, as determined by equation 8, to account for the combination of these effects[13]. A 1 percent reduction will be applied in this paper.

In summary, the thrust, as determined by equation (8) using SERT II thruster flight operating data, is reduced by 1 percent due to ion beam divergence and in addition is subject to the root-sum-square errors of Table I.

Orbit Change

As was stated previously, the thrust can be calculated from the measured change of orbit radius over a period of time. An error analysis of this method using equation (4) yields the error in thrust due to errors in the measured quantities. These individual errors will be root sum squared to obtain the error in F.

$$\left(\frac{dF}{F}\right)_{m_s} = \frac{dm_s}{m_s} \tag{10a}$$

$$\left(\frac{dF}{F}\right)_{t} = \frac{dt}{t} \tag{10b}$$

$$\left(\frac{dF}{F}\right)_{r} = \frac{\sqrt{2}dr}{\Delta r} \tag{10c}$$

$$\left(\frac{dF}{F}\right)_{\varphi} = \text{ctn}\ \varphi d\varphi \qquad (10d)$$

where

$$\Delta r = r - r_o$$

As was stated before,

$$\frac{dm_s}{m_s} = 0.22\%$$

For reasonably long averaging time (days), $\frac{dt}{t}$ is completely negligible.

For $\varphi = 10^o$ and $d\varphi = 0.5^o$
ctn $\varphi d\varphi = 5\%$

The equation given for error in thrust due to inaccuracy in measuring radius (eq. 10c) assumes that the change in radius is very small compared with the radius. This assumption is valid for the low thrust case being considered here. The quantity Δr increases with time and can be calculated from equation (3).

$$\frac{\Delta r}{\Delta t} = 570 \text{ m/day for SERT II}$$

so that

$$\left(\frac{dF}{F}\right)_r = \frac{\sqrt{2}dr}{570\ T}$$

where T is the time in days.

The stated accuracy of radius measurement is $\pm$ 300 meters.

$$\left(\frac{dF}{F}\right)_r = \frac{\sqrt{2} \times 300}{570\ T} = \left(\frac{75}{T}\right)\%$$

A plot of the total root-sum-square error in thrust as a function of time is shown in figure 5.

Results and Discussion

Thrust measurements for initial thruster 1 operation were obtained by the three described methods. Table II shows the measurement results for each phase of the thruster 1 startup operation.

Table II
SERT II COMPARATIVE THRUST MEASUREMENTS
FOR THRUSTER 1

Method	Thrust at Three Nominal Levels						Error Band
	30%		80%		100%		
	mN	mlbs	mN	mlbs	mN	mlbs	
MESA	10.4	2.33	22.7	5.11	27.4	6.16	$\pm$1%
Electrical							
Uncorrected	11.3	2.54	23.2	5.21	28.5	6.41	$\pm$2.2%
Corrected	11.2	2.52	23.0	5.17	28.2	6.34	$\pm$2.2%
Orbit Change	N/A	N/A	N/A	N/A	28.0	6.3	$\pm$5%

The MESA-obtained thrust data was derived from the MESA acceleration measurements using two different averaging techniques.

The first technique used only that MESA data which was obtained within 500 seconds before and after each step change in thrust. Figure 6 is the MESA data edited and plotted to show only these step changes. The step changes in acceleration were then summed to obtain the 80% and 100% thrust levels. The total acceleration change measured between the thruster off and full on conditions is: 0.725 + 0.866 + 0.328 = 1.919 μg.

The second averaging technique involved using all of the MESA acceleration data available at the time of writing. An average thrust-off acceleration and an average 100% thrust-on acceleration were calculated to be 0.67 μg and 2.60 μg respectively. Taking the difference results in an acceleration term due to thrust of 1.93 μg, in close (0.5%) agreement with the step change data.

Figure 7 illustrates typical MESA data for two full orbits and shows the as yet unexplained orbital variation pattern which was observed in much of the MESA data, whether the thruster was operating or not. Computer studies are being made to correlate these 0.1 μg transient peaks with spacecraft location over the earth. The close agreement between thrust calculations based on short-term and long-term averaged data supports the contention that these variations do not significantly affect the MESA thrust measurement accuracy.

Information on the MESA null bias was obtained from the accelerometer readings prior to thruster turn-on. As described earlier, the expected orbital acceleration for SERT II was 0.73 μg. The actual averaged measured value was 0.67 μg. This discrepancy can be attributed to a null bias of -0.06 μg. The null bias was expected to scale down by 10^4 from the 1 g cross axis voltage value of -50 μg to -0.005 μg at the 10^{-4} g voltage setting. If this orbital acceleration discrepancy is actually due to null bias, the null bias scaling was only 8.3×10^2. The null bias of an accelerometer should either be insignificantly small, or known and stable. For SERT II measurements a null bias of 0.06 μg is greater than 1% of the measured acceleration and hence, is not negligible. Although the long-term drift of the null bias appears to be insignificant on the basis of available data, the aforementioned orbital variation of 0.1 μg presents problems in evaluating the short-term null bias stability. On the basis of thruster-off orbital acceleration data, the total acceleration variation for periods of less than 500 seconds was generally less than $\pm$0.01 μg. On the basis of this data, therefore, the MESA null bias was sufficiently stable to result in measurement errors of less than 0.5% as was stated in the section titled "Errors".

Table III lists the thrust, and expected error, determined from telemetered electrical parameters and equation (8). No corrections have been applied.

The thrust obtained by orbit raising measurements over the period February 16 to March 21, 1970, is 6.3 mlbs or 28.1 mN. This data was obtained from the satellite tracking group at Goddard Space Flight Center. The error band on this data is 0.31 mlb or 1.4 mN.

The data obtained from beam electrical parameters is more complete than that from the MESA or orbit changing techniques. The MESA was not operating during thruster 2 operation and also ceased functioning properly about four days after thruster 1 came on. Thus, the MESA derived data for thruster 1 does not apply for data after the 100 percent thrust, 10 hour data. The orbit changing technique requires too long an averaging period and exhibits too large an error band to list a detailed table of data for all of the thruster operating levels.

F	Thrust (N)
F_P	Force on MESA proof mass (N)
$\left(\frac{dF}{F}\right)_X$	Error in F due to error in X (typical notation used throughout)
F'_p	Sensitive axis component of F_p (N)
g	Free fall standard acceleration (9.807 m/sec^2)
I_5	Thruster screen current (A)
I_6	Thruster accelerator current (A)
ΔI_6	Accelerator current due to neutralizer ions[8] (A)
I_B	Ion beam current (A)
m_s	Mass of spacecraft (1434 kg - 3162 lbs)
m_p	MESA proof mass (kg)
$\frac{m}{q}$	Mass-to-charge ratio of singly ionized propellant molecule (kg/C)

Table III
UNCORRECTED THRUST OF SERT II ION THRUSTERS AS DETERMINED BY EQUATION (9)

Nominal Thrust Level, Percent	Thruster 1				Thruster 2			
	Thrust		Root-sum-square error		Thrust		Root-sum-square error	
	mN	mlb	mN	mlb	mN	mlb	mN	mlb
30	11.3	2.54	0.6	0.01	10.5	2.36	0.6	0.01
80	23.2	5.21	0.6	0.01	23.3	5.24	0.6	0.01
100 (10 hours)[a]	28.5	6.41	0.6	0.01	28.4	6.36	0.6	0.01
100 (1000 hours)[a]	27.9	6.30	0.6	0.01				
100 (4400 hours)[a]	27.3[b]	6.14[b]	0.6[b]	0.01[b]				

[a]Time from thruster beam turn-on.

[b]Estimated from projected operation.

In conclusion, it has been shown that the thrust of the SERT II thrusters has been measured to within ± 1% by the MESA, to within ± 2.2% by the electrical parameter method, and to within ± 5% by the orbit changing method. Within these error bands the three methods are in agreement.

Symbol List

a	MESA sensitive axis acceleration (g's)
a_{on}	Total a with thrusters on (g's)
a_{off}	Total a with thrusters off (g's)
a_T	a due to thruster (g's)
a_o	Orbital acceleration (gravity gradient + centripetal)(g's)
$a_{N.B.}$	MESA null bias (g's)
d	Distance from spacecraft center of mass to that of the MESA proof mass (m)
r	Distance from center of earth to spacecraft center of mass (m) (approximately 7.400×10^6m)
r_o	r at t=0 (m)
Δr	$r - r_o$ (m)
T	Time in days (days)
t	Time in seconds (s)
V_4	Thruster anode voltage (V)
V_5	Thruster positive high voltage (V)
V_6	Thruster negative high voltage (V)
V_{BP}	Spacecraft beam probe potential (V)
V_{SP}	Spacecraft space probe potential (V)
V_{net}	Thruster net accelerating potential (V)

θ Angular deviation from horizontal zero reference during MESA calibration ($^{\circ}$)

μ Universal gravitational constant times the mass of the earth (m^3/s^2)

φ Angle between thrust vector and spacecraft yaw axis ($^{\circ}$)

ω Orbital rate (rad/s)

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E-5755

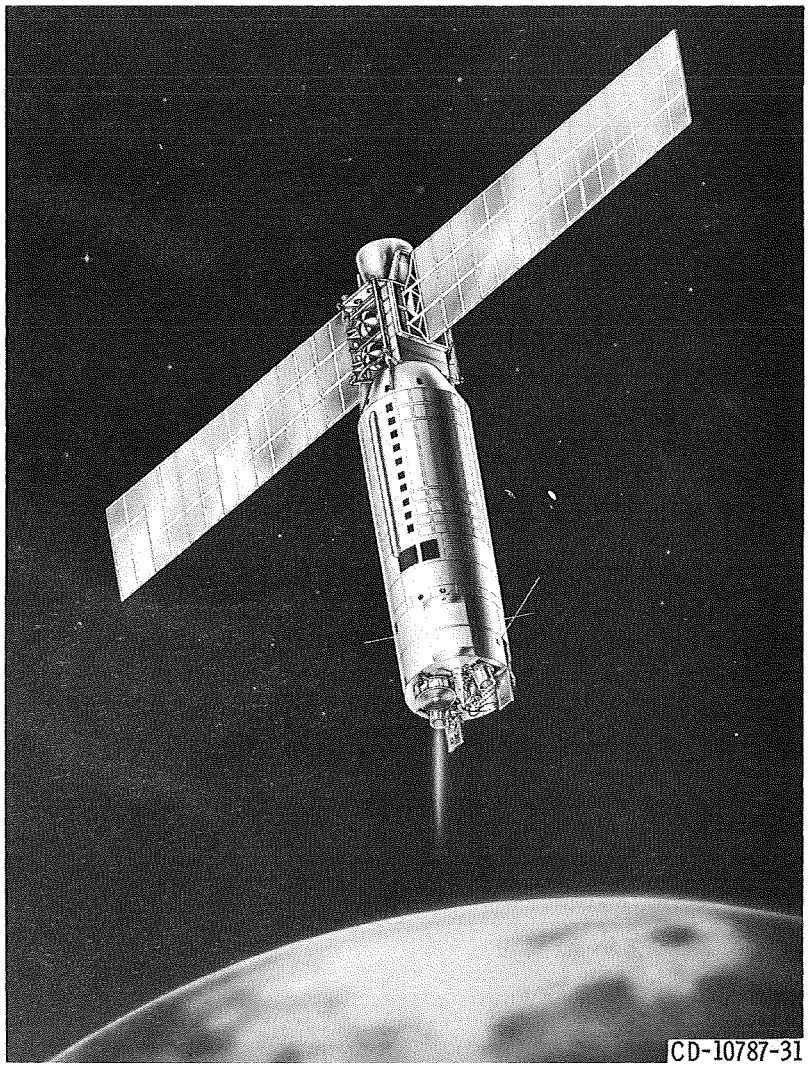

Figure 1. - SERT-II spacecraft in orbit (artists conception).

E-5755

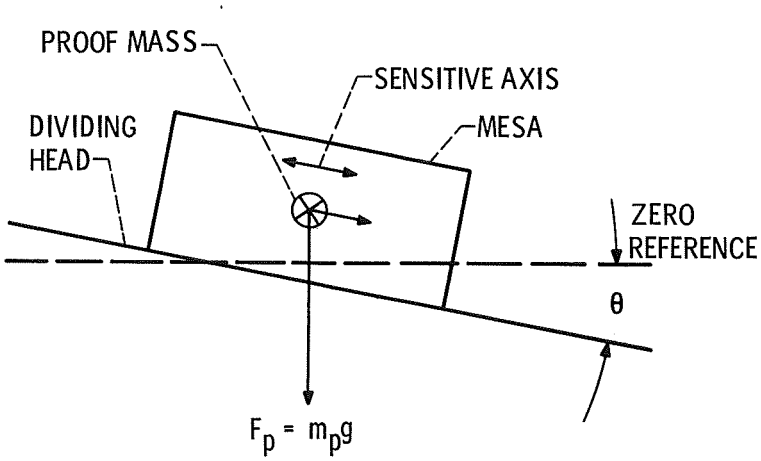

Figure 2. - MESA calibration method.

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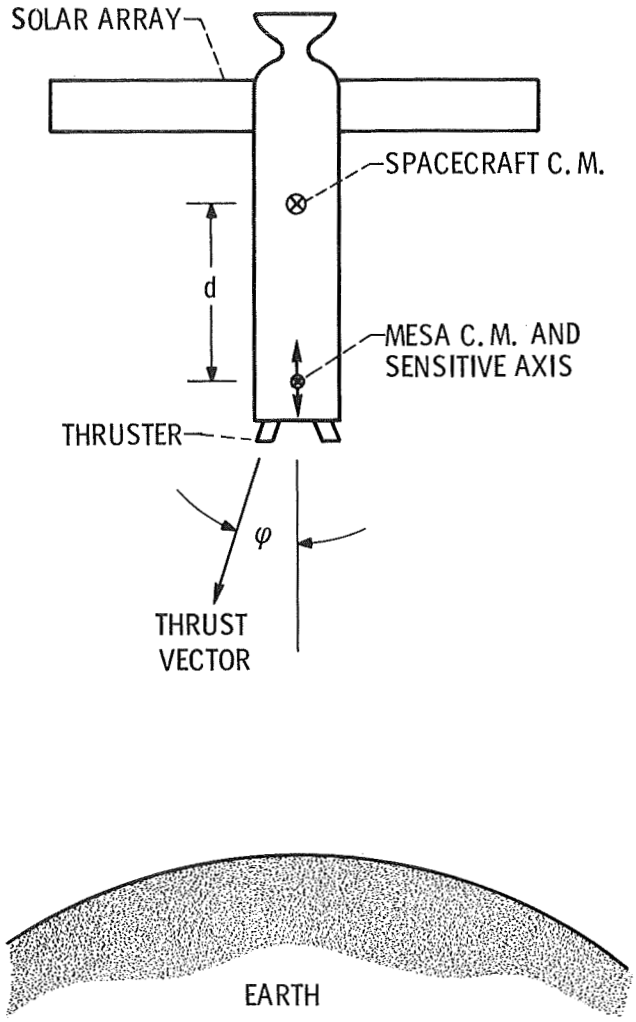

Figure 3. - SERT II acceleration measurement configuration.

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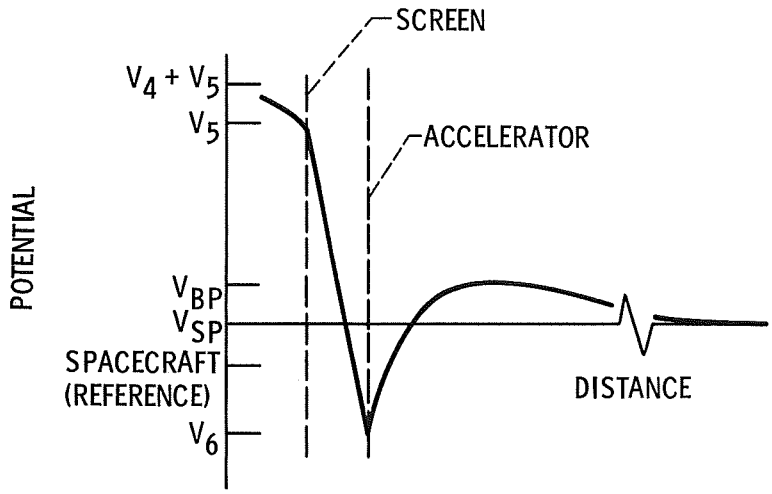

Figure 4. - Thruster potentials.

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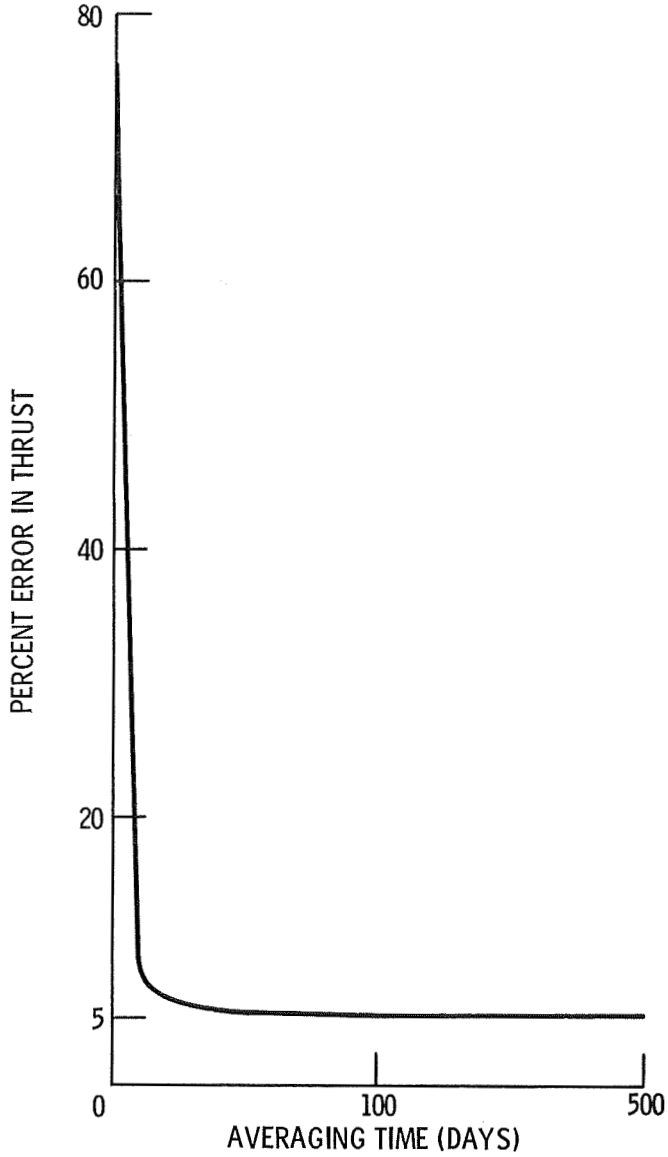

Figure 5. - RSS error in thrust versus averaging time for orbit radius change measurement.

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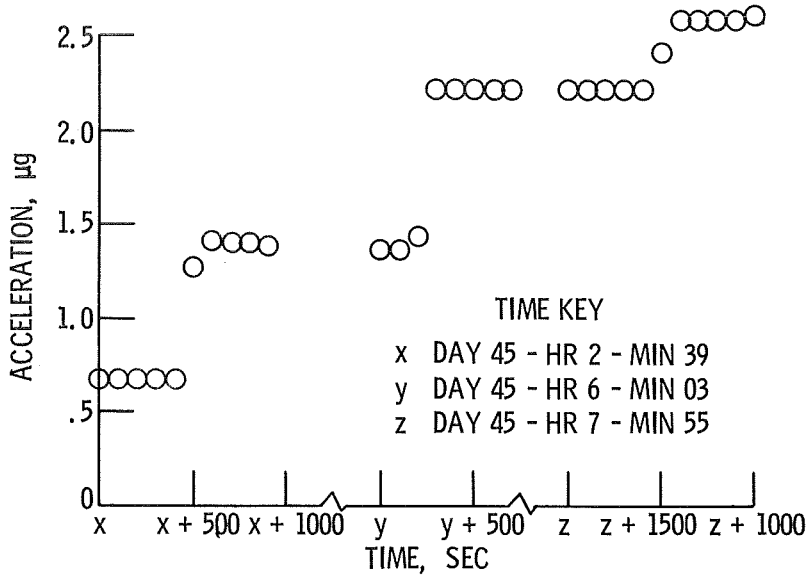

Figure 6. - MESA acceleration data during thruster turn-on procedures.

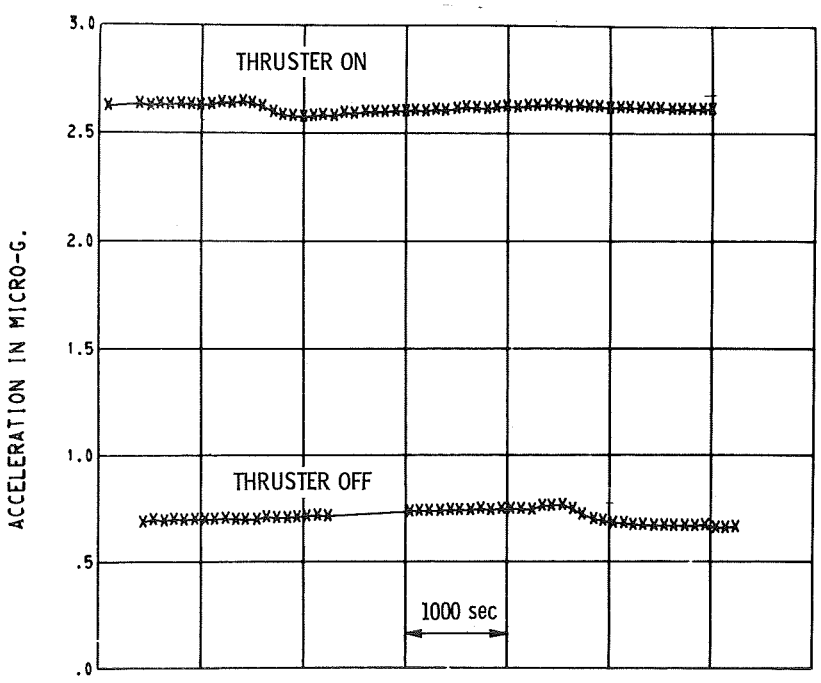

Figure 7. - MESA acceleration data.

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