Section 12

Analysis Techniques for Quasi-steady Data

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Acronyms and Abbreviations

µg	micro-g, 10^{-6}g
CM	Center of Mass
CMG	Control Moment Gyro
CGF	Crystal Growth Facility
CWC	Collapsible Water Container
DC	Direct Current (mean value)
ER	EXPRESS Rack
EVA	Extravehicular Activity
EXPRESS	Expedite the Processing of Experiments to the Space Station
FGB	Functionalui Germatischeskii Block
g	acceleration due to free-fall (9.81 m/s²)
gg	Gravity gradient
GMT	Greenwich Mean Time
GNC	Guidance, Navigation and Control
GRC	Glenn Research Center
Hz	Hertz
ISS	International Space Station
LAB	Laboratory
LAB1O2	US LAB Overhead Bay #2
LMS	Life and Microgravity Spacelab
LVLH	Local Vertical Local Horizontal

MAMS	Microgravity Acceleration Measurement System
NASA	National Aeronautics and Space Administration
OARE	Orbital Acceleration Research Experiment
OSS	OARE Sensor Subsystem
PAD	PIMS Acceleration Data
PIMS	Principal Investigator Microgravity Services
QTH	Quasi-steady Three Dimensional Histogram
RMS	Root-Mean-Square
RSS	Root-Sum-Square
s, sec	Seconds
SAMS	Space Acceleration Measurement System
TEA	Torque Equilibrium Attitude
TMF	Trimmed Mean Filter
SSA	Space Station Analysis Coordinate System
STS	Space Transport System
USML-2	2nd United States Microgravity Laboratory
USMP-3	3rd United States Microgravity Payload
XPOP	X Principal Axis Perpendicular to the Orbit Plane
XVV	X body axis toward the Velocity Vector
YVV	Y-axis toward Velocity Vector
ZLV	Z-axis in Local Vertical

Overview of Topics

Topics for discussion

- **OARE and MAMS Data Description**

- **Description of trimmed mean filter (TMF)**

- **Bias calibration**

- **Data storage**

- **Analysis and display of quasi-steady data**

OARE and MAMS Data Description

OARE and MAMS Data

- **OARE and MAMS data are recorded and stored in an inertial frame of reference**
  - an acceleration of the vehicle in the positive x-axis direction is reported as a positive x-axis acceleration even though a free particle may appear to move in the negative x-axis relative to the accelerating vehicle

- **MAMS OSS (OARE Sensor Subsystem) is located onboard the International Space Station, inside the US Module.**
  - Since Flight 6A (April 2001), EXPRESS Rack 1, LAB1O2

- **OARE stored in Orbiter body coordinates and MAMS OSS Trimmed Mean Filtered (OSSBTMF) data is stored in Space Station Analysis Coordinates.**

- **Sensor Coordinate systems**

  OARE vs. Orbiter Body

  $$\begin{bmatrix} X_b \\ Y_b \\ Z_b \end{bmatrix} = \begin{bmatrix} X_{OARE} \\ Z_{OARE} \\ -Y_{OARE} \end{bmatrix}$$

  MAMS OSS vs. SSA

  $$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} X_{OSS} \\ -Z_{OSS} \\ Y_{OSS} \end{bmatrix}$$
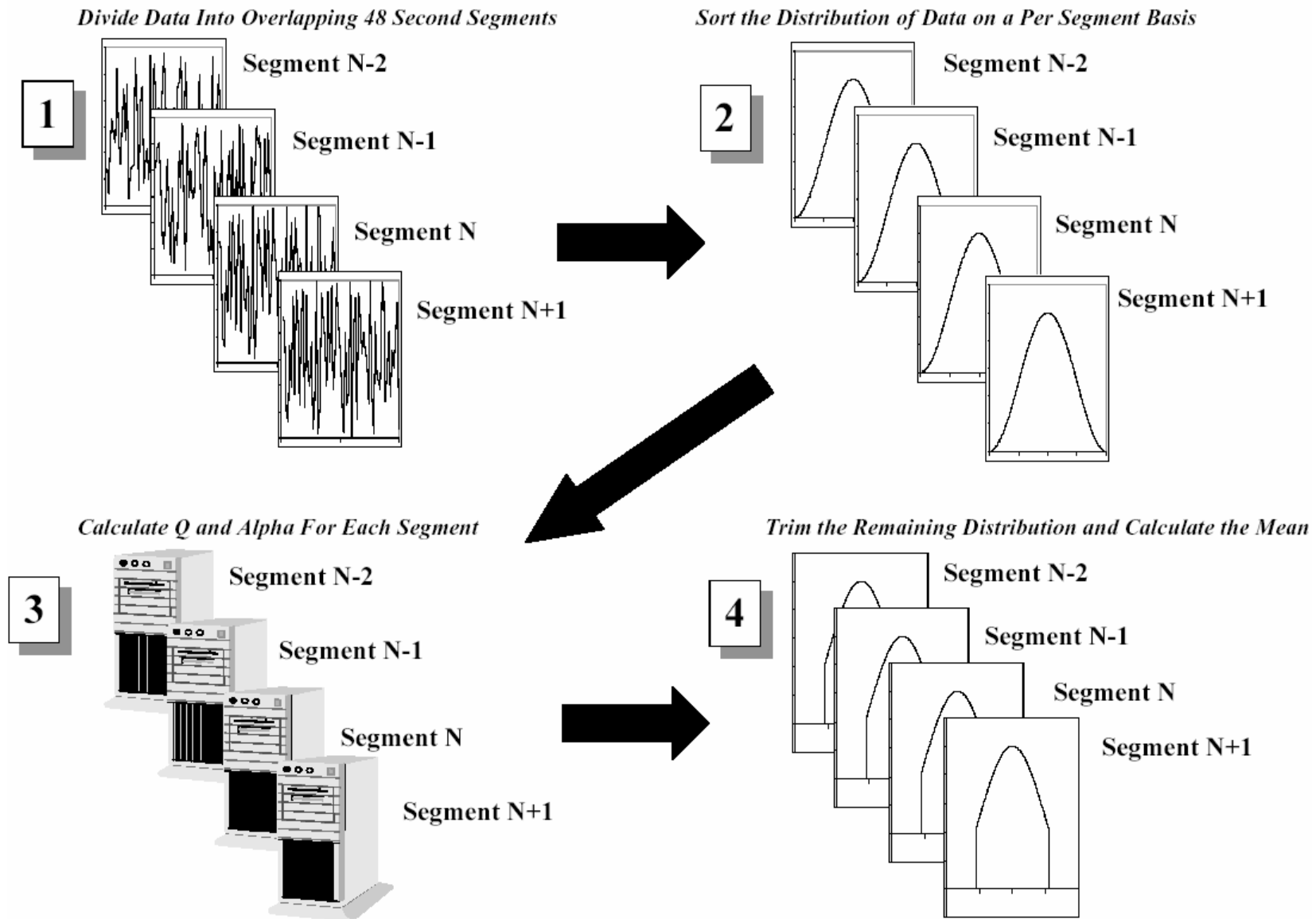
Trimmed Mean Filter Definition

Trimmed Mean Filter Description

- **The trimmed mean filter (TMF) is an adaptive, robust[1] estimator designed to compute a "good" estimate of the quasi-steady acceleration signal by rejecting higher-frequency transients (thruster firings, crew activity, etc.)**

- **TMF utilizes a sliding window to operate on a segment of data of pre-defined length**

- **The sliding window operates such that a segment of the Nth window of data is included in the (N+1)th window, resulting in some portion of data being considered in two consecutive TMF operations.**

1. Hogg, Robert V., "Adaptive Robust Procedures: A Partial Review and Some Suggestions for Future Applications and Theory", Journal of the American Statistical Association, Vol. 69 (December 1974).

Trimmed Mean Filter Process

Trimmed Mean Filter Q Statistic

Trimmed Mean Filter Description

- **Consider a window of data of length 48 seconds.**
  - **Step 1 - Divide the data into overlapping segments**
  - **Step 2 - Sort the acceleration data in order of increasing magnitude**
  - **Step 3 - Calculate the parameter Q according to the equation below**

$$Q = \frac{[U(20\%) - L(20\%)]}{[U(50\%) - L(50\%)]}$$

- 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
- Q is a measure of the departure of the distribution contained in the sample from a normal distribution, similar to kurtosis

Trimmed Mean Filter Description

- **Step 4A - Trim off each tail of the ordered distribution according to the value of the TMF parameter alpha**

$$alpha(Q) = \begin{cases} 0.05 & Q <= 1.75 \\ 0.05 + 0.35 * \dfrac{(Q - 1.75)}{0.25} & 1.75 < Q < 2.0 \\ 0.4 & Q >= 2.0 \end{cases}$$

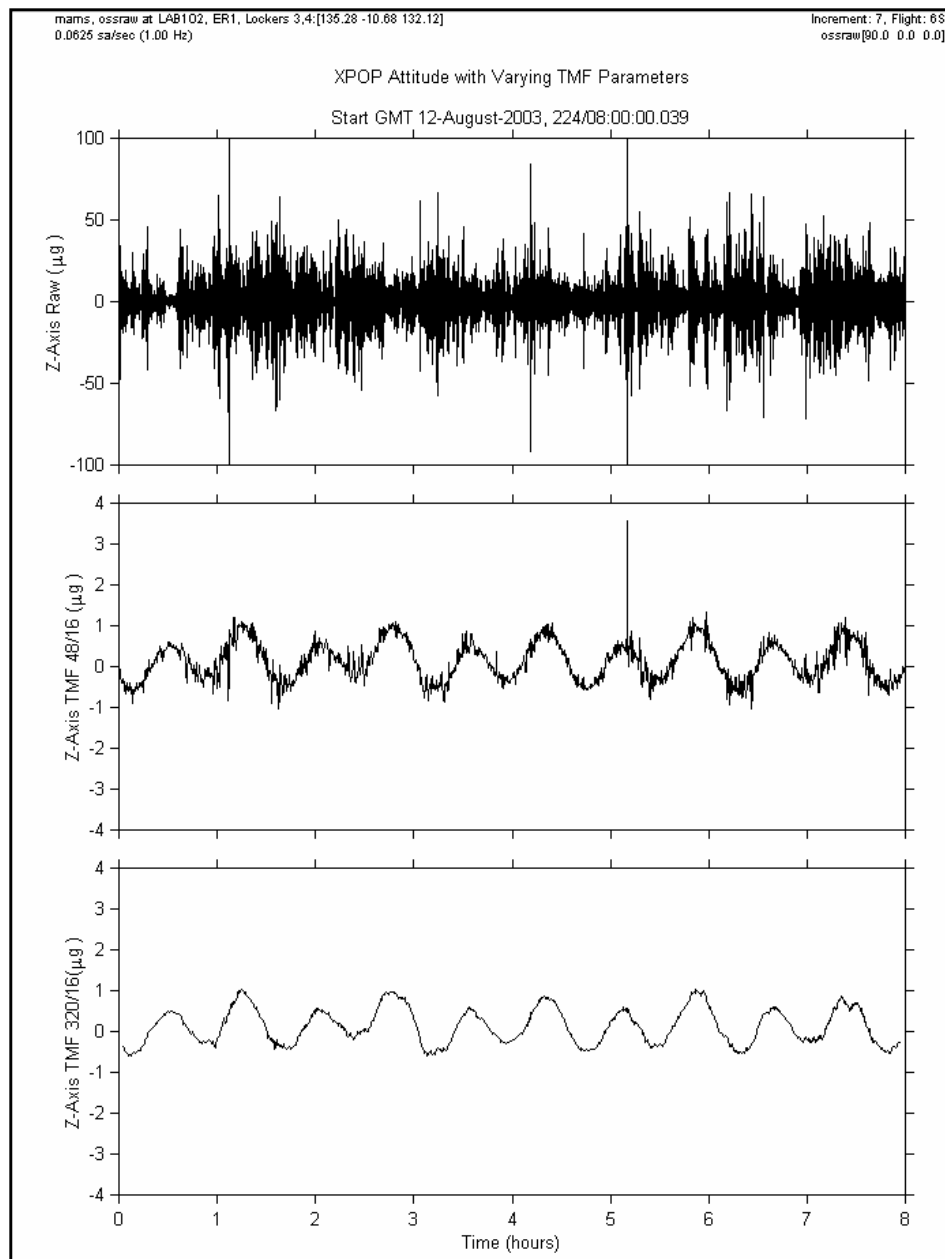- **Step 4B - The quasi-steady acceleration signal is computed to be the arithmetic mean of the trimmed data set.**

More Trimmed Mean Filter Information

Trimmed Mean Filter Description

- **The TMF assumes the signal distribution is symmetric, but not necessarily Gaussian. For a pure Gaussian distribution of data, 5 percent of the data is trimmed from each tail of the original sorted distribution**

- **For a given segment of time, a maximum of 40 percent of the data is trimmed off <u>each tail</u>.**

- **Typical 30-50 percent of the original data being rejected for ISS Operations. (~86% of the time less than 50 percent is rejected.)**

Trimmed Mean Filter Parameters

mams, ossraw at LAB1O2, ER1, Lockers 3,4:[135.28 -10.68 132.12]
0.0625 sa/sec (1.00 Hz)
Increment: 7, Flight: 6S
ossraw[90.0 0.0 0.0]

XPOP Attitude with Varying TMF Parameters

Start GMT 12-August-2003, 224/08:00:00.039

- **Most PIMS implementations of the TMF operate on 480 sample window every 16 seconds (48/16)*.**

- **For past shuttle flights, OARE data was processed with a 500 sample window every 25 seconds (50/25).**

- **Other parameter pairs used in the past include:**
  - **3000 samples every 8 seconds(300/8)**
  - **3000 samples every 30 seconds(300/30)**
  - **3200 samples every 16 seconds(320/16)**

- **Example shows MAMS OSSRAW, Z-axis data from ISS subjected to 48/16 and 320/16 trimmed mean filters.**

*Note: When referring to TMF parameters, often the number of seconds in a sample window is used. MAMS and OARE raw data is recorded at 10 samples per second, so a 480 sample every 16 seconds filter is 48/16.

OARE and MAMS Bias Calibrations

OARE/MAMS Bias Operations

- **Initial transient in OARE bias is caused primarily by dielectric charging of the ceramic insulator material that surrounds the cylindrical axis electrodes**

- **Dielectric charging effects not seen in MAMS. However there is a transient effect in bias due to temperature during warm up period of 4 to 6 hours.**

- **Bias calibrations are nominally performed throughout each mission at regularly programmed intervals**
  - **in-flight correction for bias**
  - **performed for the following additional conditions**
    - sensor instrument temperature change of 5 degrees Celsius since the completion of the last calibration sequence
    - sensor "down ranges" to range not calibrated in the previous calibration sequence
    - ground command initiation

Bias Calibration Sequence

OARE/MAMS Bias Operations

- **Bias calibration sequence of steps for a given axis**
  - **48 seconds of data collected (Measurement 1)**
  - **Trimmed mean filter (TMF) applied to 480 data points**
  - **sensor is rotated 180 degrees and another 48 seconds of data are collected**
  - **TMF applied to the second 480 data points**
  - **the outputs of the two TMF operations are summed and divided by two**
  - **resulting value represents the bias value**

- **It is assumed that between successive data collections during bias calibrations, that the quasi-steady vector does change significantly.**
  - **IDEAL CASE: Quasi-steady environment is identical for both data takes.**

Bias Calibration Illustration
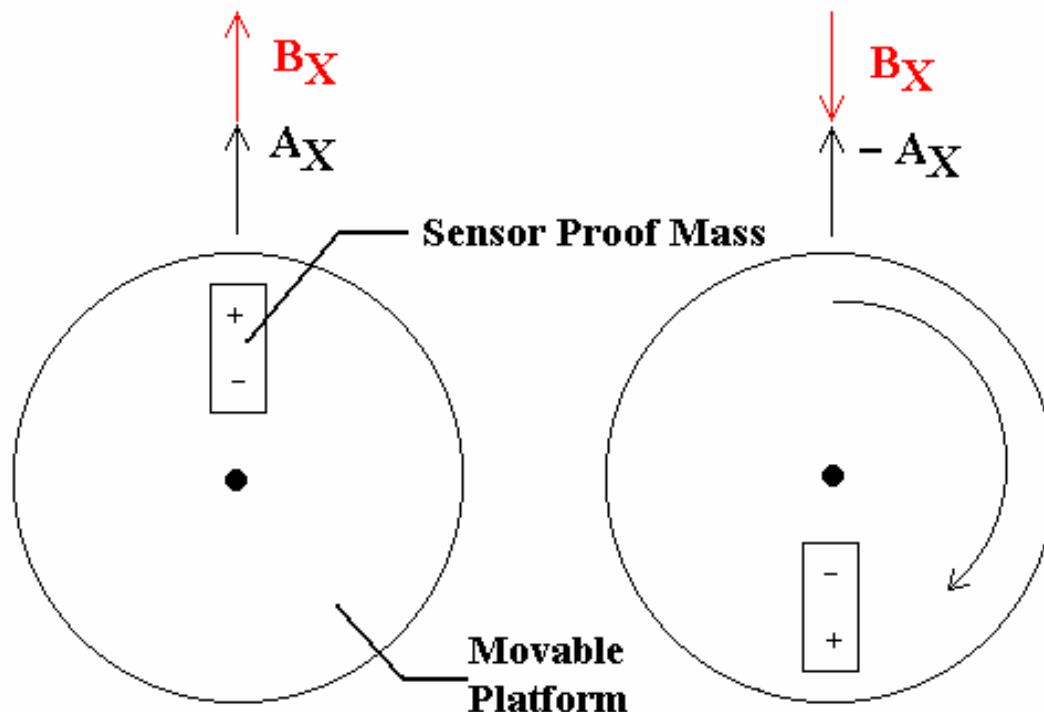
Table at 0 Degrees
$$M_1 = A_X + B_X$$

Table at 180 Degrees
$$M_2 = -A_X + B_X$$

$$\text{Bias} = B_X = \frac{M_1 + M_2}{2}$$

A_X = Acceleration
B_X = Instrument Bias
M = Measurement

X-Axis Bias Calibration Illustration

Quasi-Steady Plot Types

Analysis and Display of Quasi-steady Data

Display Format	Notes
Acceleration versus Time	precise accounting of measured data with respect to time; best temporal resolution
Interval Min/Max Acceleration versus Time	displays upper and lower bounds of peak-to-peak excursions of measured data good display approximation for time histories on output devices with resolution insufficient to display all data in time frame of interest
Interval Average Acceleration versus Time	provides a measure of net acceleration of duration greater than or equal to interval parameter
Trimmed Mean Filtered Acceleration versus Time	removes infrequent, large amplitude outlier data
Quasi-Steady Mapped Acceleration versus Time	use rigid body assumption and vehicle rates and angles to compute acceleration at any point in the vehicle
Quasi-Steady Three-Dimensional Histogram (QTH)	summarize acceleration magnitude and direction for a long period of time indication of acceleration "center-of-time" via projections onto three orthogonal planes

Time Domain Plots

Analysis and Display of Quasi-steady Data

- **No frequency transform applied to quasi-steady acceleration data; looking at time series plot and noting orbital rate is frequency domain analysis.**

- **Data recorded at a rate of 10 samples per second**

- **Time domain plot types available**
  - **Raw acceleration data – Not recommended for general consumption (use with caution)**
    - g vs. t plot of 10 sample per second data
  - **TMF acceleration data**
    - g vs. t plot, t is a function of the TMF interval selected
  - **Interval average acceleration data**

$$x_{avgk} = \frac{1}{M} \sum_{i=1}^{M} x_{[(k-1)*M+i]} \qquad k = 1,2,..., \left\lfloor \frac{N}{M} \right\rfloor$$

  - M=number of points in the time series interval selected, typically 1 second intervals
  - N=total number of points in the time series being considered

Acceleration Domain Plots

Analysis and Display of Quasi-steady Data

- **Acceleration domain plot types available**
  - **Quasi-steady Three-dimensional Histograms (QTH)**
    - displays a summary of acceleration vector magnitude and alignment projected on three orthogonal planes
    - uses a 2-dimensional histogram for each combination of the three axes: XY, XZ, YZ
    - accumulates the number of times the acceleration vector magnitude falls within user-defined 2-dimensional bins
    - count is divided by the total number of points to normalize the results
      - gives a percentage of time representative of the magnitude and orientation of the quasi-steady acceleration vector
      - Makes meaningful comparisons of quasi-steady data between STS missions, ISS increments, or other periods of interest.

Steps for Producing an Example QTH Plot

Analysis and Display of Quasi-steady Data
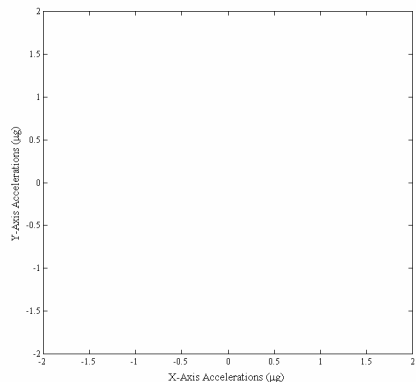
For the XY plane, choose area of interest by selecting limits.
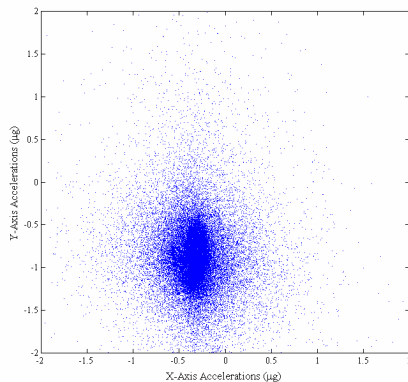
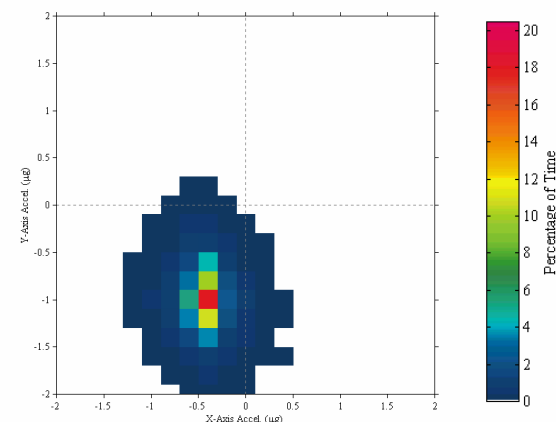**Plot X and Y components of quasi-steady vector.**
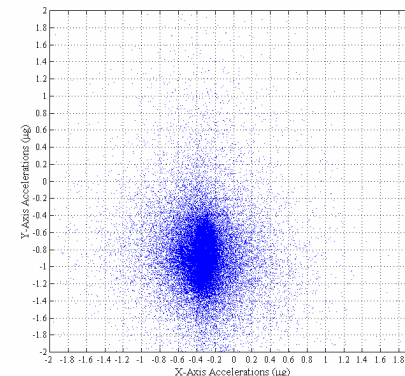
Divide area into equal size bins.
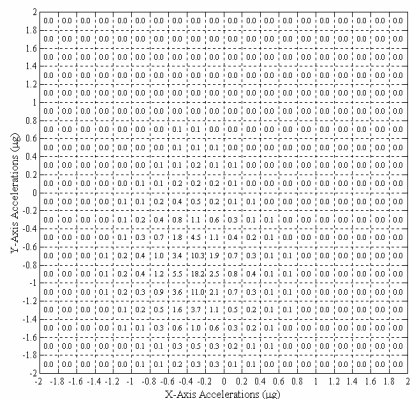
Count the number of "hits" in each bin.
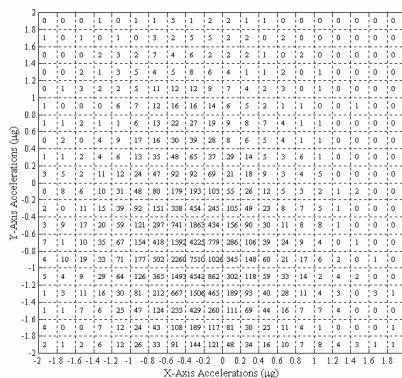
Calculate the percentage of total number of data points for each bin.

Assign a color gradient to percentage points.

Mapping of Quasi-steady Data

Analysis and Display of Quasi-steady Data

- **Additional options for quasi-steady plot types**
  - **Mapping is an estimate of the quasi-steady vector at a location other than measurement location. (e.g. the vehicle center of mass (CM) or to an experiment location)**
    - Rigid body assumptions, no relative motion of "vehicle parts"
    - requires use of the vehicle (Orbiter or ISS) telemetry data
    - mapping is accomplished via the following equations

$$A^{EL} = A^{ML} - A^{ML}_{gg} - A^{ML}_{rot} + A^{EL}_{rot} + A^{EL}_{gg}$$

$$A^{CM} = A^{ML} - A^{ML}_{gg} - A^{ML}_{rot}$$

    - Where
      - ML = measurement location
      - EL = experiment location
      - A_{gg} = gravity gradient component of acceleration
      - A_{rot} = rotational components of acceleration

    - A_{gg} and A_{rot} for experiment location are zero when mapping to CM

Gravity Gradient Equation

Analysis and Display of Quasi-steady Data

- gravity gradient component
  - The gravity gradient component are accelerations from forces acting on a particle that is away from the center of gravity.

- An independent particle will tend to accelerate towards the CM if it is in front or behind the CM or to the left or right of the vehicle. The gravity gradient will tend to accelerate a particle away from the CM if it is above or below the CM.[2]

  - A_{gg} at any location is given by the equation (in μg):

$$A_{gg} = \left(\frac{g_e \cdot r_e^2}{r_O^3} \right) \cdot \begin{bmatrix} rx \\ ry \\ -2 \cdot rz \end{bmatrix} \cdot \left(\frac{1x10^6}{g_e} \right)$$

  - Where
    - r_e is the radius of the Earth
    - r_0 is the distance of the vehicle to center of the Earth
    - [x,y,z] is the distance from the CM
    - $g_e = 9.81$ m/s^2

2. Matisak, B.P., Rogers M.J.B, Alexander J.I.D., "Analysis of the Passive Accelerometer System (PAS) Measurements During USML-1", AIAA 94-0434 (January 1994).

Gravity Gradient Equation for LVLH Attitudes

Analysis and Display of Quasi-steady Data

- **For LVLH attitudes, the vehicle is rotating about a single axis and an approximation can be used[2]:**

$$\left(\frac{g_e \cdot r_e^2}{r_O^3} \right) = \omega_O^2$$

- Where
  - ω_o is the angular velocity of the vehicle

- **For Shuttle flights, this approximation was frequently used.**

- **For ISS, extensive XPOP attitude in early flights will limit it's usefulness.**

Rotational Acceleration Equation

Analysis and Display of Quasi-steady Data

- **rotational component**
  - **The rotational acceleration effects are comprised of tangential and radial components.**
    - The tangential acceleration components contribute mainly during thruster firings and are not part of the quasi-steady domain. Therefore they are assumed negligible.
    - The radial components are given:

$$A_{rot} = \begin{bmatrix} -(\omega_y^2 + \omega_z^2) & \omega_x\omega_y & \omega_x\omega_z \\ \omega_x\omega_y & -(\omega_x^2 + \omega_z^2) & \omega_y\omega_z \\ \omega_x\omega_z & \omega_y\omega_z & -(\omega_x^2 + \omega_y^2) \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

  - Where
    - $\omega_x, \omega_y, \omega_z$ are the rotational velocities about the x,y,z axes
    - [x,y,z] is the distance from the CM

Frame of Reference and Coordinate Systems

Analysis and Display of Quasi-steady Data

- **Additional options for quasi-steady plot types**
  - **Select frame of reference as either inertial or science**

  - **Select the coordinate system based on vehicle**
    - For Orbiter, use either Orbiter body, Orbiter structural, or specialized coordinate system (i.e., CGF coordinates on USML-2)
    - For ISS, many coordinates systems are available

Data Storage

Post-Mission Quasi-steady Data Storage

- **OARE data available on request. Stored on NASA GRC file server *beech.grc.nasa.gov, which has been made unavailable to the public via WWW.***

- **MAMS data is stored on NASA GRC file server at *pims.grc.nasa.gov***
    - ftp and automated web server to generate MATLAB plots and distribute data on an as-needed basis
    - ossbtmf (TMF and bias compensation applied
    - ossraw – 10 samples per second data + temperature + bias status

Example Raw and TMF Plots

Analysis and Display of Quasi-steady Data

- **Raw OARE acceleration data**
  - **Figure 12-1 LMS Water Dump and Attitude Change**
  - **Figure 12-3 USML-2 Solar Inertial Attitude**
  - **Figure 12-5 USMP-3 Vernier Thruster Firings**

- **TMF OARE acceleration data**
  - **Figure 12-2 LMS Water Dump and Attitude Change**
  - **Figure 12-4 USML-2 Solar Inertial Attitude**
  - **Figure 12-6 USMP-3 Vernier Thruster Firings**
  - **Figure 12-7 USML-2 Supply Water Dump**

Example QTH Plots

Analysis and Display of Quasi-steady Data

- **QTH plots**
  - **Figure 12-8** LMS Mission Plot
  - **Figure 12-9** USML-2 Solar Inertial Attitude
  - **Figure 12-10** USMP-2 Mission Plot
  - **Figure 12-11** LMS Crew Active Period
  - **Figure 12-12** LMS Crew Sleep Period

OARE, Raw Data
OARE Location

MET Start at 006/00:00:00.000

Frame of Reference: Orbiter
LMS
Body Coordinates
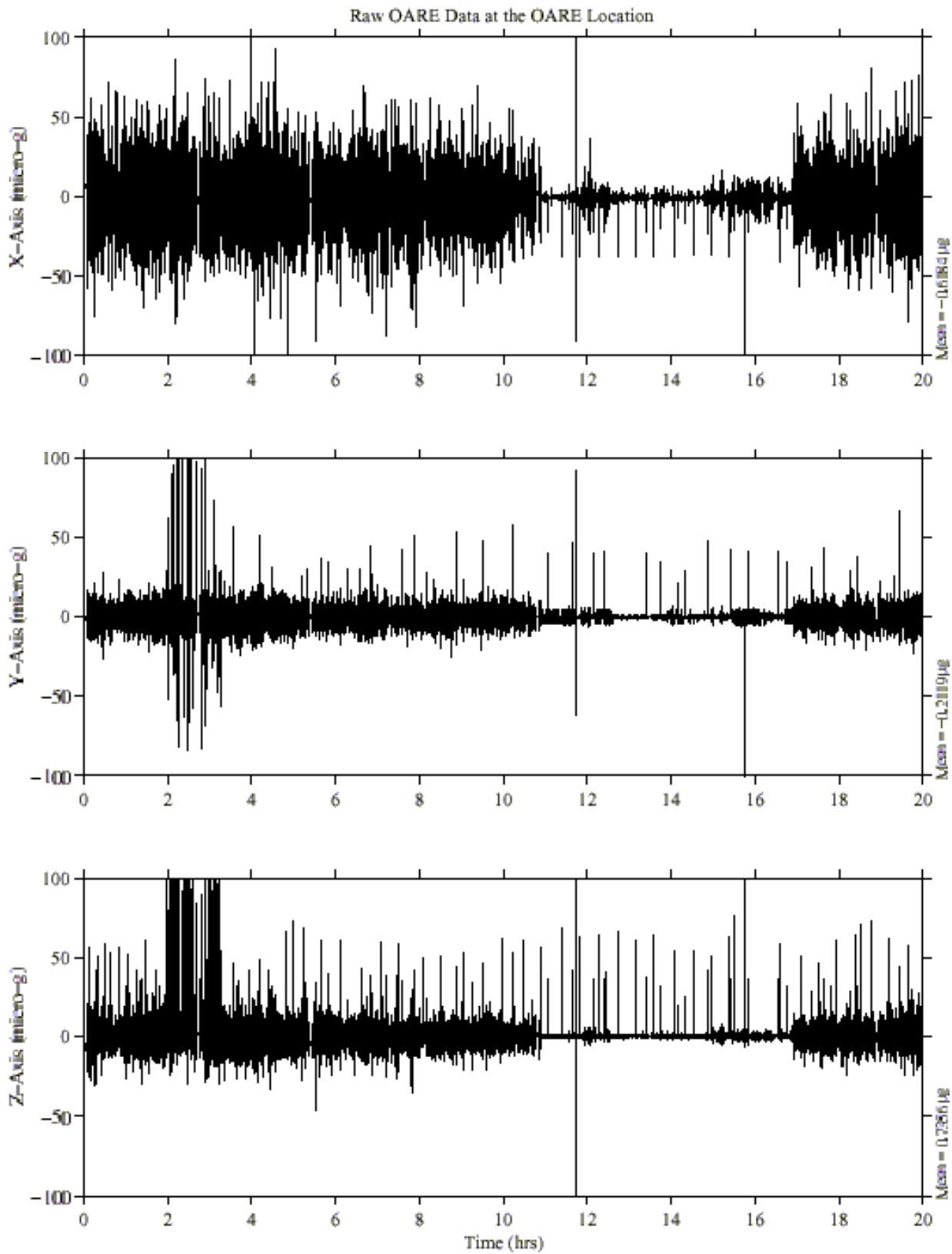
MEIT-2004 Figure 12-1: OARE Raw Data During Water Dump and Attitude Change from STS-78 (LMS)

OARE, Trimmed Mean Filtered
OARE Location

MET Start at 006/00:04:14.160

Frame of Reference: Orbiter
LMS
Body Coordinates

OARE Trimmean Filter Data at the OARE Location
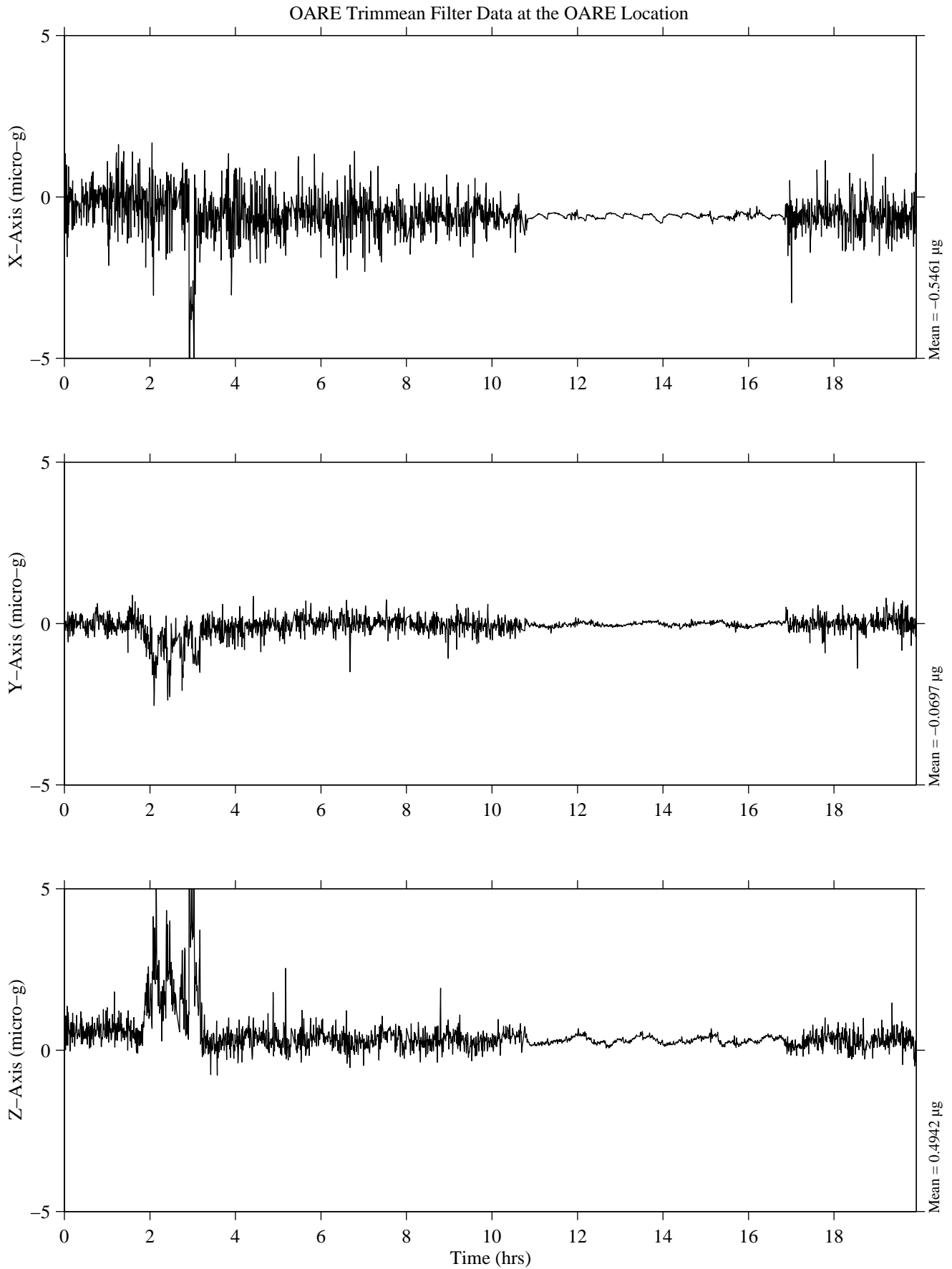
MEIT-2004 Figure 12-2: OARE TMF Data During Water Dump and Attitude Change from STS-78 (LMS)

MET Start at 010/18:00:00.000

Solar Inertial Attitude
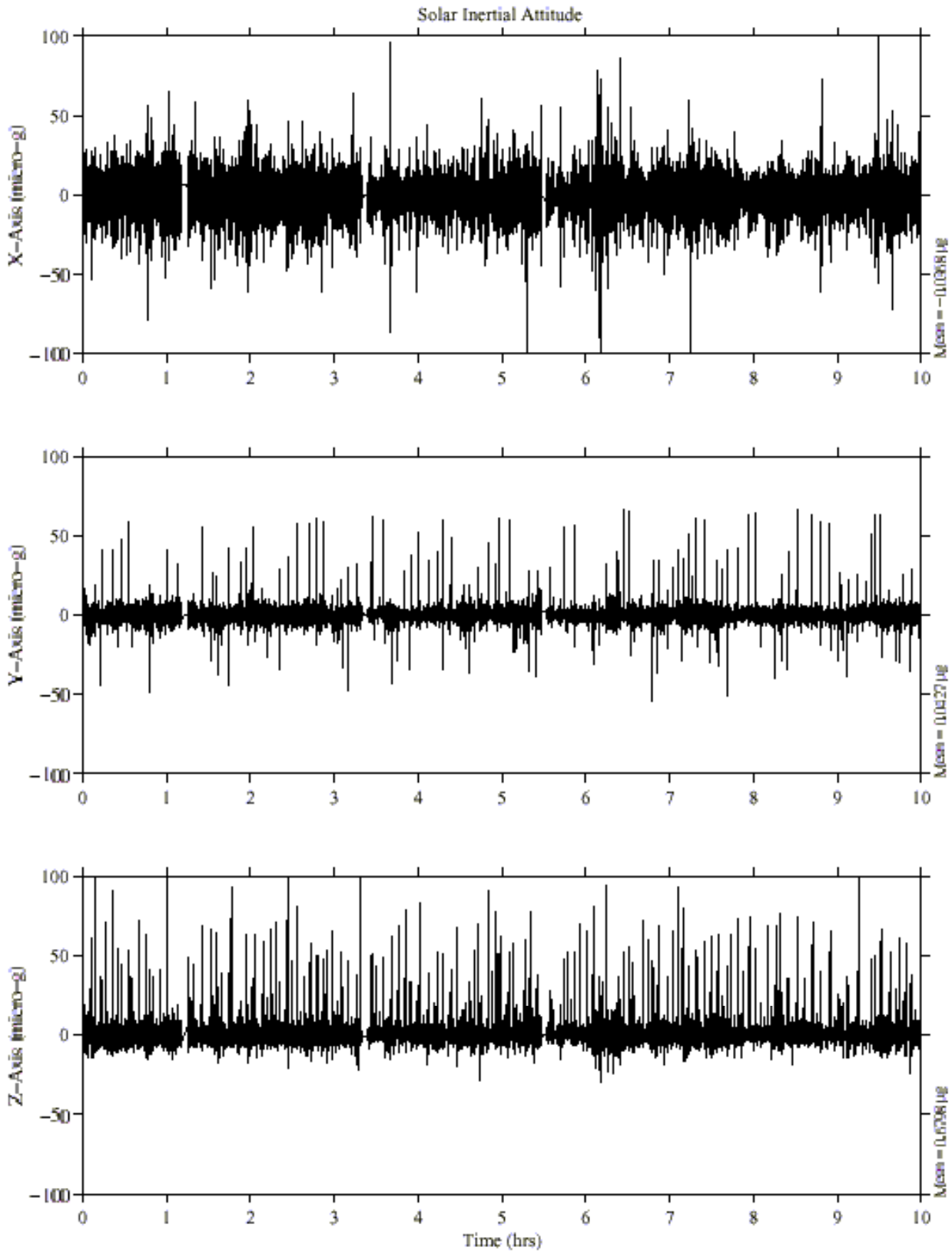
MEIT-2004 Figure 12-3: OARE Raw Data During Solar Inertial Attitude from STS-73 (USML-2)

MET Start at 010/18:00:16.920

Solar Inertial Attitude

MATLAB: 30−Aug−96, 9:55 am
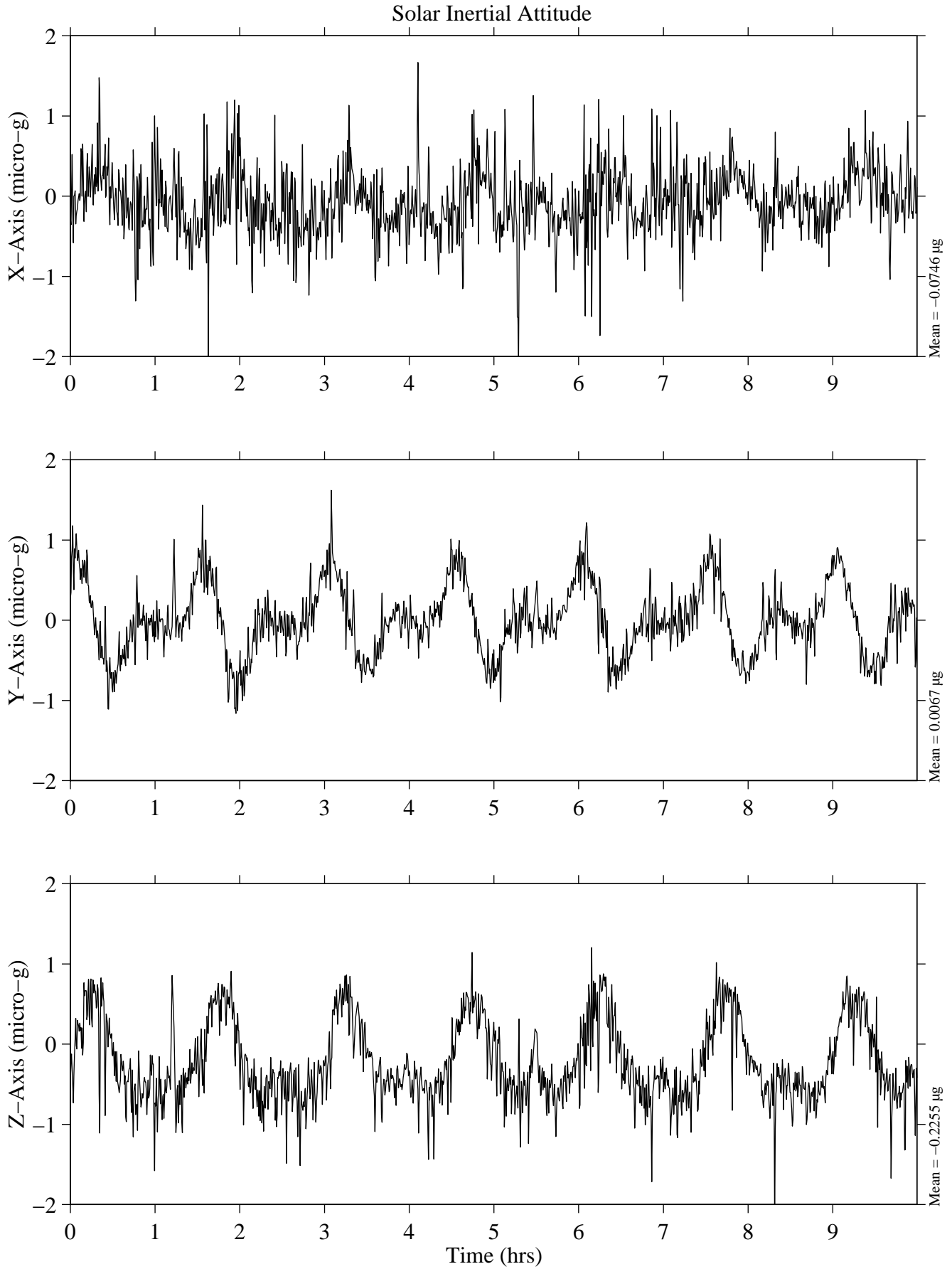
MEIT-2004 Figure 12-4: OARE TMF Data During Solar Inertial Attitude from STS-73 (USML-2)

Vernier Thruster Firings

MATLAB: 02−Oct−1997, 06:09 pm
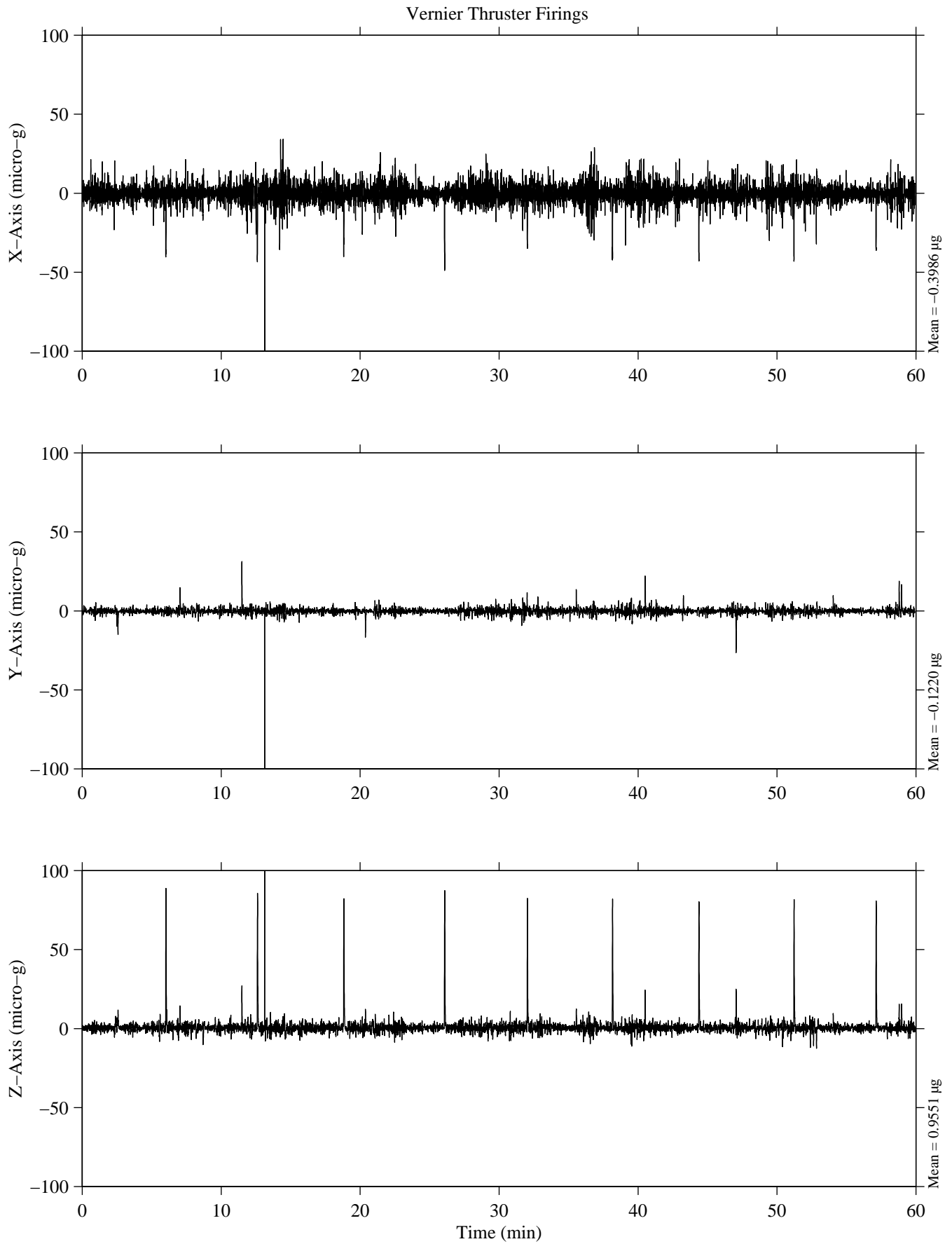
MEIT-2004 Figure 12-5: Raw OARE Data Showing Vernier Thruster Firings from STS-75 (USMP-3)

OARE, Trimmed Mean Filtered
OARE

MET Start at 010/03:18:23.400

Frame of Reference: Orbiter
USMP−3
Body Coordinates

Vernier Thruster Firings

Mean = −0.2316 μg

Mean = −0.1083 μg

Mean = 0.4595 μg

Time (min)

MATLAB: 02−Oct−1997, 06:13 pm
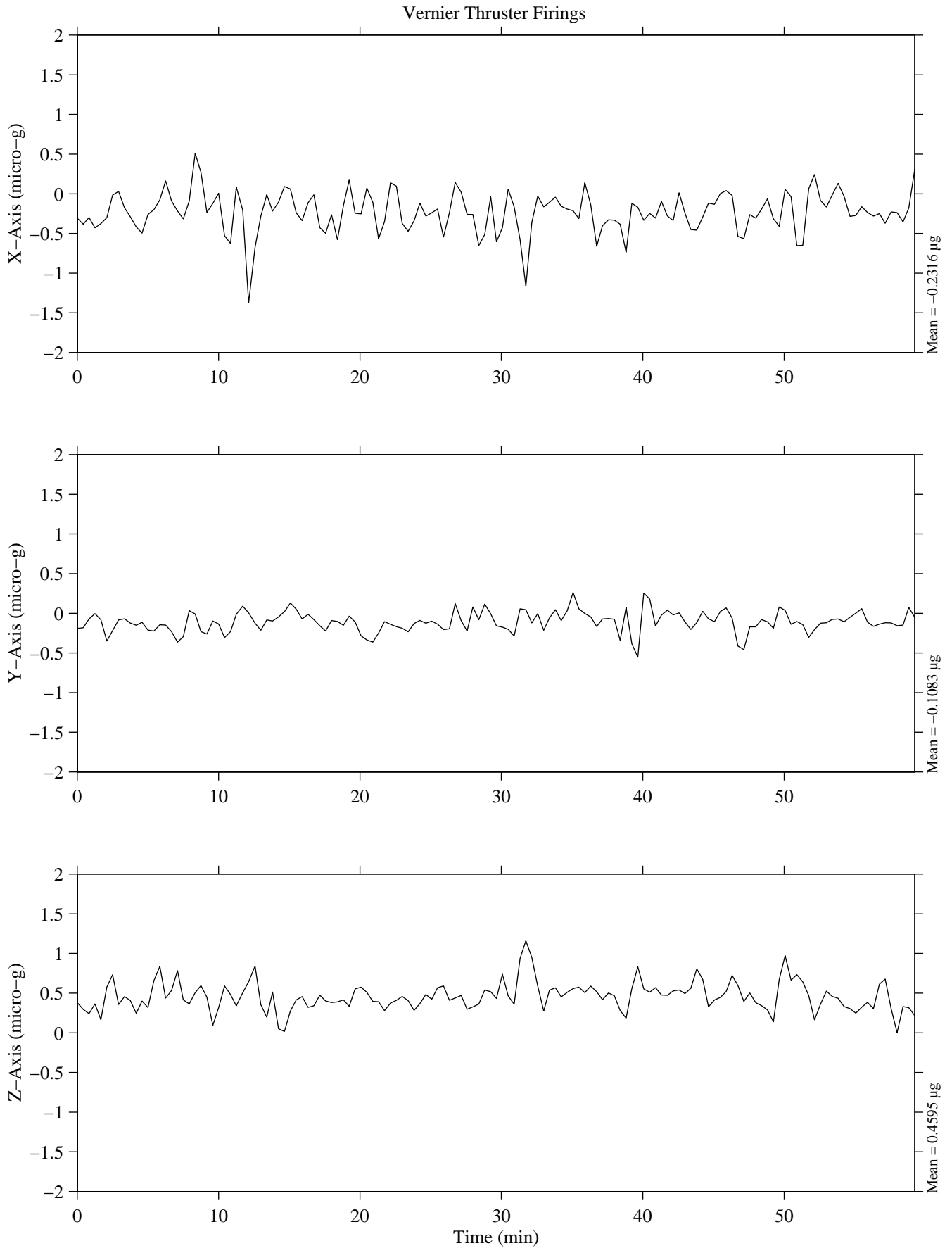
MEIT-2004 Figure 12-6: OARE TMF Data NOT Showing Vernier Thruster Firings from STS-75 (USMP-3)

OARE, Trimmed Mean Filtered
OARE Location

MET Start at 004/08:00:20.160

Frame of Reference: Orbiter
USML−2
Body Coordinates

Supply Water Dump

MATLAB: 23−Sep−96, 3:11 pm
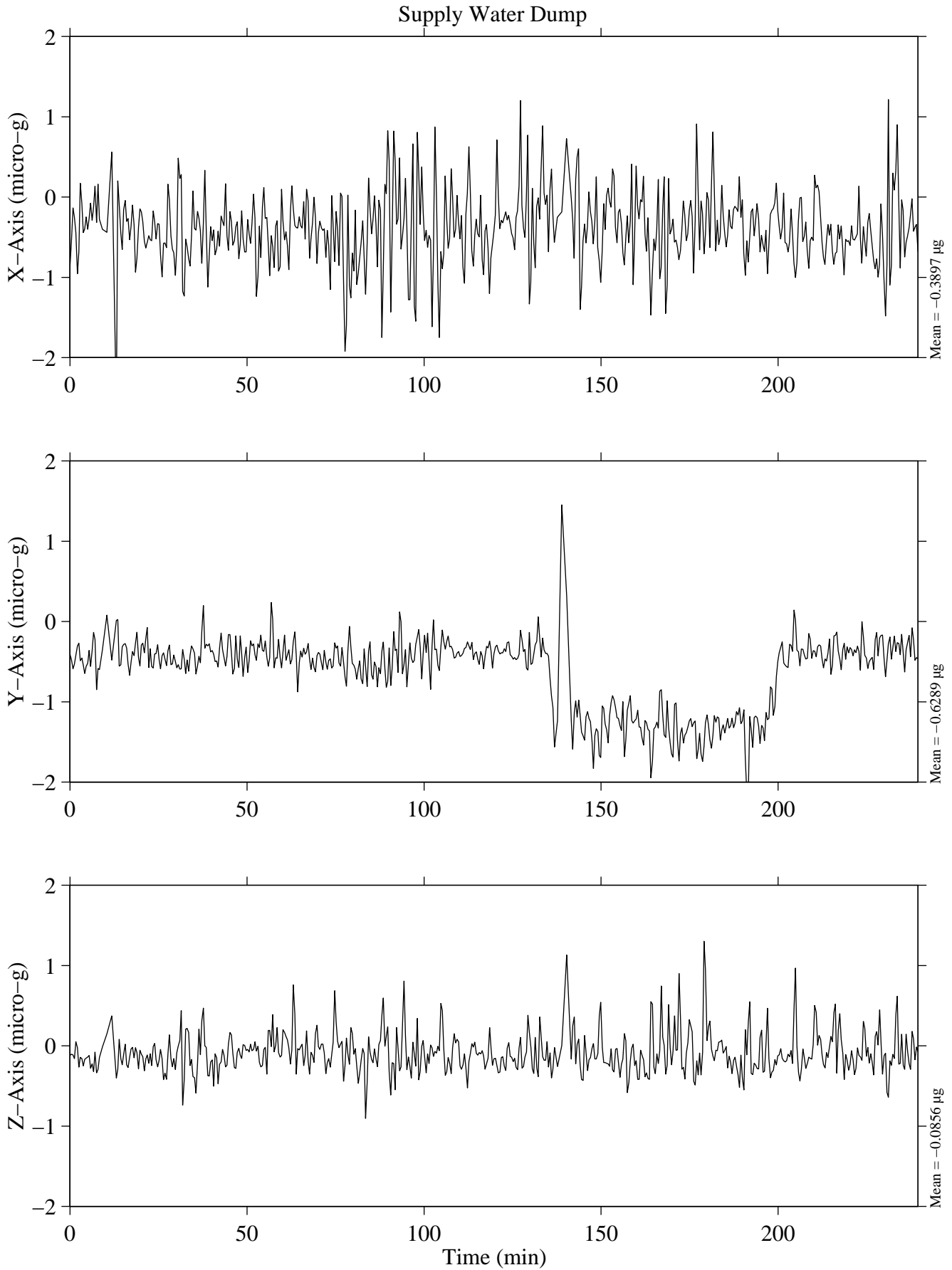
MEIT-2004 Figure 12-7: OARE TMF Data Showing Water Dump from STS-73 (USML-2)

OARE, Trimmed Mean Filtered

OARE Location

MET Start at 000/00:13:17.040

LMS

LMS Quasi−Steady Acceleration Environment

Body Coordinates

T=404.9 hours

Xct = −0.3264 μg

Yct = −0.1135 μg

Zct = 0.4965 μg

MATLAB: 28−Oct−96, 4:15 pm
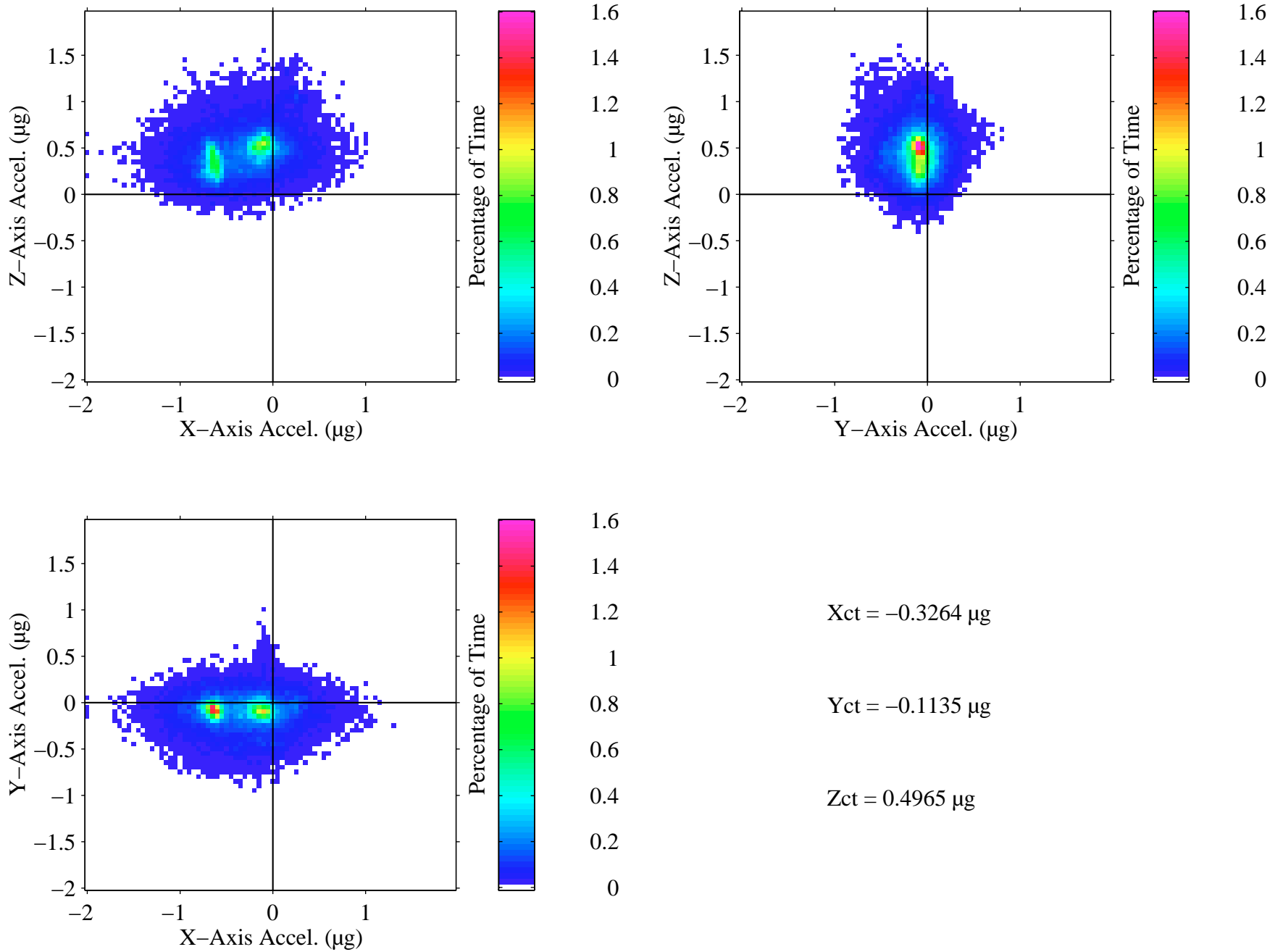
MEIT-2004 Figure 12-8: Quasi-Steady Three-Dimensional Histogram Plot for Entire STS-78 (LMS) Mission

USML−2 Solar Inertial Attitude Data
Quasi−Steady Three Dimensional Histogram
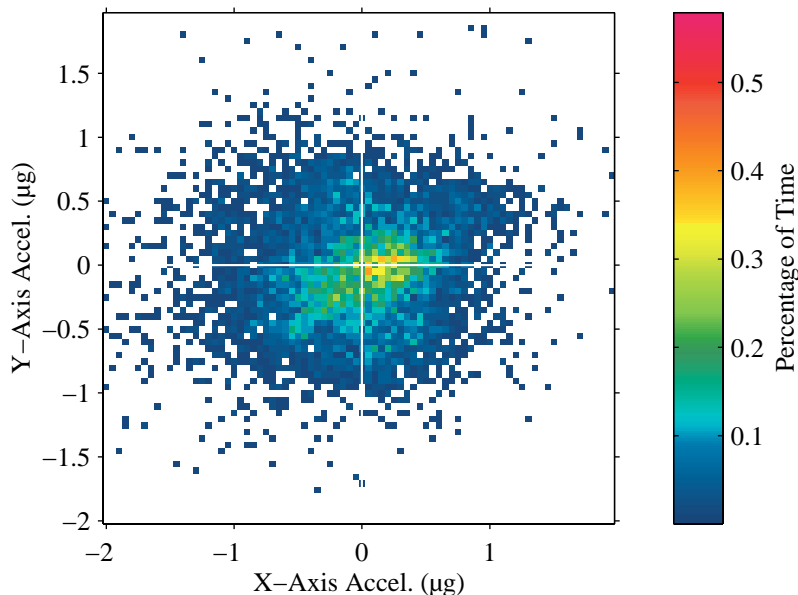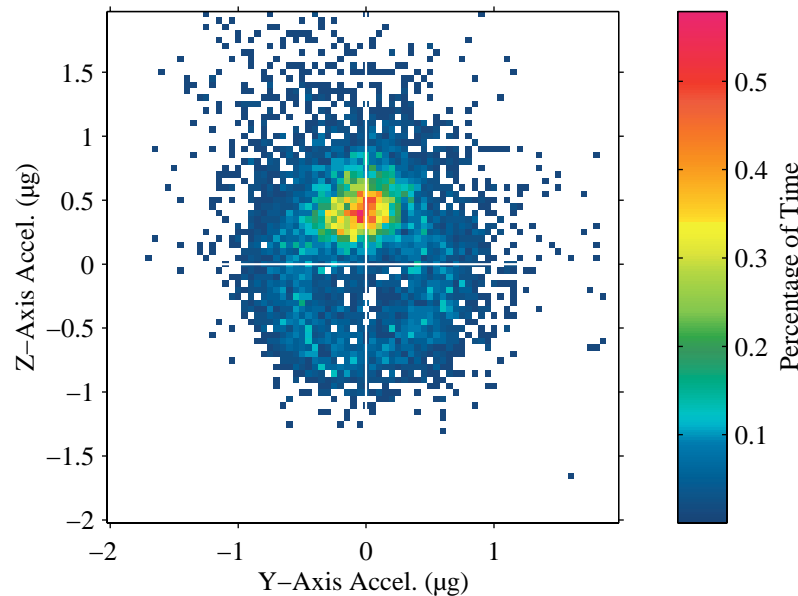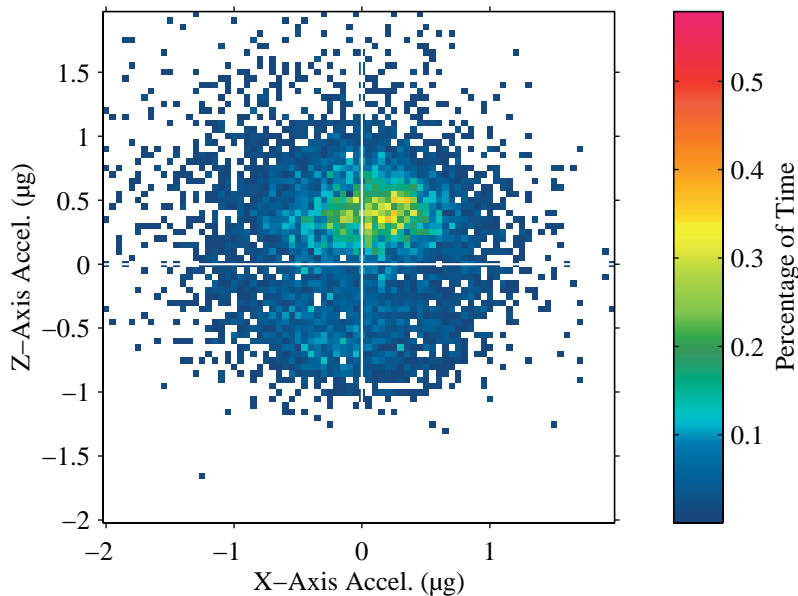
Xct = −0.037792 μg

Yct = −0.039693 μg

Zct = 0.21086 μg

MEIT-2004 Figure 12-9: Quasi-Steady Three-Dimensional Histogram Plot for Solar Inertial Attitude from STS-73 (USML-2)

MATLAB: 03−Feb−2000, 02:27 pm

Body Coordinates

Frame of Reference: Orbiter

T = 333.4 hours

MATLAB: 1−Feb−97, 10:45 am

MEIT-2004 Figure 12-10: Quasi-Steady Three-Dimensional Histogram Plot for Entire STS-62 (USMP-2) Mission
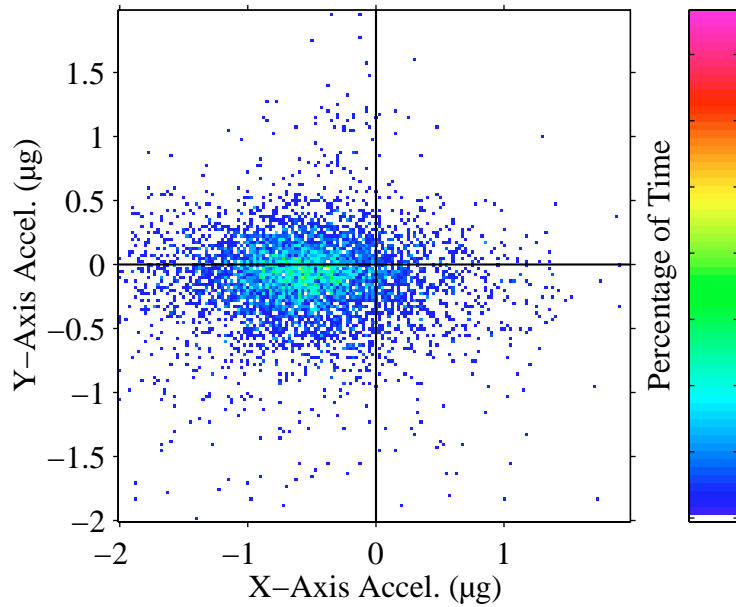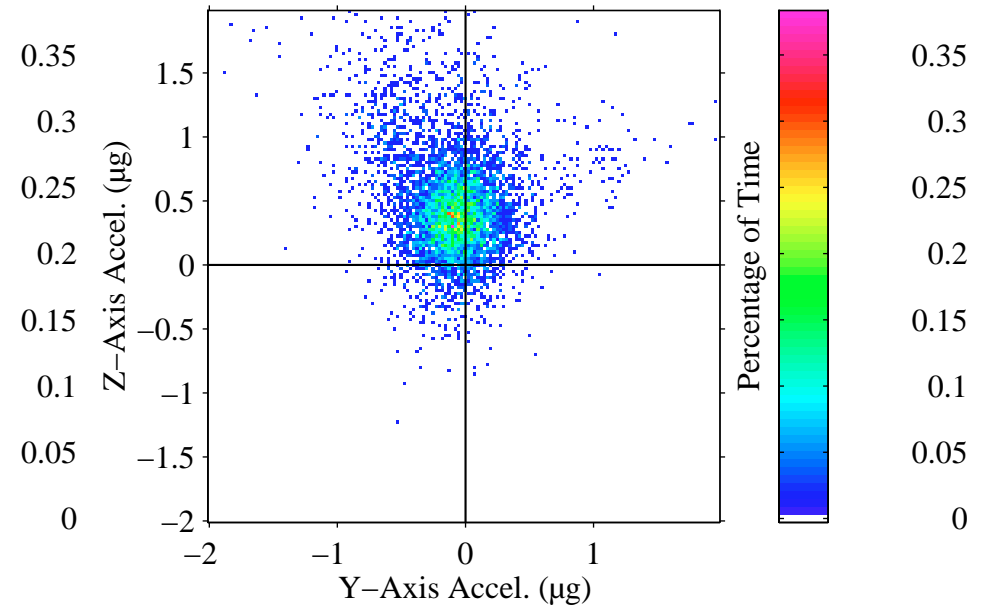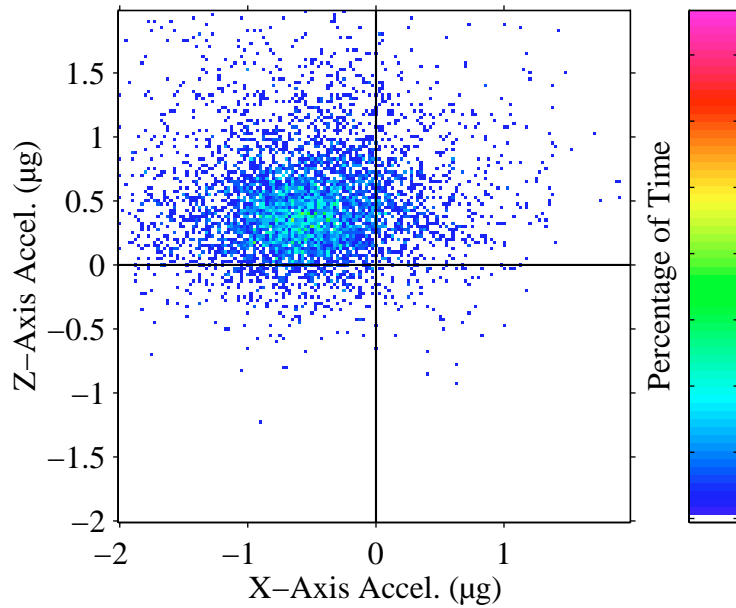
Body Coordinates

Frame of Reference: Orbiter

T = 46.0 hours

MATLAB: 1−Feb−97, 10:31 am

MEIT-2004 Figure 12-11: Quasi-Steady Three-Dimensional Histogram Plot Crew Active Period STS-78 (LMS)

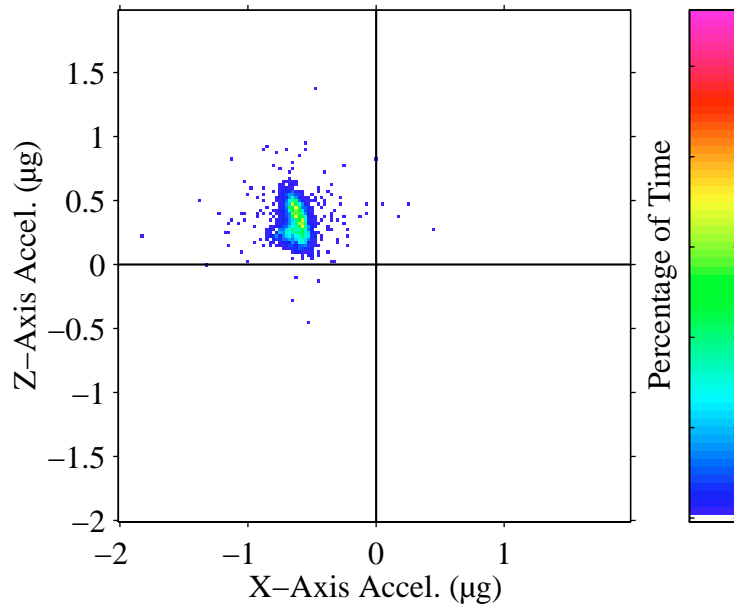MET Start at 009/09:00:07.920
LMS Mission – Sleep Cycles
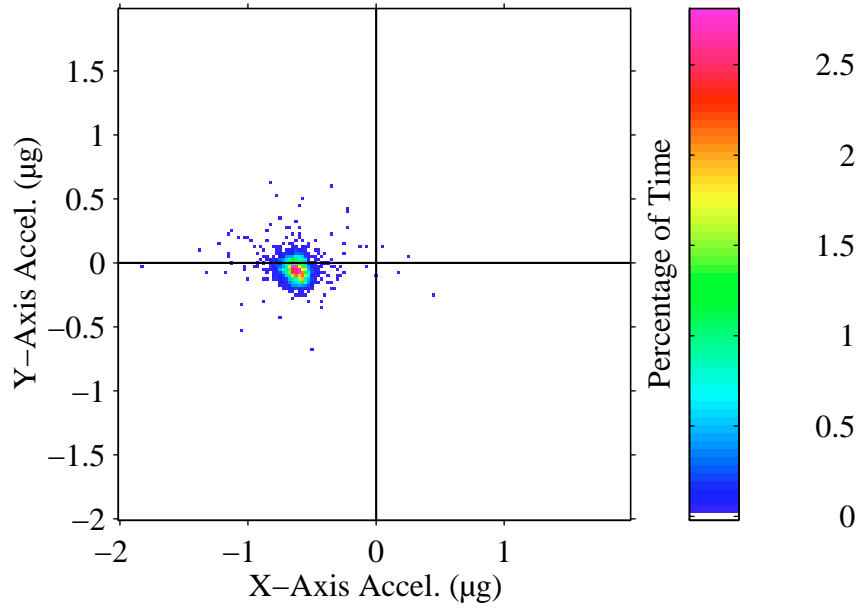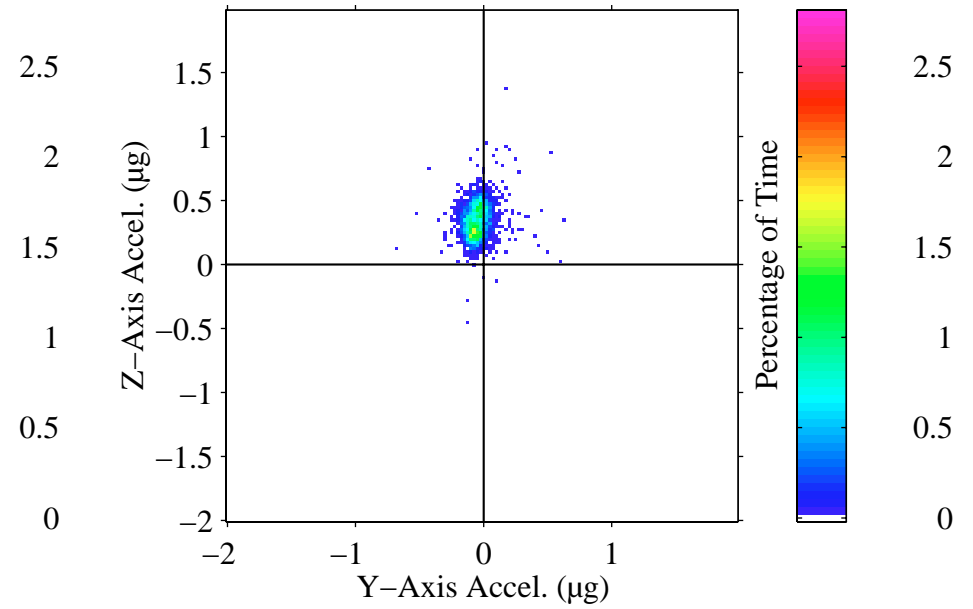
Body Coordinates

Frame of Reference: Orbiter

T = 24.0 hours

MEIT-2004 Figure 12-12: Quasi-Steady Three-Dimensional Histogram Plot Crew Sleep Period STS-78 (LMS)