NASA/CR—1998-207933

OARE STS–94 (MSL–1R) Final Report

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Prepared under Contract NAS3–26556

National Aeronautics and
Space Administration

Lewis Research Center

June 1998

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076
Price Code: A03

National Technical Information Service
5287 Port Royal Road
Springfield, VA 22100
Price Code: A03

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1.0 INTRODUCTION

The report is organized into sections representing the phases of work performed in analyzing the STS-94 (MSL-1R) results. STS-94 (MSL-1R) is a reflight of the STS-83 (MSL-1) mission which was terminated early because of a fuel cell problem. Section 1 briefly outlines the OARE system features, coordinates, and measurement parameters. Section 2 describes the results from STS-94. The mission description, data calibration, and representative data obtained on STS-94 are presented. Also, the anomalous performance of OARE on STS-94 is discussed. Finally, Section 3 presents a discussion of accuracy achieved and achievable with OARE. Appendix A discusses the calibration and data processing methodology in detail.

1.1 OARE System Features

The Orbital Acceleration Research Experiment (OARE) contains a tri-axial accelerometer which uses a single free-floating (non-pendulous) electrostatically suspended cylindrical proofmass. The accelerometer sensor assembly is mounted on dual-gimbal platform which is controlled by a microprocessor in order to perform in-flight calibrations. Acceleration measurements are processed and stored in the OARE flight computer memory and, simultaneously, the unprocessed data are recorded on the shuttle payload tape recorder. These raw data are telemetered periodically to ground stations at several hour intervals during flight via tape recorder playback (data dumps).

OARE's objectives are to measure quasi-steady accelerations, to make high resolution low-frequency acceleration measurements in support of the micro-gravity community, and to measure Orbiter aerodynamic performance on orbit and during reentry. There are several features which make the OARE well suited for making highly accurate, low-frequency acceleration measurements. OARE is the first high resolution, high accuracy accelerometer flight design which has the capability to perform both bias and scale factor calibrations in orbit. Another design feature is the OARE sensor electrostatic suspension which has much less bias temperature sensitivity than pendulous accelerometers. Given the nature of the OARE sensor and its in-flight calibration capability, OARE stands alone in its ability to characterize the low-frequency environment of the Orbiter with better than 10 nano-g resolution and approximately 50 nano-g on-orbit accuracy.

1.2 Coordinate Systems

Two coordinate systems are used in this report -- the OARE axes centered at the OARE sensor proofmass centroid and the Orbiter aircraft body axes centered at the Orbiter's center of gravity. The direction from tail to nose of the orbiter is +X in both systems. The direction from port wing to starboard wing is +Z in the OARE system and +Y in the Orbiter body system. The direction from the Orbiter belly to the top of the Orbiter fuselage is +Y in the OARE system and -Z in the Orbiter body system. This sensor-to-body coordinate alignment referred to above is the nominal flight alignment and was utilized for OARE data collection during STS-94.

In discussions of OARE calibrations of bias and scale factor, the OARE reference system is used. However, the flight acceleration data are given in the Orbiter body reference system. The sign convention is such that when there is a forward acceleration of the Orbiter (such as the OMS firing), this is then reported as a positive X-axis acceleration, even though a free particle may appear to move in the -X direction relative to the accelerating shuttle. All accelerations given in this report refer to the OARE location.

1.3 Sensor Measurement Parameters

There are three sensor ranges, A, B, and C, for each OARE axis, which are controlled by auto-ranging software logic. The full scale ranges and resolutions (corresponding to one count) are given in Table 1. In order to denote in the data when the sensor channel is driven into saturation, the output is set to 1.5 times full scale of range A with the sign of the saturation signal included.

Table 1. OARE Sensor Ranges and Resolutions

	Nominal Full Scale Range in micro-Gs	
Range	**X-Axis**	**Y & Z Axes**
A	10,000	25,000
B	1,000	1,970
C	100	150
	Resolution in nano-Gs SF_N in nano-Gs/count	
Range	**X-Axis**	**Y & Z Axes**
A	305.2	762.9
B	30.52	60.12
C	3.052	4.578

2.0 STS-94 (MSL-1R) MISSION RESULTS

This section describes the results from STS-94 as derived from post-flight processing of the trim-mean OARE acceleration data stored on the on-board EEPROM. During the mission, preliminary calibrations and accelerations were reported in near-real time by NASA Lewis Research Center using the telemetered data from the payload tape recorder.

2.1 STS-94 (MSL-1R) Mission Plan

The STS-94 adaptation parameters anticipated a mission of up to 17 days long. In order to make better use of the calibration time, the software was modified prior to STS-73 so that only C-range calibrations would occur in the "Quiet" mode, and calibrations would occur on all three ranges during the "Normal" mode. Since past experience had indicated that the Scale Factor had minimal variations and that, on-orbit, the instrument remains almost entirely in the C-range, the adaptation parameters were selected to use most of the allotted calibration time for C-range bias calibrations in order to obtain the most accurate measurements possible. When operating in the "Quiet" mode, C-range bias calibrations are to be performed every 158 minutes, and a bias calibration begins within one minute after the "Quiet" mode is asserted. A C-range scale factor calibration is to be performed after every 15th bias calibration in the "Quiet" mode. In the "Normal" mode, a full bias calibration is to be performed every 432 minutes, and a full scale factor calibration is performed after every 6th bias calibration.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE** June 1998	**3. REPORT TYPE AND DATES COVERED** Final Contractor Report

4. TITLE AND SUBTITLE

OARE STS–94 (MSL–1R) Final Report

5. FUNDING NUMBERS

WU–963–60–0C–00
NAS3–26556

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

E–11205

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—1998-207933

11. SUPPLEMENTARY NOTES

Project Manager, William O. Wagar, Microgravity Science Division, NASA Lewis Research Center, organization code 6727, (216) 433–3665.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 19 Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The report is organized into sections representing the phases of work performed in analyzing the STS–94 (MSL–1R) results. STS–94 (MSL–1R) is a reflight of the STS–83 (MSL–1) mission which was terminated early because of a fuel cell problem. Section 1 briefly outlines the OARE system features, coordinates, and measurement parameters. Section 2 describes the results from STS–94. The mission description, data calibration, and representative data obtained on STS–94 are presented. Also, the anomalous performance of OARE on STS–94 is discussed. Finally, Section 3 presents a discussion of accuracy achieved and achievable with OARE. Appendix A discuss the calibration and data processing methodology in detail.

14. SUBJECT TERMS Acceleration measurement; Microgravity; Space sensors	**15. NUMBER OF PAGES** 29 **16. PRICE CODE** A03

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT**

A5 REFERENCES

1) R.V. Hogg, "Adaptive Robust Procedures: A Partial Review and Some Suggestions for Future Applications and Theory," Journal of American Statistical Association, Vol. 69, Number 348, December 1974, pp 909-927.

2) T. DeWet, J.W.J. VanWyk, "Efficiency and Robustness of Hogg's Adaptive Trim Means," Commun. Stastist.-Theor. Meth., A8(2), pp 117-128, 1979.

3) "STS-62 Final Report," OARE Technical Report #145: Canopus Systems, Inc., July 1994.

4) "OARE Flight Maneuvers and Calibration Measurements on STS-58," NASA TM-109093, R.C. Blanchard, J.Y. Nicholson, J.R. Ritter, K.T. Larman, April 1994

5) "STS-73 (USML-2) Final Report," OARE Technical Report #147, Canopus Systems, Inc., February 1996

6) "STS-78 (LMS-1) Final Report," OARE Technical Report #149, Canopus Systems, Inc., September 1996

7) “OARE Scale Factor Calibration and Flight Data Analysis Results,” Presentation by J.E. Rice at MicroGravity Measurement Group Meeting 14, 21-23 March 1995, Johnson Space Center, Texas

2.2 STS-94 Actual Mission Description

Launch for STS-94 was at about 2:02 p.m. EDT on 1 July 1997. The actual length of the STS-94 mission was 376.74 hours or about 15 days and 16 3/4 hours with touch down at 6:46:34 a.m. EDT on 17 July 1997. Shutdown occurred in REENTER mode under the condition of "re-capture duration error" in sub-mode 4. This means that the OARE instrument continued to collect data until the Y-axis signal was saturated for at least 2 minutes in the final REENTER sub-mode. This is considered normal termination of the mission and represents adequate adaptation parameter settings for the reenter file size and correct timing of the reenter discrete.

OARE was powered on during the launch. Since the Quiet mode was set at MET 5.96 hours, the necessary elapsed time of 432 minutes has not occurred from power-on to generate a Normal full bias calibration or scale factor calibration of all ranges on OARE early in the mission. The Quiet Mode lasted until about MET of 133.55 hours when the system was again switched to Normal mode.

During STS-94, 82 C-range bias measurements were made. 34 bias measurements were made on the A and B ranges after 140.8 hours MET. There were 10 and 7 scale factor measurements made on the C and A&B ranges, respectively.

All engineering parameter values were within normal range. Hardware performance was normal.

2.3 STS-94 Data Analysis

This section treats the several analyses carried out on the STS-94 flight data and summarizes the significant results. The processed acceleration data have already been delivered to the Microgravity Measurements and Analysis Branch Program (MMAP) at NASA Lewis Research Center.

The Orbital Acceleration Research Experiment (OARE) is designed to measure quasi-steady accelerations from below 10 nano-g up to 25 milli-g where quasi-steady indicates the frequency range from 10^{-5} to 10^{-1} Hz. To accomplish this, the sensor output acceleration signal is filtered with a Bessel filter with a cut-off frequency of 1 Hz. and cut-off rate of 120 dB per decade The output signal is initially processed at 10 samples per second and is then further processed and digitally filtered onboard the OARE instrument with an adaptive trimmean filter prior to the normal EEPROM storage. The trimmean data samples cover 50 second periods every 25 seconds. The regular 10 sample per second data were recorded on the payload tape recorder.

In flight, the OARE instrument is subjected to higher amplitude and higher frequency accelerations (due to the Reaction Control System (RCS) thrusters, structural vibrations, and crew activities) in addition to the quasi-steady accelerations due to the gravity gradient, on-orbit drag, slow shuttle body rotations, and long period venting.

In order to obtain the optimum estimate of the quasi-steady acceleration under these conditions, a robust adaptive estimator has been implemented as part of the OARE analysis system. The particular estimator used is known as the Hogg Adaptive Trimmean estimator [1,2]. The bias estimate using the trimmean estimator of the acceleration is critical to the accuracy of acceleration measurements. During all previous missions, the data have been processed using the trimmean estimator because it provides the best estimate of the quasi-steady acceleration.

It has been the conventional wisdom that the quasi-steady acceleration effects are the most relevant to fluid experiments (as well as others) since in these experiments the processes have a finite reaction time and are believed to be quite insensitive to high frequency accelerations. However, although the structural vibrations and crew activities induce only AC components of acceleration, the thruster firings produce a significant DC component of acceleration even though it is mostly high frequency relative to 0.1 Hz. The Trimmean filter tends to exclude these measurements from the 50 second trimmean averages, and thus, these short thruster firings do not normally appear in the trimmean processed data appearing in this report. In order to quantify these effects, the 10 sample per second data recorded on the payload taper recorder would need to be processed. This has not been done in this report, but was done on STS-75 where the EEPROM trimmean data were lost [8].

Thus, for STS-94 (MSL-1R) the only measure of acceleration presented is the 50 second trimmean average calculated every 25 seconds as has been done on all previous OARE missions.

A detailed discussion of the data analysis undertaken for STS-94 is presented in Appendix A along with the bias estimates using estimated measurement errors based upon the distributions of the measured data. This mission incorporated a full weighted least squares estimate of bias as was done on STS-73. [6]

The complete digital acceleration data presented in this report, as well as the raw payload tape recorder data at 10 samples per second which have not been processed by the trimmean filters, are available from the Microgravity Measurements and Analysis Program (MMAP) at NASA Lewis Research Center.[7]

The temperature environment was relatively benign except for the large temperature excursion during the initial thermal pulse generated during launch on STS-94. The instrument temperature in degrees Celsius (measured on the proofmass housing) is shown in Figure 1.

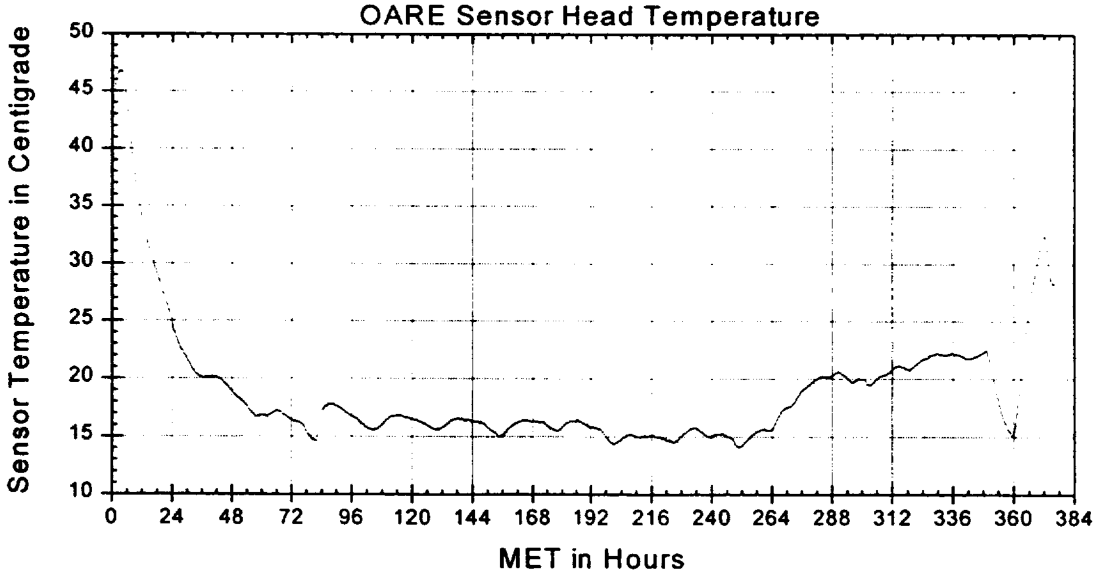

Figure 1. STS-94 Instrument (Sensor Head) Temperature.

2.4 Orbiter Body Axis Acceleration Results

The accelerations measured by OARE at the OARE location in the Shuttle Body Axes coordinate system (X, toward the nose; Y, toward the starboard wing; Z, down through the belly) are shown in Figures 2a through 2d.

Figures 2a through 2d show the trimmean acceleration measured at the OARE location during the entire OARE operational time. This measure of acceleration represents the acceleration due to the quasi-steady forces in that the larger short-period pulses are effectively removed from the data by this filter. The acceleration measurement set has small gaps in it during the periods when bias and scale factor calibrations are being made.

This gives an overview of the data, but it may not be in enough detail to meet the requirements of each experimenter. Also, the experimenter may want the acceleration transformed to the particular experiment's location. For additional detail, the complete set of data is available from the PIMS Group at Lewis Research Center. [7] The low frequency accelerations can also be calculated at the experimenter's location by the PIMS group using the OARE measurements and other shuttle parameters. Canopus Systems would be happy to answer any questions about OARE operations or the processed OARE data at the OARE location.

2.5 STS-94 Anomalous Performance

OARE's performance on STS-94 was similar to that on previous missions The Z-axis C-range scale factor calibration was still affected by jitter to a small degree.

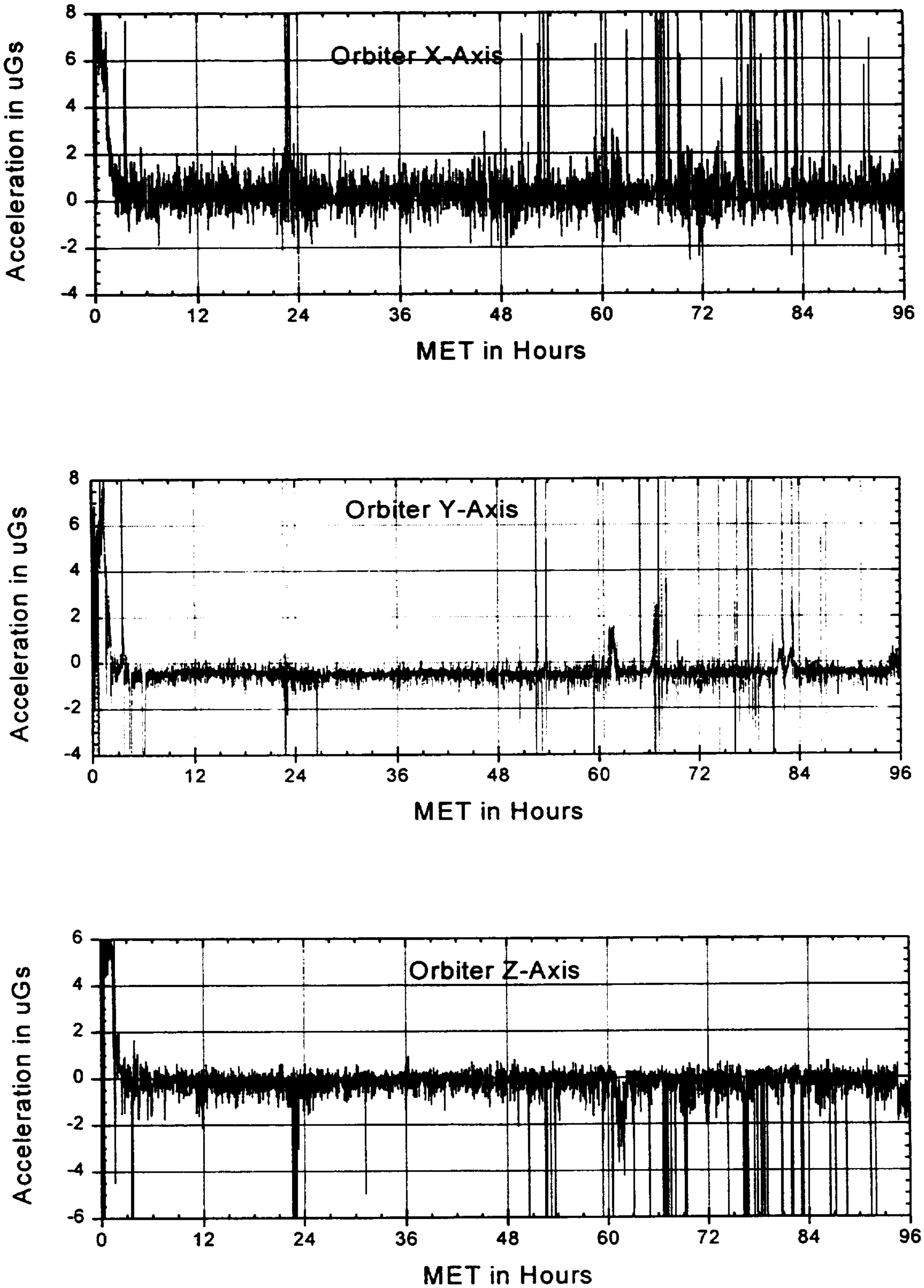

Figure 2a. Quasi-Steady Acceleration at the OARE Location, MET 0-96 Hours.

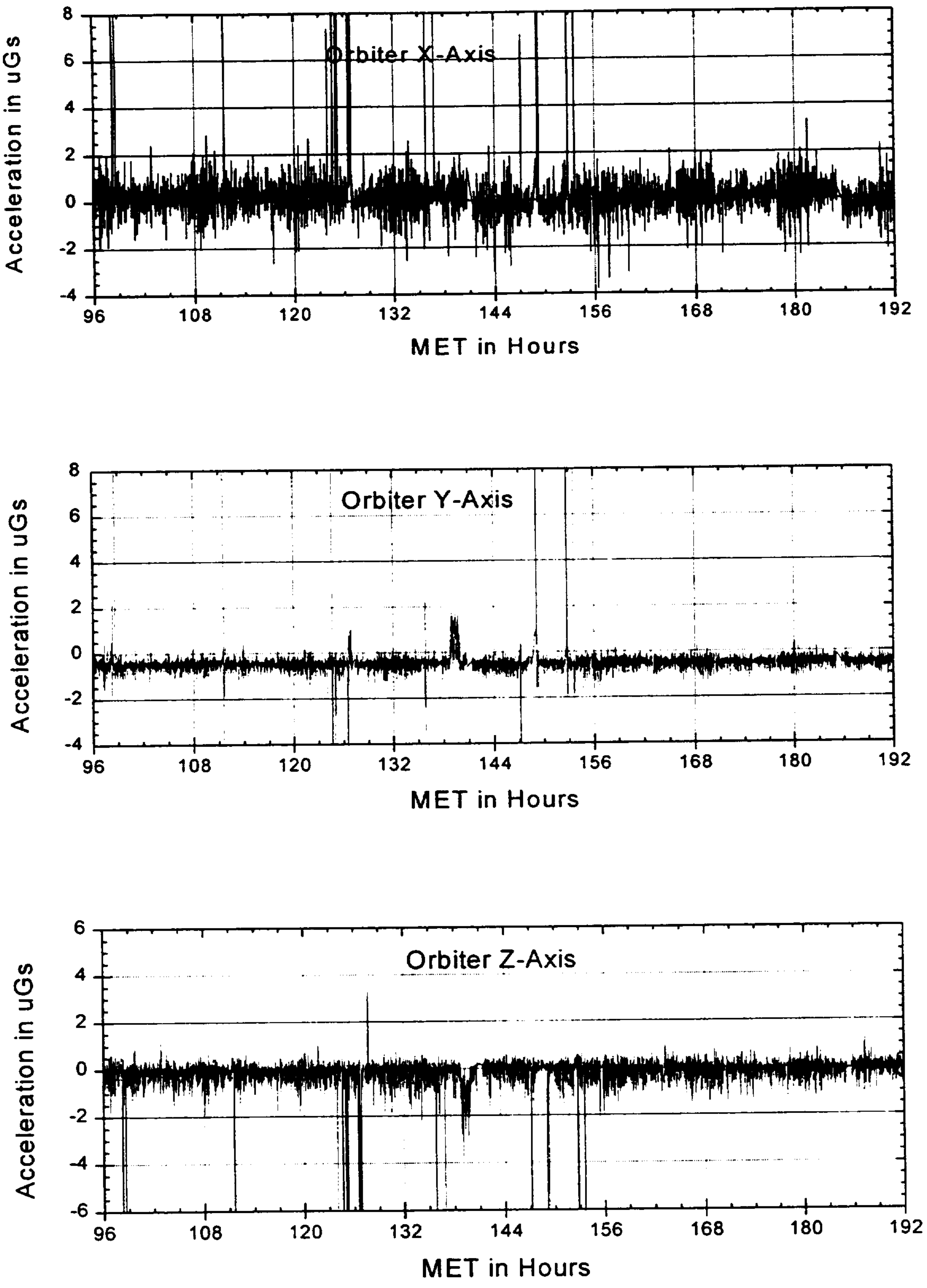

Figure 2b. Quasi-Steady Acceleration at the OARE Location, MET 96-192 Hours.

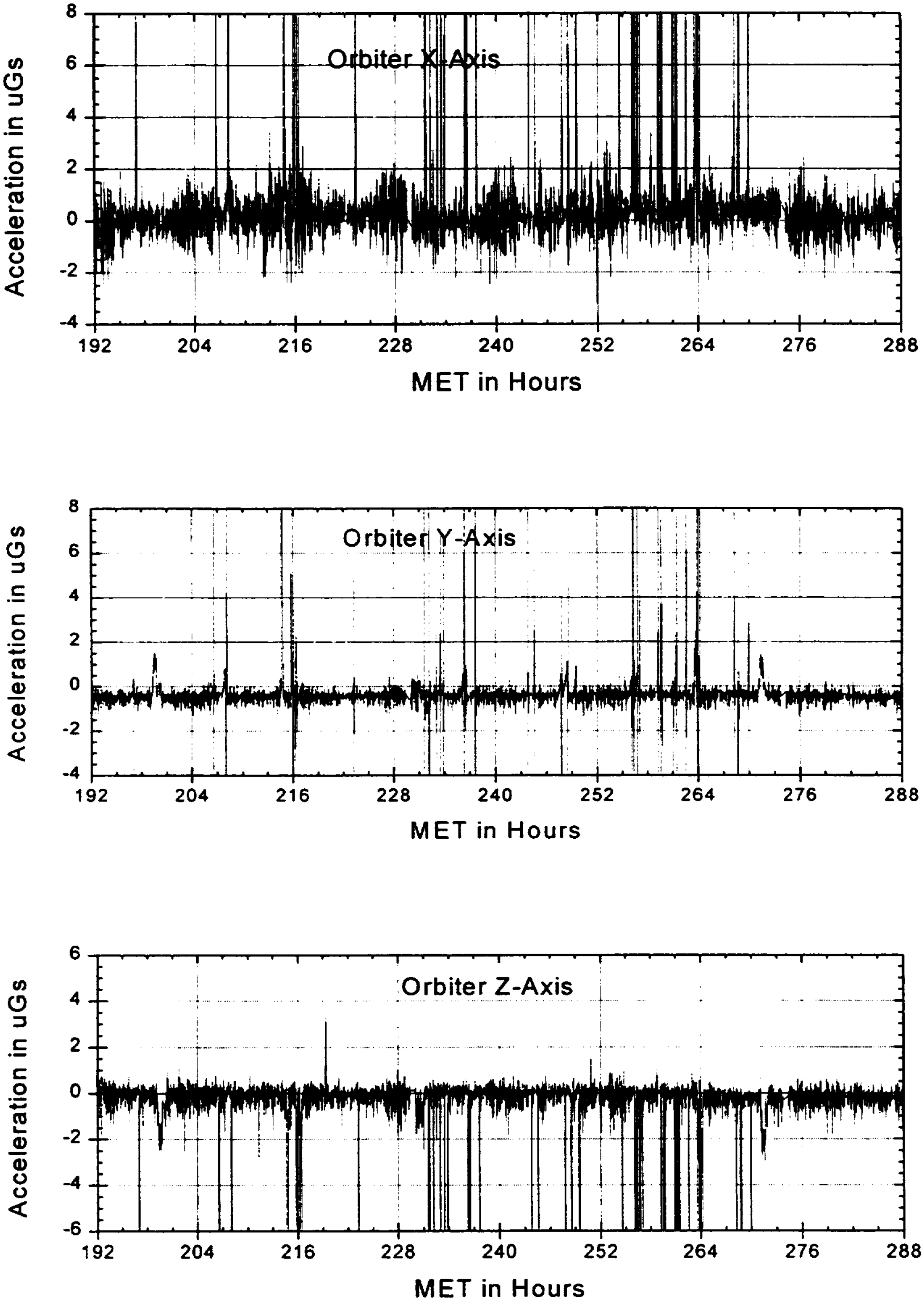

Figure 2c. Quasi-Steady Acceleration at the OARE Location, MET 192-288 Hours.

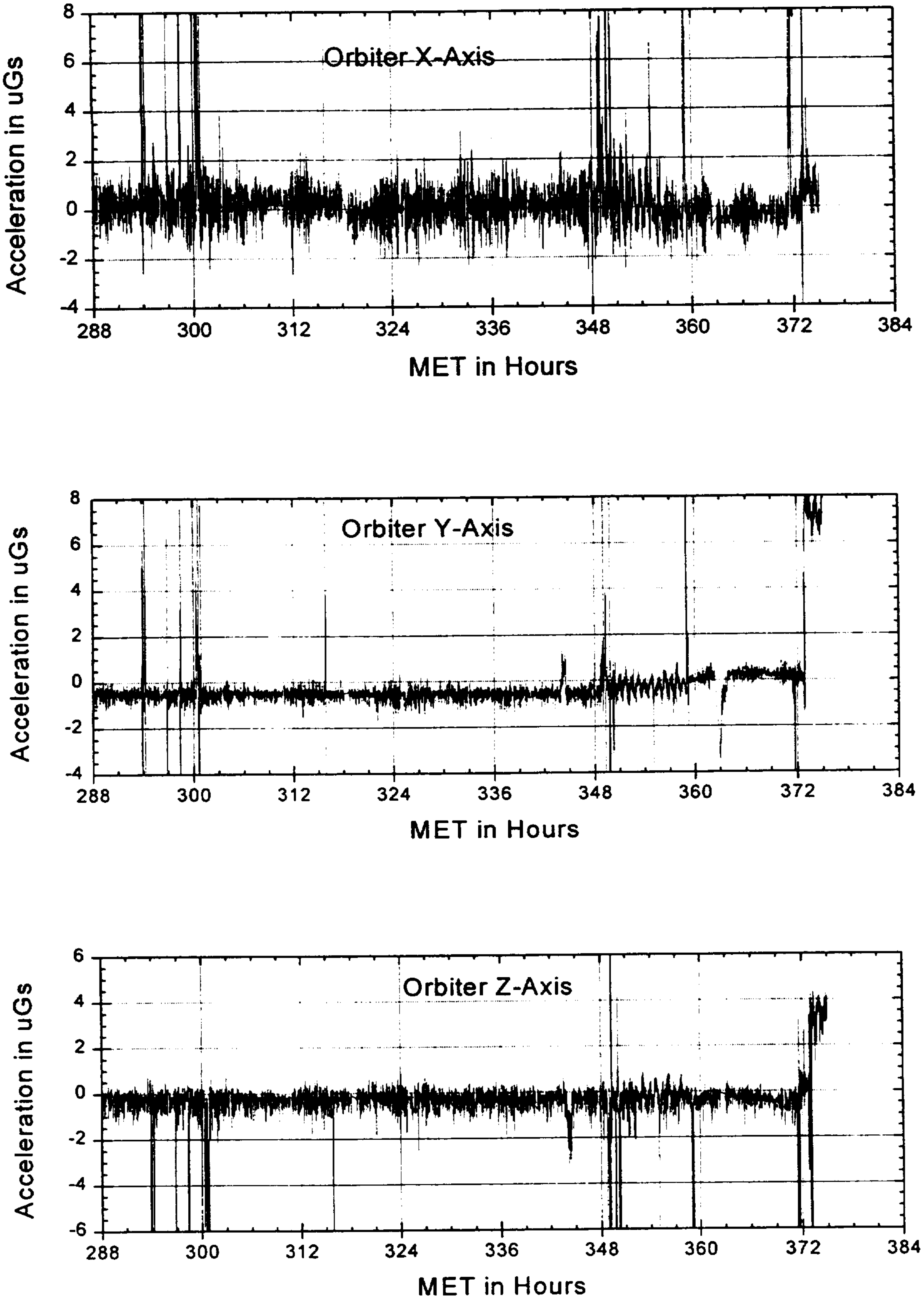

Figure 2d. Quasi-Steady Acceleration at the OARE Location, MET 288-384 Hours.

3.0 OARE ACCURACY ANALYSIS

The OARE instrument provides high resolution measurements of sensor input axes accelerations, 3.05 nano-Gs in the X-axis and 4.6 nano-Gs for the Y and Z axes. The accuracy of these measurements is primarily determined by the degree to which the instrument can be calibrated over the time period of the measurements. Major sources of potential errors are the accuracy obtainable from the bias and scale factor calibrations.

3.1 Bias Errors

On STS-94, the bias was measured 82 times. From these measurements, the true bias was estimated by the fitting procedure discussed in Appendix A. Potential errors in these bias estimates arise from the statistical nature of the bias measurements as well as from potential systematic errors which have not been identified. Based upon the analysis contained in Appendix A, we estimate that the bias errors on range C are approximately 50 nano-Gs. These are consistent with the earlier analysis contained in the STS-65 Final Report [5].

3.2 Scale Factor Errors

In the microgravity environment of the Orbiter, the quasi-steady trimmean acceleration measurements are typically on the order of 1 micro-g or less. Under these conditions, the bias errors are larger than the scale factor errors.

Measurements of the scale factors made during flight and those on the ground are now consistent to within 1 to 2 percent. We estimate the scale factor errors to be about 1 to 2 percent of the measured acceleration. These could be reduced with further study. At a 1 micro-g level, this corresponds to a 10 to 20 nano-G error. These should be added in quadrature with the bias errors. So overall, this gives estimated errors for the on-orbit acceleration measurements of about 50 to 60 nano-Gs. Scale Factors were estimated from the Scale Factor measurements made on this mission.

3.3 Quasi-Steady Acceleration Measurements

As indicated, the primary OARE data recorded on the flight computer is processed through an adaptive trimmean filter. This trimmean filter provides a near optimum estimate of the mean of the quasi-steady acceleration population of measurements over the 50 second sampling period. This estimate is particularly beneficial in the calculation of the bias estimate and the estimate of the quasi-steady acceleration due to orbital drag, gravity gradient, and slow body rotations. However, it tends to reject the effects of crew activity, thruster firings, and other exogenous events. Experimenters may be interested in the regular average of the acceleration measurements over the 50 second sample period or other acceleration measurement metrics. In any case, the regular average and other filters could be applied to the payload tape recorder data for those periods where the data exist.

4.0 REFERENCES

1) R.V. Hogg, "Adaptive Robust Procedures: A Partial Review and Some Suggestions for Future Applications and Theory," Journal of American Statistical Association, Vol. 69, Number 348, December 1974, pp 909-927.

2) T. DeWet, J.W.J. VanWyk, "Efficiency and Robustness of Hogg's Adaptive Trim Means," Commun. Stastist.-Theor. Meth., A8(2), pp 117-128, 1979.

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5)"STS-65 Final Report," OARE Technical Report #146, Canopus Systems, Inc., November 1994.

6) "STS-73 (USML-2) Final Report," OARE Technical Report #147, Canopus Systems, Inc., February 1996.

7) Microgravity Measurement and Analysis Program (MMAP) at Lewis Research Center. Program Manager of Principle Investigator of Microgravity Services (PIMS) is Duc Truong, (216) 433-8394. E-mail to duc.truong@lerc.nasa.gov. Data file server is beech.lerc.nasa.gov.

8) "STS-75 (USMP-3) Final Report," OARE Technical Report #148, Canopus Systems, Inc., June 1996.

9) "STS-78 (LMS-1) Final Report," OARE Technical Report #149, Canopus Systems, Inc., September 1996.

10) "STS-83 (MSL-1) Final Report," OARE Technical Report #150, Canopus Systems, Inc., May 1997.

APPENDIX A
OARE DATA CALIBRATION AND PROCESSING

This Appendix reviews the methods used to calculate the Orbiter body triaxial acceleration based on the OARE instrument measurements which were recorded on the EEPROM, downloaded, and then processed by Canopus Systems. The method of estimating the sensor bias has evolved over the past several missions; STS-73 was the first mission where a full weighted least squares methodology has been implemented in estimating the instrument bias. The Appendix begins with the instrument model (A1), discusses the trimmean filter used in processing the raw OARE accelerometry data (A2), presents the weighted least squares estimate of the bias of the instrument (A3)and finally presents a short discussion of Scale Factor calibration (A4).

A1 INSTRUMENT MODEL

The OARE instrument acceleration for each axis and range is calculated from an equation of the form

$$A_A = -SF_C * SF_N * (CTS - 32768 - BIAS) \quad \text{(eq. 1), where}$$

A_A is the calibrated actual acceleration in uGs,
SF_C is the Scale Factor Calibration term,
SF_N is the Nominal Scale Factor in uGs per count,
CTS is the counts out of the instrument A/D converter, and
BIAS is the estimated Bias in counts as a function of time and temperature,
where each of the terms is dependent upon the particular axis and range.

In the above equation, the number 32768 appears because the 16-bit A/D converter is single-ended; this value is the offset required to obtain a zero measured acceleration for a zero input acceleration when there is no bias.

An Actual Scale Factor SF_A term is defined by

$$SF_A = SF_C * SF_N \quad \text{(eq. 2).}$$

Values of the nominal scale factor, SF_N, are given in Table 1 of the main report for each OARE axis and range. Values of SF_C for the OARE X, Y, and Z axes are approximately 1.02, 1.11, and 1.10, respectively, but are determined through calibration on each STS mission for each axis and range.

The output of the A/D converter provides a raw digital acceleration data sample which is effectively processed at a rate of 10 times per second. Data are normally stored on the EEPROM at a rate of once every 25 seconds, and these data represent the trimmean filtered estimate of the quasi-steady acceleration value over a 50-second period.

A2 HOGG ADAPTIVE TRIMMEAN FILTER USED IN PROCESSING OARE ACCELERATION MEASUREMENTS

The OARE instrument is designed to measure the quasi-steady acceleration from below 10 nano-Gs up to 25 milli-Gs and over the quasi-steady bandwidth from 10^{-5} to 10^{-1} Hz. The quasi-steady acceleration components of primary interest are those due to gravity gradient, on-orbit drag, inertial rotations, and perhaps long period venting or gas leaks. However, the instrument is subjected to higher amplitude and higher frequency accelerations (such as structural vibration, station keeping thruster firings, and crew effects) in addition to the quasi-steady accelerations. These higher level accelerations are not well characterized nor statistically invariant over the OARE measurement periods.

In order to obtain a more optimum estimate of the quasi-steady acceleration under the conditions of intermittent thruster firings and crew activities, a robust adaptive estimator has been implemented. For a discussion of robust estimators, see Reference 1. The particular estimator implemented in OARE is known as the Hogg Adaptive Trimmean estimator and is described in more detail in Reference 2.

In essence, the trimmean adaptive filter removes a percentage of the distribution from each tail and then calculates the mean of the remaining distribution. It first measures the departure of the sample distribution from a normal (Gaussian) distribution as measured by a parameter called Q, then adaptively chooses the amount of the trim to be used on the distribution, and finally calculates the mean of the remaining distribution after the trim. This filter is designed to remove the effect of a contaminating distribution (such as a thruster firing) superimposed on a normal distribution (of instrument noise, high frequency vibrations, crew activities, quasi-steady accelerations, etc.),

As implemented, Q is defined by the following equation:

$$Q = [U(20\%) - L(20\%)]/[U(50\%) - L(50\%)] \quad \text{(eq. 3), where}$$

U(X%) is the average of the upper X% of the ordered sample, and
L(X%) is the average of the lower X% of the ordered sample.

In the OARE case, the ordered sample has been a sample of 500 acceleration measurements of the A/D output over a 50-second measurement period.

Q is a measure of the outlier content in the sample. For a Gaussian distribution, Q is 1.75; for samples which have larger tails, Q > 1.75. The value of Q is used to estimate the extent that the quasi-steady acceleration measurements may be contaminated by thruster firings, crew activities, etc.

In order to improve the estimate of the quasi-steady acceleration, a trimmean is used to estimate the mean of the quasi-steady population. A trim parameter alpha is determined by the following algorithm:

$$\text{alpha}(Q) = \begin{cases} 0.05 & \text{for } Q <= 1.75 \\ 0.5 + 0.35^{*} (Q-1.75)/(2-1.75) & \text{for } 1.75 < Q < 2.0 \quad \text{(eq. 4)} \\ 0.4 & \text{for } Q >= 2.0, \end{cases}$$

where alpha is the fraction of the distribution which is trimmed off each tail of the ordered distribution before the mean of the remainder of the distribution is calculated.

Then, for an underlying distribution of n points or measurements with a value of alpha, the trimmean is given by

$$\text{trimmean} = [X_{(k+1)} + X_{(k+2)} + \ldots\ldots + X_{(n-k)}]/(n-2^{*}k), \quad \text{(eq. 5)},$$

where $k = \text{alpha} * n$ (eq. 6) and
$X_{(i)}, X_{(i+1)}, \ldots, X_{(n)}$, is the ordered set of n points making up the sample distribution.

In summary, OARE measures the quasi-steady level of acceleration for each axis every 25 seconds by taking the trimmean of 50 seconds of A/D counts (500 samples in total) according to equations 3 through 6, and then substituting this trimmean for CTS in equation 1. It should be noted that for large pulses in one direction, the effect of the trimmean is to shift the estimate of the mean; it does not preserve the DC component in this case.

The trimmean is particularly appropriate for estimating the bias of the OARE instrument, since one wishes to remove the effect of the thruster on the bias measurement if a thruster firing should occur during the bias measurement period.

Data recorded on the EEPROM and available to support the acceleration calculations include the trimmean of the 50-second distribution every 25 seconds, the Q of this sample distribution, the Average Deviation from the trimmean of the distribution used to calculate the trimmean, the instrument temperature, the Mission Elapsed Time (MET), and numerous housekeeping parameters.

The widths of the 500 sample distributions (as measured by the standard deviations) are almost entirely due to the environment aboard the shuttle and not due to sensor noise. This has been illustrated in the figures of the STS-78 Final Report [6]. On STS-78, the whole crew had common sleep periods; this gave rise to very small variations in the data obtained during a sleep period. During these periods, the instrument output is extremely quiet as opposed to periods when there is crew activity. On most missions as on STS-94, the crew has been active 24 hours per day and consequently noisier data from a quasi-steady point-of-view has resulted.

A3 BIAS MEASUREMENTS AND ESTIMATED MEASUREMENT ERRORS

As can be seen in Equation 1, the calculated acceleration depends upon the instrument bias. This is a critical parameter in accelerometers that are designed to measure quasi-steady or DC accelerations below 1 milli-G. For on-orbit conditions, the typical quasi-steady or DC acceleration is less than 1 micro-G. Thus, the bias estimate is absolutely critical to accurate acceleration measurements in this regime.

The OARE accelerometer uses an electrostatically suspended proofmass in order to minimize the effects of temperature and mechanical suspension hysteresis on the bias. In addition, OARE incorporates a two-axis gimbal calibration table by which the OARE instrument can be calibrated on-orbit for bias and scale factor in each of its three axes.

A3.1 Bias Measurements

The bias measurement for a single axis consists of the following sequence: 1) measuring the acceleration output in trimmean counts for 50 seconds in the normal table position for a given axis (called $BIAS_N$), 2) rotating the input axis 180^o, and then 3) measuring the acceleration output in trimmean counts (called $BIAS_I$, for inverted position). Assuming that the actual input acceleration remains constant during this period (about 125 seconds), as might be expected for quasi-steady accelerations, then the bias can be calculated by

$$BIAS_M = (BIAS_N + BIAS_I)/2 - 32768 \qquad \text{(eq. 7), where}$$

$BIAS_M$ is the measured bias for a particular axis,
$BIAS_N$ is the bias measurement in the normal position, and
$BIAS_I$ is the bias measurement in the inverted position.

During a single mission, the bias is measured for each axis many times for the C-range. These bias measurements then provide the basis for estimating the bias time history throughout the mission. The bias estimates are ultimately determined by fitting a functional form through these bias measurements.

A3.2 Sources of Noise Associated with the Bias Measurement

The sources of noise which contribute to measurement errors on the bias measurements are largely associated with crew activity. The bias measurement accuracy depends upon the input acceleration remaining constant during the time that the bias measurements are being made. The time difference between the two positions used in the bias measurements is about 75 seconds. Clearly, the input acceleration is varying except during the times when the whole crew is asleep. During most missions, one segment of the crew is active at all times. Under these conditions, the bias measurements contain significant measurement errors which cannot be eliminated. A method of estimating the measurement errors on the bias has been developed and is discussed in Reference 5.

A3.3 Bias Estimates Based Upon Weighted Least Squares Fits

The bias was measured 82 times on STS-94 for each of the three axes on the C-range. Using the methodology discussed in Reference 5, estimates of the measurement errors associated with each bias measurement were calculated. The results for the OARE X, Y, and Z axes are shown in Figures A-1, A-2, and A-3, respectively. The bias measurements are shown along with their associated measurement error bars.

As can be seen, there is considerable variation of the individual bias measurements, but the variation is generally explained by the measurement errors associated with the bias measurements. There are a few bias measurements which are widely separated from the others. These could be a result of thruster firing during the bias sequence. During the times that the crew was inactive, measurements were more accurate as indicated by the smaller estimated measurement errors.

The bias can be characterized by an initial transient after launch as a function of time and a small dependence upon temperature. In the same manner since STS-62 [3] except for this case we used only one exponential, we have fitted the measured bias data with a function of the following form:

$$\text{Bias} = A_1 + A_2 * e^{-(t/t0)} + A_3 * e^{-(t/t1)} + A_4 * T \quad \text{(eq. 8)},$$

where A_1, A_2, A_3, A_4, t0 and t1 are fitted coefficients, t is the mission elapsed time in hours, and T is the instrument temperature in degrees Celsius.

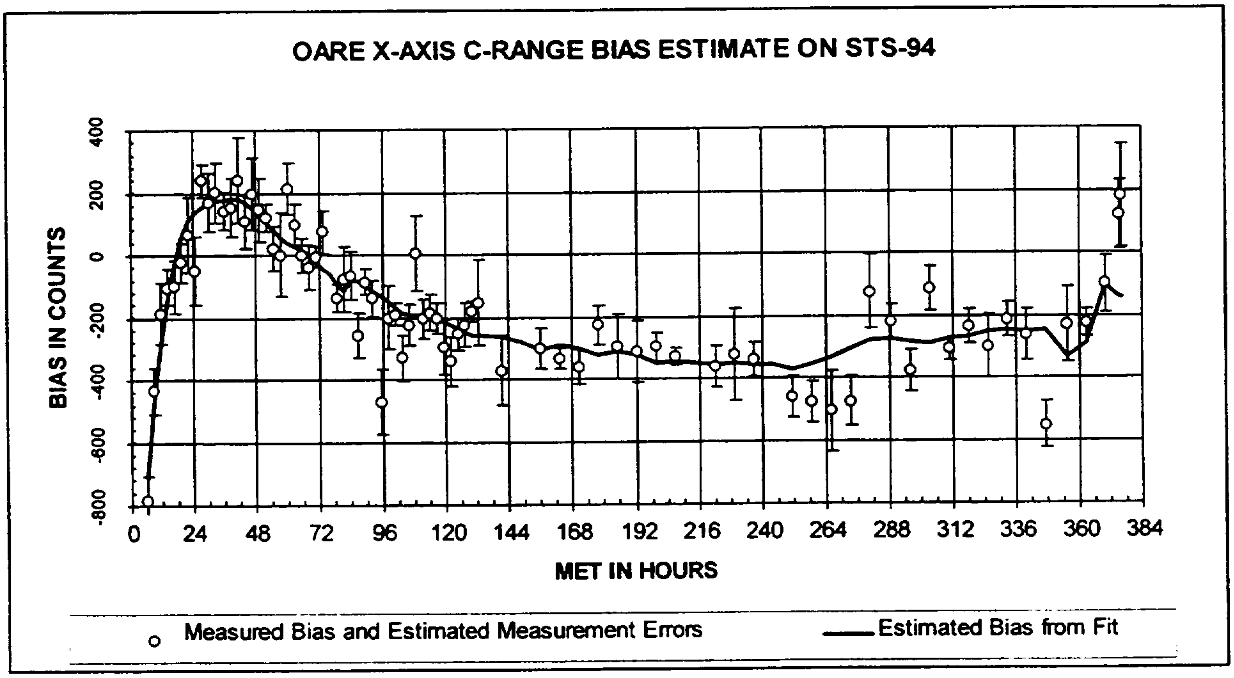

Figure A-1. Bias Measurements and Fitted Estimate for OARE X-Axis on STS-94.

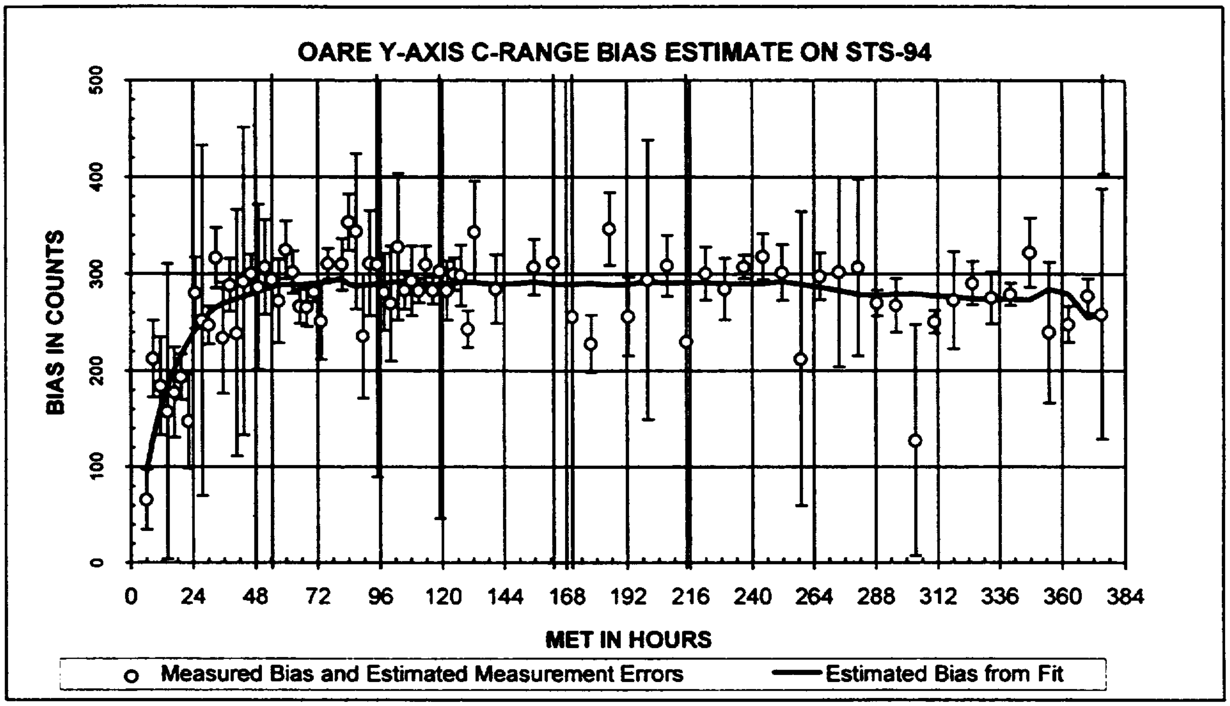

Figure A-2. Bias Measurements and Fitted Estimate for OARE Y-Axis on C-range.

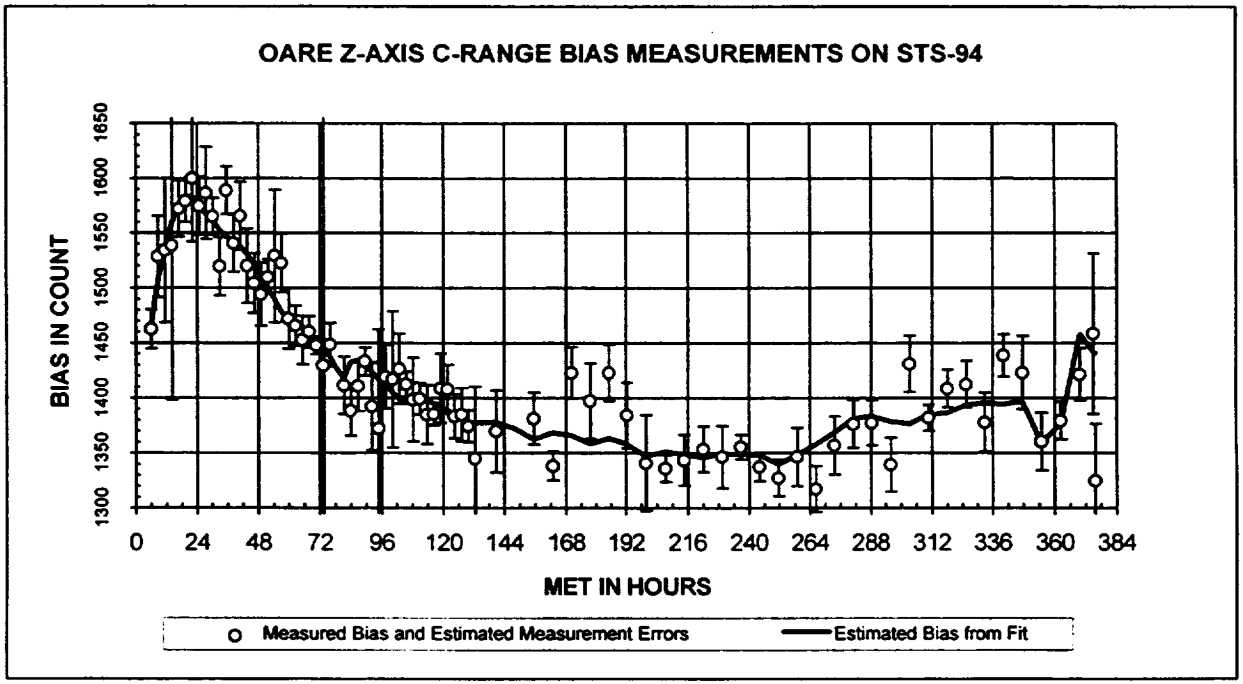

Figure A-3. Bias Measurements and Fitted Estimate for OARE Z-Axis on C-Range.

A weighted least squares procedure was used to determine the coefficients for the C-range. As part of the fitting procedure, several data, which were significantly off the fitted curve or which appeared to occur when there was thruster activity as indicated by large acceleration signals, were removed from those included in the fit and the fitting procedure was repeated for the C-range fits. The plots show all the data points whether they were included in the fit or not. For the B and A ranges where there were not bias calibrations prior to MET 140 hours at which time the bias is changing, the bias was estimated for these times by performing a linear regression between the C bias estimates and the B bias measurements or between C bias estimates and A bias measurements for those times where there were bias measurements. As a result, the B and A bias estimates are linearly related to the C range estimates. This implies that the B and A range estimates have the same time constants as the C range estimates for each axis. Results from these fits are shown in the following table.

The bias calculated by equation 8 is then used to estimate the actual bias during the mission as a function of MET and instrument temperature. This bias is then used to calculate the actual acceleration using equation 1. We believe that the error in the acceleration measurements associated with this bias estimation procedure is about 50 nano-Gs. The error could be further reduced if there were more quiet periods during the mission when a low noise bias calibration could be performed.

Table A-1. STS-94 Bias Fits to EEPROM Data

OARE X-AXIS			
Range	**A**	**B**	**C**
Fitted Constant A1	13.78	-58.68	-626.03
Fitted Constant A2	-67.91	-354.65	-3210.35
Fitted Constant A3	28.02	144.36	1324.83
Fitted Constant A4	0.361	1.884	17.051
Fitted Constant to	12.8	12.8	12.8
Fitted Constant t1	51	51	51
R-Squared of Fit			0.913
Number of Measurements			68
Degrees of Freedom			64
Chi-Squared			62.96
OARE Y-AXIS			
Range	**A**	**B**	**C**
Fitted Constant A1	15.56	33.12	320.58
Fitted Constant A2	-76.60	-56.48	-219.36
Fitted Constant A3	3.86	28.48	11.06
Fitted Constant A4	-0.774	-0.571	-2.217
Fitted Constant to	13.5	13.5	13.5
Fitted Constant t1	200	200	200
R-Squared of Fit			0.981
Number of Measurements			71
Degrees of Freedom			67
Chi-Squared			54.56
OARE Z-AXIS			
Range	**A**	**B**	**C**
Fitted Constant A1	170.95	203.49	1232.50
Fitted Constant A2	-31.06	-94.05	-760.46
Fitted Constant A3	15.70	47.53	384.30
Fitted Constant A4	0.301	0.912	7.377
Fitted Constant to	10.5	10.5	10.5
Fitted Constant t1	51	51	51
R-Squared of Fit			0.999
Number of Measurements			73
Degrees of Freedom			69
Chi-Squared			63.88

A4 SCALE FACTOR CALIBRATION

Scale factor measurements are made by applying a known non zero signal to the sensor and electronics for each channel and each range. These measurements may be contaminated by noise in the external environment or by internal noise in several forms.

For OARE, the method of scale factor calibration involves rotating the Motor/Table Subsystem (MTS) (sometimes called "the table") at a known angular rate ω with a fixed sensor to center-of-rotation offset radius r. The known signal is thus the controlled centripetal acceleration. While collecting scale factor data, the sensor also experiences a bias (assumed constant) and is exposed to an external signal. Data collected before and after the scale factor slew assists in removing the bias and external signal effect.

The basic scale factor measurement model is shown in Figure A-4.

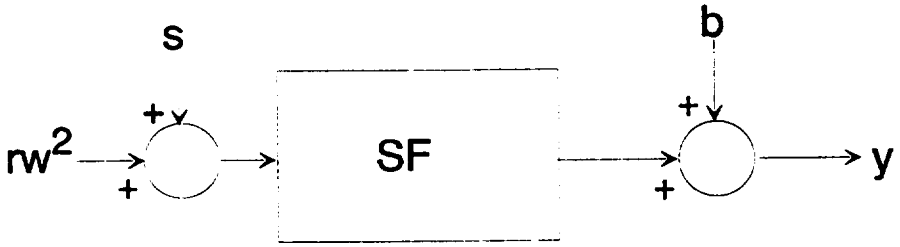

Figure A-4. Scale Factor Measurement Model

From this model, the k^th^ measurement y_k is given by

$$y_k = (r\omega^2 + s_k)/SF_A + b_k \quad \text{(eq. 9)},$$

where s_k is the signal at the kth measurement time and b_k is the internal bias at the kth measurement time. We assume that ω is constant throughout the slew. We also assume that s_k contains two components: (1) an acceleration signal which is fixed with respect to the MTS base throughout the slew and (2) a noise input with zero mean. To eliminate noise, consider averages of the measurements over the data set (with length n)

$$\bar{y} = (r\omega^2 + \frac{1}{n}\sum_{k=1}^{n} s_k)/SF_A + \bar{b} \quad \text{(eq. 10)},$$

where $(\bar{\ })$ is the average value of ( ).

From this equation we can find the actual scale factor SF_A. Here, $\bar{y}$ is the average of the measurements and $r\omega^2$ is known. The remaining unknown, s_k, is a combination of the external signal and noise. This is related to the midpoint measurement (MP). During the slew, the sensor records varying magnitudes of the external signal. The bias and centripetal acceleration, however, remain fixed in magnitude. If the measurements are centered around the midpoint, the midpoint measurement can be used to estimate this external signal and remove it from the scale factor equation. It can be shown that the influence that the external signal and bias have on the scale factor measurements is related to the sinc function (sin (x)/x) of the angular travel. The actual scale factor can then be found from the following equation:

$$1/SF_A = \frac{\bar{y} - MP(\sin(\delta)/\delta) - (1-(\sin(\delta)/\delta))\bar{b}}{r\omega^2} \quad \text{(eq. 11).}$$

Previous analysis has shown that these scale factors vary by less that 2% [7].

Table A-2. Scale Factor Correction Factors for STS-94 OARE Axes and Ranges

AXIS	RANGE	VALUE
X	A	1.050
X	B	1.035
X	C	1.035
Y	A	1.142
Y	B	1.142
Y	C	1.108
Z	A	1.097
Z	B	1.120
Z	C	1.086*

*This Scale Factor Correction was computed from the B range measurement.