Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Acceleration Measurement Comparison Program Report

May 4, 1995

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41st Annual Meeting of the Institute of Environmental Sciences

Anaheim, California

ABSTRACT

In 1989, the NASA Metrology Working Group implemented an Acceleration Measurement Comparison Program (AMCP) in order to allow each center to assess the quality of accelerometer calibrations being performed by their respective calibration laboratories. This report presents the data which has been submitted to the program during the time period between May 1994 and March 1995. Included is a detailed compilation of the transfer standard frequency response measurements anti an interlaboratory comparison analysis of the 100 Hz pick-up sensitivity measurements which have been performed by the participants. Additionally, possible sources of measurement errors, which have surfaced in some of the AMCP data, are discussed. The report also analyzes the 100 Hz pick-up sensitivity measurements which have been submitted to the program over the last three years and looks for trends which would indicate the statistical measurement control status of the accelerometer calibration systems utilized at the participating NASA centers.

INTRODUCTION

The Jet Propulsion Laboratory has been assigned the responsibility for developing and conducting an acceleration measurement comparison program (AMCP) and serves as the pivot laboratory for the project. The purpose of the AMCP is to provide a dependable and cost effective method for participating NASA installations to assess the quality of measurements made for accelerometer calibration. The following are just a few of the benefits that result from participation in this program:

1) Provides NIST traceability.

2) The possible discovery of bias and precision errors which may have been previously undetected.

3) Allows participator-rg centers to quantitatively assess the measurement errors associated with their accelerometer calibration systems and procedures.

4) Allows NASA to gain an understanding on the quality of accelerometer calibrations being performed on an agency-wide basis.

The method of implementation for this MCP is the “hub of the wheel” concept. In this way, two transfer standards are paired (designated as accelerometer “A” and “B”) and shipped from JPL to the participating facilities and back to JPL after the test. This method provides various benefits such as facilitation of the formulation of Youden diagrams, multiple test runs for data confirmation, periodic reinspection of the equipment to ensure no damage has occurred in transit, and also the ability to accumulate data in a progressive fashion throughout the MCP cycle.

PARTICIPANTS

The following is the list of current AMCP participants:

Dryden Flight Research Center
Goddard Space Flight Center
Jet Propulsion Laboratory
Johnson Space Center
Kennedy Space Center
Langley Research Center
Lewis Research Center
Marshall Space Flight Center
Stennis Space Center

AMCP OVERVIEW

Each center was shipped two Endevco model 2270M8 transfer standard accelerometers along with instructions to calibrate them as though they were test units. Special mounting instructions were also provided, but no information regarding the accelerometers' sensitivity or frequency response was given other than that which can be obtained from the manufacturer's specifications.

The AMCP concentrates on two specific accelerometer calibration measurements. These are:

1) The single point sensitivity in pC/g, to four significant figures, using a frequency of 100 Hz at an acceleration level between 2 and 10 g.

2) The frequency response curve. Participant data was presented to JPL as a plot or table of percent deviation or sensitivity versus frequency. Any range between 10 Hz to 10 KHz is acceptable.

As part of the AMCP, the four transfer standard accelerometers were sent to the National Institute of Standards and Technology (NIST) for calibration. The NIST frequency response measurements have an estimated uncertainty of ± 2% from 10 Hz to 50 Hz, ± 1% from 100 Hz to 2500 Hz, and ±2% from 2500 Hz to 10 KHz.

The NIST calibrations are used as guide-lines for the estimated uncertainties of the transfer standards and are used for comparison purposes. Ultimately, it is the responsibility of each NASA participant to determine whether or not their particular accelerometer calibration requirements are being satisfied. These comparisons are merely a tool which may aid them in this process.

FREQUENCY RESPONSE MEASUREMENTS

An analysis of the frequency response curves submitted by each of the seven participating centers is presented in figures 1 through 7. These plots show the deviation (in percent) between the participants' frequency response measurements and those performed by NIST. The bold lines indicate the estimated limits of uncertainty of the AMCP standard calibration and is based on quoted NIST uncertainties. The serial number corresponding to the transfer standard accelerometer which was calibrated is shown to the right of the graph. Brief explanations of possible sources of measurement errors are provided, however, Endevco Technical Paper TP 299 (Sill, R. D.) should be consulted for more detailed information.

DFRC

The Dryden Flight Research Center participated in the AMCP by calibrating two of the transfer standard accelerometers between the frequency range of 30 Hz to 5 KHz (Note: one accelerometer was only calibrated out to 4.5 KHz). The two curves are repeatable to within approximately 0.5% out to 4000 Hz, Beyond this frequency, there is a deviation of approximately 1.4% (Figure 1). Both frequency response curves are within the NIST uncertainty limit throughout the tested frequency range.

GSFC

The Goddard Space Flight Center also calibrated two transfer standard accelerometers as part of their participation in the AMCP (Figure 2). Analysis of the AMCP data indicates that a bias (with respect to NIST) on the order of +1% is present in the GSFC accelerometer calibration system. In reviewing the 100 Hz pickup sensitivity data, we find that the GSFC measured value for accelerometer JA62 is approximately 0.8% higher than that which was measured by NIST. For accelerometer JM63, the deviation is approximately +1%. It is possible that this bias has been passed on to the GSFC accelerometer calibration system by a transfer standard accelerometer which was used to calibrate the GSFC working standard. However, the level of repeatability between the two calibrations indicates that precision errors are minimal.

JPL

The Jet Propulsion Laboratory recently procured a new accelerometer calibration system and two AMCP accelerometers were used to evaluate the quality of the calibration data provided by this system. Roth calibrations submitted by JPL span the range from 10 Hz to 10 KHz. The two curves are repeatable to within 0.3%, except at 10 Hz where the deviation approaches 0.8%, and are well within the estimated uncertainty limits of the AMCP transfer standards (Figure 3).

JSC

Participation by the Johnson **Space** Center in previous AMCP cycles indicated the presence of a bias in the results obtained by the JSC accelerometer calibration system. In order to reduce this bias, two AMCP transfer standards were shipped to JSC for use in calibrating their working standard accelerometers. Figure 4 shows the resulting frequency response measurement comparison curves after this process was completed. As is evident, both JSC calibrations are within the NIST uncertainty and show an excellent degree of repeatability. At approximately 7000 Hz, however, the JSC frequency response curves show an increase as compared to the NIST high frequency sensitivity measurements. This could be due to a combination of the AMCP and working standard accelerometer responses on the calibrator and is considered normal.

KSC

As part of their participation in the AMCP, the Kennedy Space Center calibrated two transfer standard accelerometers. The KSC frequency response curves are mostly within the transfer standard uncertainty limits throughout the frequency range of 30 Hz to 10 KHz (Figure 5). In reviewing the 100 Hz pickup sensitivity data, we find that the KSC measured value for accelerometer JA62 is approximately 1.1 % lower than that which was measured by NIST. For accelerometer JM63, the deviation is approximately -0.9%. It is possible that this bias has been passed on to the KSC accelerometer calibration system by a transfer standard accelerometer which was used to calibrate the KSC working standard. Also, beyond 6 KHz, the curves become erratic. Some factors which might cause deviations from a straight line at high frequencies are the use of an isolating stud with the sensor, burrs on the armature head of the shaker, or problems associated with high frequency filtering of tile calibration system.

LaRC

Langley Research Center calibrated two transfer standard accelerometers as part of their participation in the AMCP. Both calibrations span the range from 10 Hz to 10 KHz. The two curves are repeatable to within 0.5?'., except at 10 Hz where the deviation approaches 0.7%, and are well within the estimated uncertainty limits of the AMCP transfer standards (Figure 6).

LeRC

The Lewis Research Center is in the process of relocating its accelerometer calibration capabilities. Due to these constraints, they were unable to participate during this AMCP cycle.

MSFC

Due to time constraints, the Marshall Space Flight Center was unable to participate during this AMCP cycle.

. SC

Participation by the Stennis Space Center in previous rounds of the AMCP indicated the presence of a bias in the SSC working standard accelerometers. In order to reduce this bias, two AMCP transfer standards were shipped to SSC for use in calibrating their working standards. Once this process was completed, two additional AMCP transfer standards were shipped to SSC for system evaluation. Figure 7 shows the resulting frequency response measurement comparison curves. As is evident, both SSC calibrations are within the NIST uncertainty except at 10 Hz and at frequencies above 7 KHz. Beyond 5 KHz, the two curves become extremely erratic.

YOUDEN DIAGRAM

A Youden diagram is a statistical toed which is widely used to graphically represent and analyze interlaboratory comparison data (Youden, W. J., 1969). Essentially, Youden diagrams are formed by setting up a scale on the X axis of a Cartesian plot which will cover the range of measured values for one transfer standard and repeating the process for another transfer standard on the Y axis. The results reported by each participating center, for both transfer standards, are used to plot a point on the graph. There will be as many points as there are reporting laboratories.

Analysis of the interlaboratory comparison data is achieved by adding four key elements to the Youden diagram (Conroy, B. F., 1991). First, the median of the measured values submitted by each participant, for both transfer standards, is calculated and a line is drawn through the median value perpendicular to the corresponding axis. The next element is a 45 degree tangent line which is drawn through the intersection of the median lines. An uncertainty circle, of radius three times the standard deviation of the measured values used in calculating the median, is also added to the Youden diagram. For comparison purposes and to assess the accuracy of the measurements submitted by each of the participating centers, NIST data is included on the graph. The NIST point is shown as an asterisk on the plot and the error bars indicate the NIST estimated uncertainty.

Based on the information provided by the Youden diagram developed from the data submitted for evaluation as part of the AMCP, it is possible to quantitatively assess the errors associated with the accelerometer calibration systems and procedures utilized at each of the participating NASA facilities. The Youden diagram, which is based on the 100 Hz accelerometer output sensitivities of the AMCP transfer standards, can be found in figure 8.

AMCP ERROR ANALYSIS

The two components which make up a calibration laboratory's total measurement error are known as precision errors and bias errors. Precision errors result from the inability of a given laboratory to make precise, repeatable measurements and are caused by factors such as calibration drift in the equipment used to perform the measurements, stability of the environment, faulty cables and standards, and non repeating operator errors. In reviewing the Youden diagram, laboratories whose measurements are primarily influenced by precision errors will have data points which fall into the upper left and lower right quadrants and will be far from the 45 degree tangent line. On the other hand, laboratories whose data point does fall along the 45 degree tangent line have performed repeatable measurements which are primarily influenced by bias errors caused by inherent biases in the standards and procedures employed. In either case, the magnitude of the total measurement error can be ascertained from the distance between a laboratory's data point and the NIST measured values.

Figure 8 shows the Youden diagram which was formed by plotting the difference between the NIST and participant 100 Hz sensitivity measurements (as a percentage) for the "A transfer standards versus those designated as "B" transfer standards. All of the points representing the AMCP participants fall within close proximity of the 45 degree tangent line which provides evidence that the precision component of the participant's measurement errors are small. Thus, bias errors account for the majority of the deviation between the NIST measurements and the participant's measurements. The magnitude of the bias error for each particular participant is indicated by the distance between the NIST datapoint and the participants' datapoints. Six of the seven participants whose data point is shown on this diagram fall completely within the estimated NIST uncertainty limits and none lie outside of the 3 sigma uncertainty circle.

LONG TERM 100 HZ SENSITIVITY MEASUREMENT ANALYSIS

An analysis of the 100 Hz sensitivity measurements which have been performed by the nine participating centers over the last three years is presented in figures 9 through 17. These plots show the deviation (in percent) between the participants' 100 Hz sensitivity measurements and those performed by NIST. The dashed lines indicate the estimated limits of uncertainty of the AMCP standard calibrations and are based on the quoted NIST uncertainties, The serial number corresponding to the transfer standard accelerometer which was calibrated is shown to the right of the graph.

DFRF

As evidenced in figure 9, the calibrations submitted to the AMCP by the Dryden Flight Research Center have consistently been between 0.5% and 1.2 % higher than those provided by NIST. The exception to this is the most recent measurements which are approximately 0.2% lower than the NIST measurements.

GSFC

The Goddard Space Flight Center 100 Hz sensitivity measurements (Figure 10) exhibit a steady increase of approximately 1% with each AMCP cycle. Such a trend is often the result of a measurement process which is not in statistical control. Corrective action may be required in order to assure that the accuracy of future GSFC calibrations are within tolerance.

JPL

Figure 11 provides the JPL 100 Hz sensitivity measurements which have been submitted to the program over the last three years. 1 hese calibrations have consistently been 0.1 % to 0.9 % lower than those provided by NIST.

JSC

As discussed previously, participation by the Johnson Space Center in prior AMCP cycles indicated the presence of a bias in the JSC accelerometer calibration system which was on the order of +1.3%. In October of 1993, two AMCP transfer standards were shipped to JSC for use in calibrating their working standards. After this was done, the bias error was reduced to within -0.4% of the NIST measurements (Figure 12).

KSC

As shown in figure 13, the calibrations submitted to the AMCP by the Kennedy Space Center have consistently been between 0% and 0.5% lower than those provided by NIST. The exception to this is the most recent measurements which are approximately 1 % lower than the NIST data.

LaRC

Figure 14 provides the LaRC 100 Hz sensitivity measurements which have been submitted to the program over the last three years. These calibrations have consistently been 0°/0 to 0.5 % higher than those provided by NIST.

LeRC

The Lewis Research Center 100 Hz sensitivity measurements (Figure 15) exhibit a steady decrease of approximately 1.2% with each AMCP cycle. Such a trend is often the result of a measurement process which is not in statistical control. Corrective action may be required in order to assure that the accuracy of future LeRC calibrations are within tolerance.

MSFC

Figure 16 provides the MSFC 100 Hz sensitivity measurements which have been submitted to the program over the last three years. These calibrations have consistently been within -0.2% and +0.6 % of the NIST 100 Hz sensitivity values.

Ssc

Early calibrations from the Stennis Space Center exhibited large biases, with respect to NIST, which were on the order of +2.8%. In February of 1994, two AMCP transfer standards were shipped to SSC for use in calibrating their working standards. After this was done, the bias has been reduced to within ±0.2% of the NIST measurements (Figure 17).

FUTURE PLANS

The present AMCP program covers only a limited region of the accelerometer calibration spectrum. Funding for expansion of the AMCP to include transportation shock (up to 10,000 g) and pyrotechnic shock (up to 100,000 g) has been provided by NASA, The objective of this effort is to develop the NASA Acceleration Measurement Comparison Program (AMCP) in continuum from low frequency, low amplitude acceleration through high level shock. For centers which do not currently possess shock calibration capabilities, the expanded AMCP will serve as a resource which can be utilized for obtaining this type of specialized measurement. Also, the expanded AMCP will be useful in determining the competency of off-site providers of shock transducer calibrations. These new AMCP services should be available to NASA metrology laboratories in January of 1996.

CONCLUSION

Through this iteration of the NASA Metrology Working Group's Acceleration Measurement Comparison Program the seven participants have submitted fourteen calibrations which were performed on the four transfer standard accelerometers used in the MCP. With respect to the frequency response calibrations, ten of the fourteen submitted calibrations were completely within the estimated uncertainty limits of the AMCP transfer standard accelerometers as certified by NIST.

A Youden diagram was used to graphically display the 100 Hz pickup sensitivity data. Based on the information contained in these plots, it was possible to qualitatively assess the measurement errors in each of the seven participating NASA centers' accelerometer calibration systems and procedures. The total measurement errors can be quantitatively ascertained from the distance between a participant's data point and the NIST measured value. The significance of these measurement uncertainties is left to each center to evaluate. Any center whose calibrations did not fall within the NIST estimated uncertainty limits is encouraged to review this data and determine if their accelerometer calibration capabilities satisfy their center's requirements.

Currently, the shock transducer calibration portion of the AMCP is in the process of being implemented and should be operational in early 1996. Surveys will be distributed to the AMCP participants in order to determine the requirements of centers which plan to participate in this phase of the program. Also as part of the shock transducer calibration portion of the AMCP, a calibration service will be made available to all NASA centers.

REFERENCES

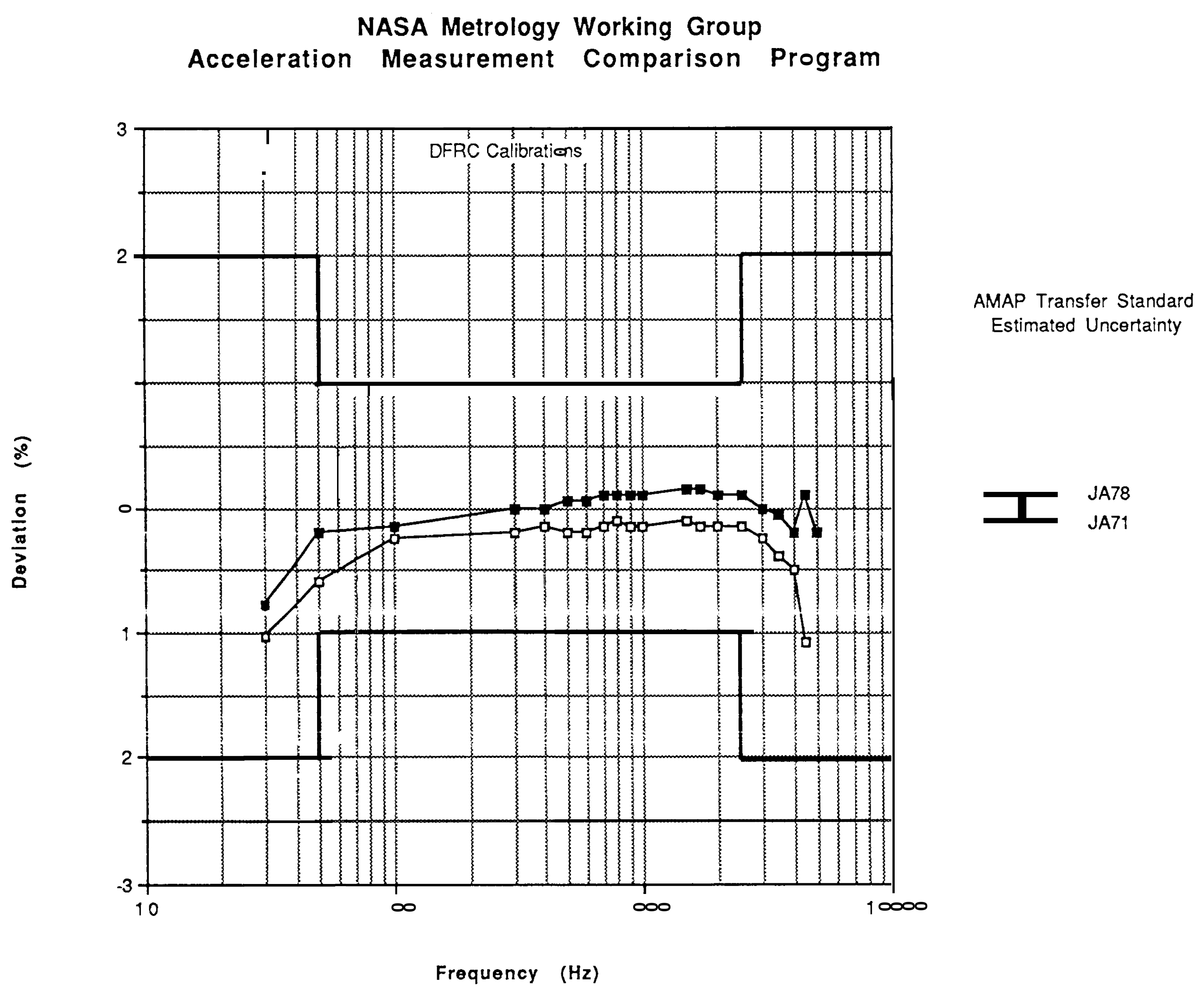
Youden, W. J., "Graphical Diagnosis of Interlaboratory Test Results", Precision Measurement and Calibration: Statistical Concepts and Procedures, NBS Special Publication 300; vol. 1, 1969.

Conroy, B. F., "A Round-Robin Measurement Assurance Program for Thread Gage and Pitch Diameter Measurements", Paper presented at the National Conference of Standards Laboratories Workshop and Symposium, Albuquerque, NM, 1991.

Sill, R. D., "Minimizing Measurement Uncertainty in Calibration and Use of Accelerometers," Endevco Technical Paper TP299.

ACKNOWLEDGMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautical and Space Administration.



NASA Metrology Working Group
Acceleration Measurement Comparison Program
DFRC Calibrations
3
2
0
1
2
-3
10
1000
Deviation (%)
Frequency (Hz)
AMAP Transfer Standard
Estimated Uncertainty
JA78
JA71

Figure 1

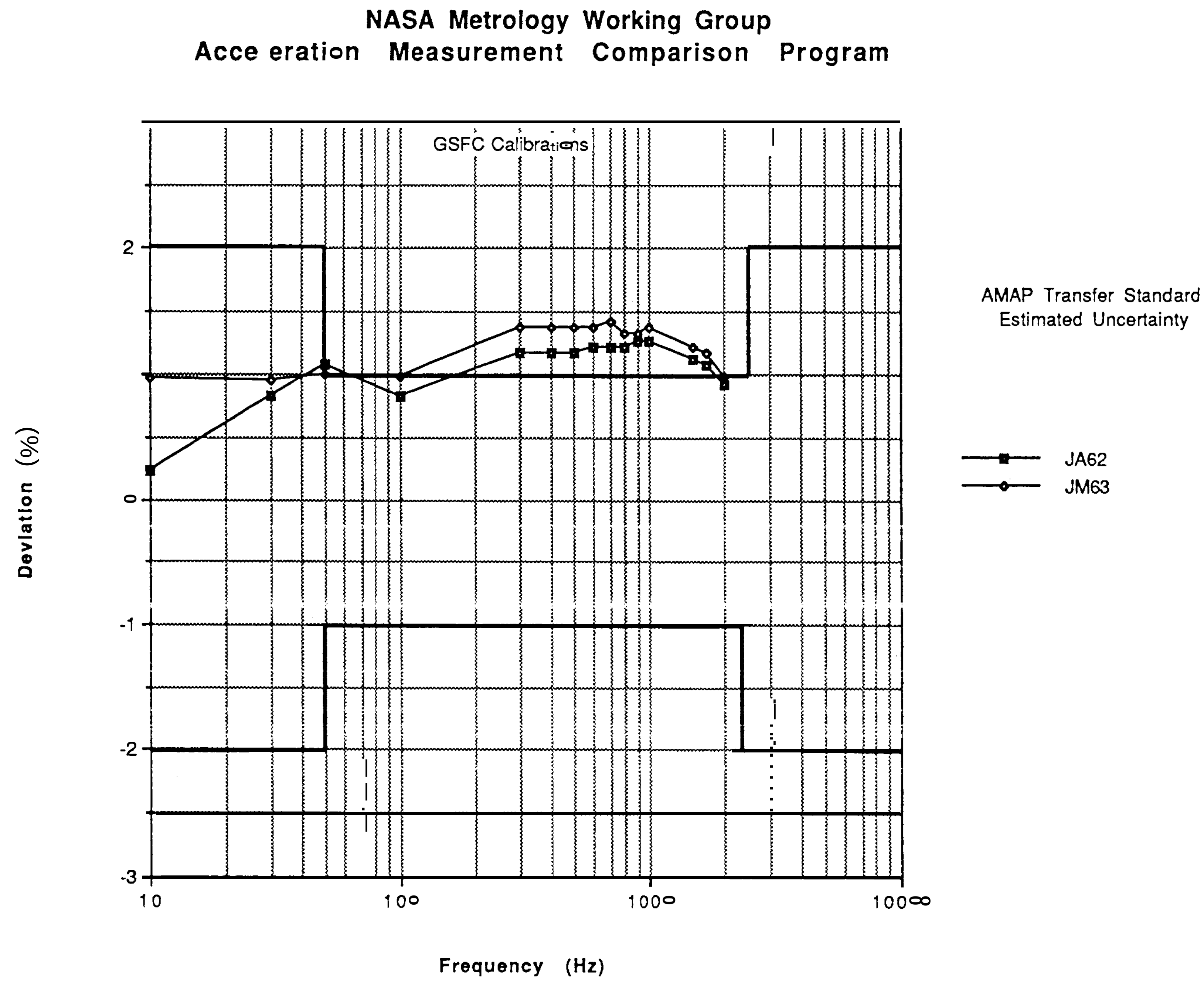

NASA Metrology Working Group
Acceleration Measurement Comparison Program
GSFC Calibrations
Deviation (%)
2
0
-1
-2
-3
10
100
1000
10000
Frequency (Hz)
AMAP Transfer Standard
Estimated Uncertainty
JA62
JM63

Figure 2

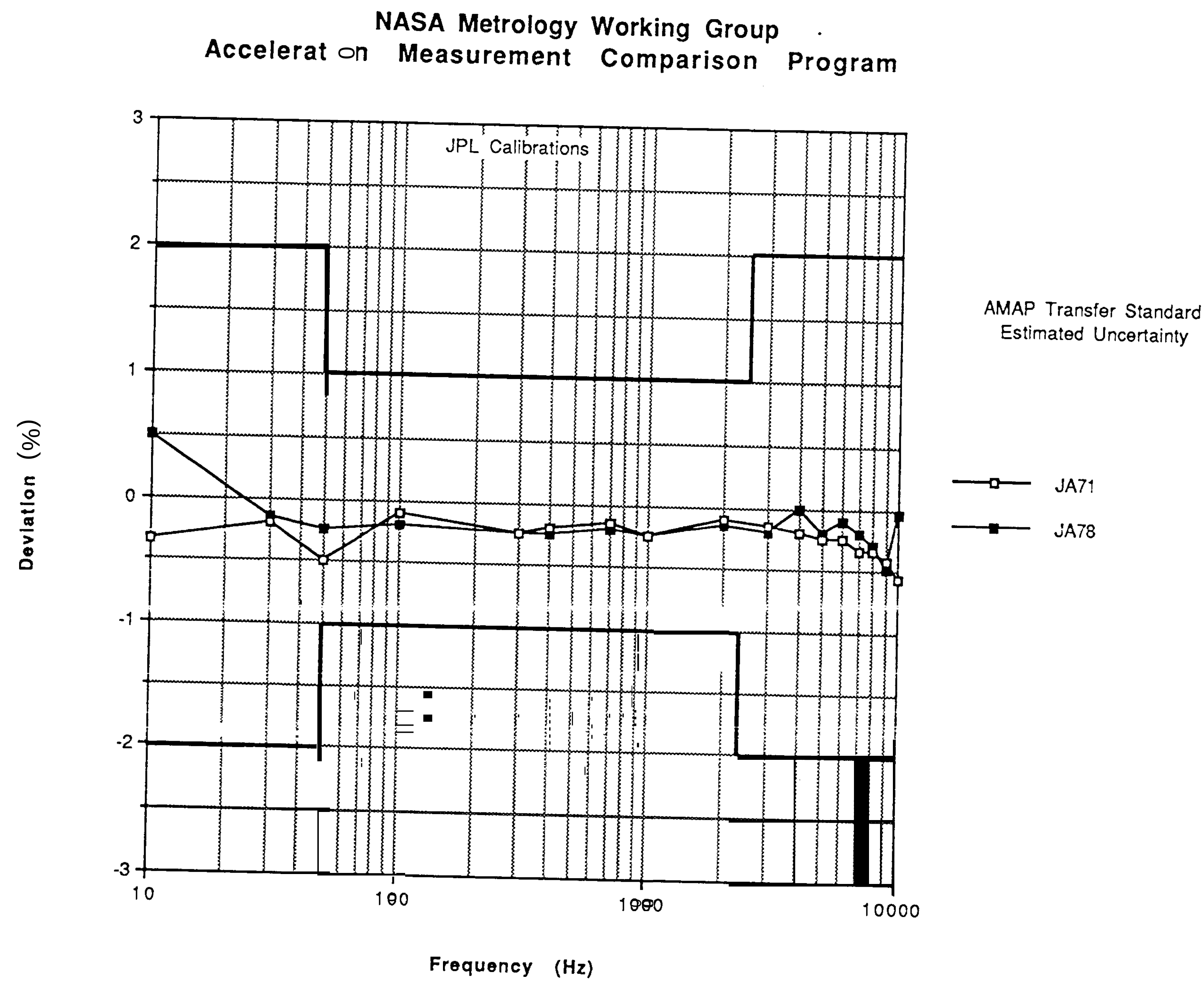

NASA Metrology Working Group
Accelerat on Measurement Comparison Program
JPL Calibrations
3
2
1
0
-1
-2
-3
Deviation (%)
10
100
1000
10000
Frequency (Hz)
AMAP Transfer Standard
Estimated Uncertainty
JA71
JA78

Figure 3

NASA Metrology Working Group
Acceleration Measurement Comparison Program

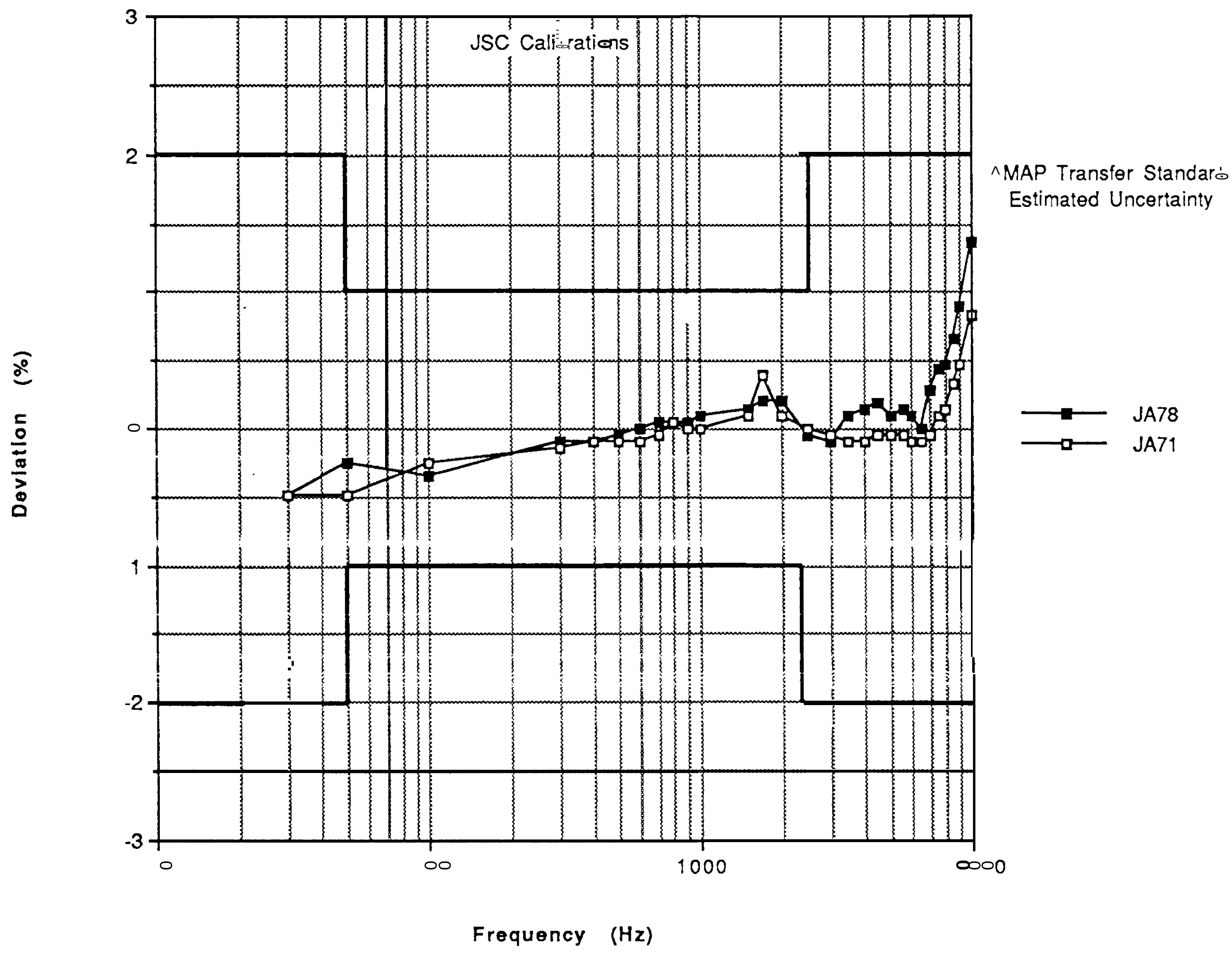


Figure 4

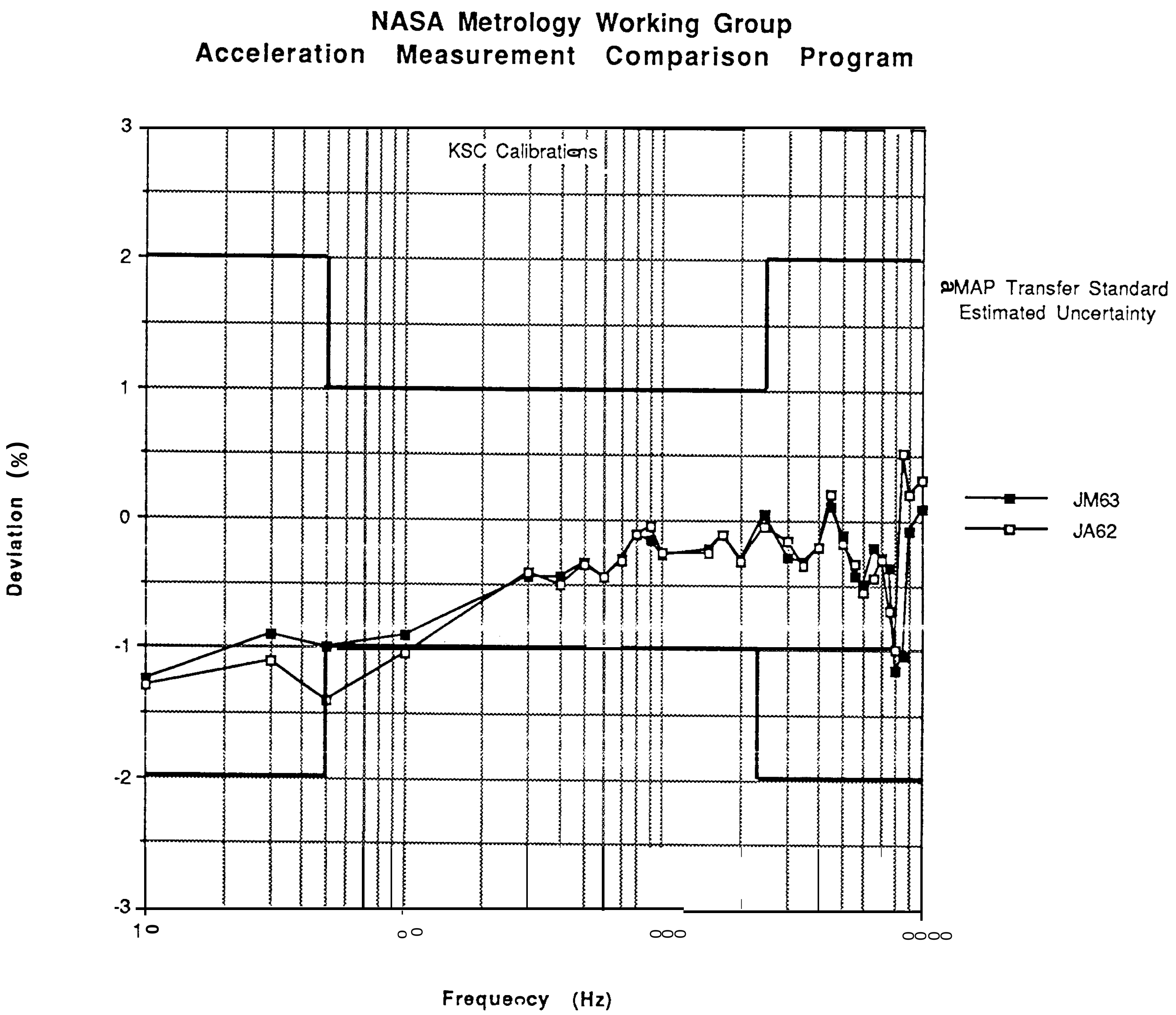

NASA Metrology Working Group
Acceleration Measurement Comparison Program
KSC Calibrations
Deviation (%)
3
2
1
0
-1
-2
-3
Frequency (Hz)
1
0
00
000
0000
MAP Transfer Standard
Estimated Uncertainty
JM63
JA62

Figure 5

NASA Metrology Working Group
Acceleration Measurement Comparison Program

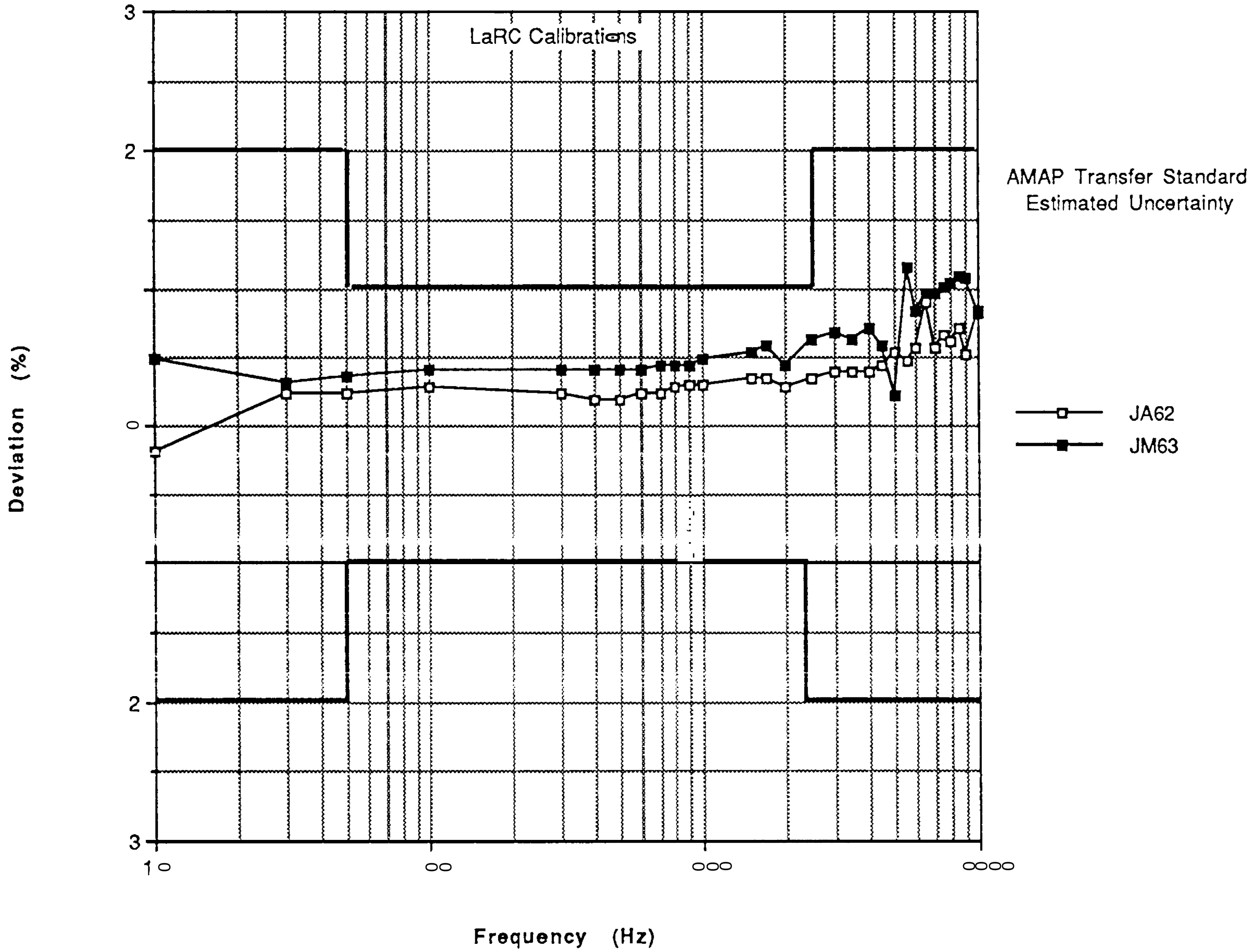
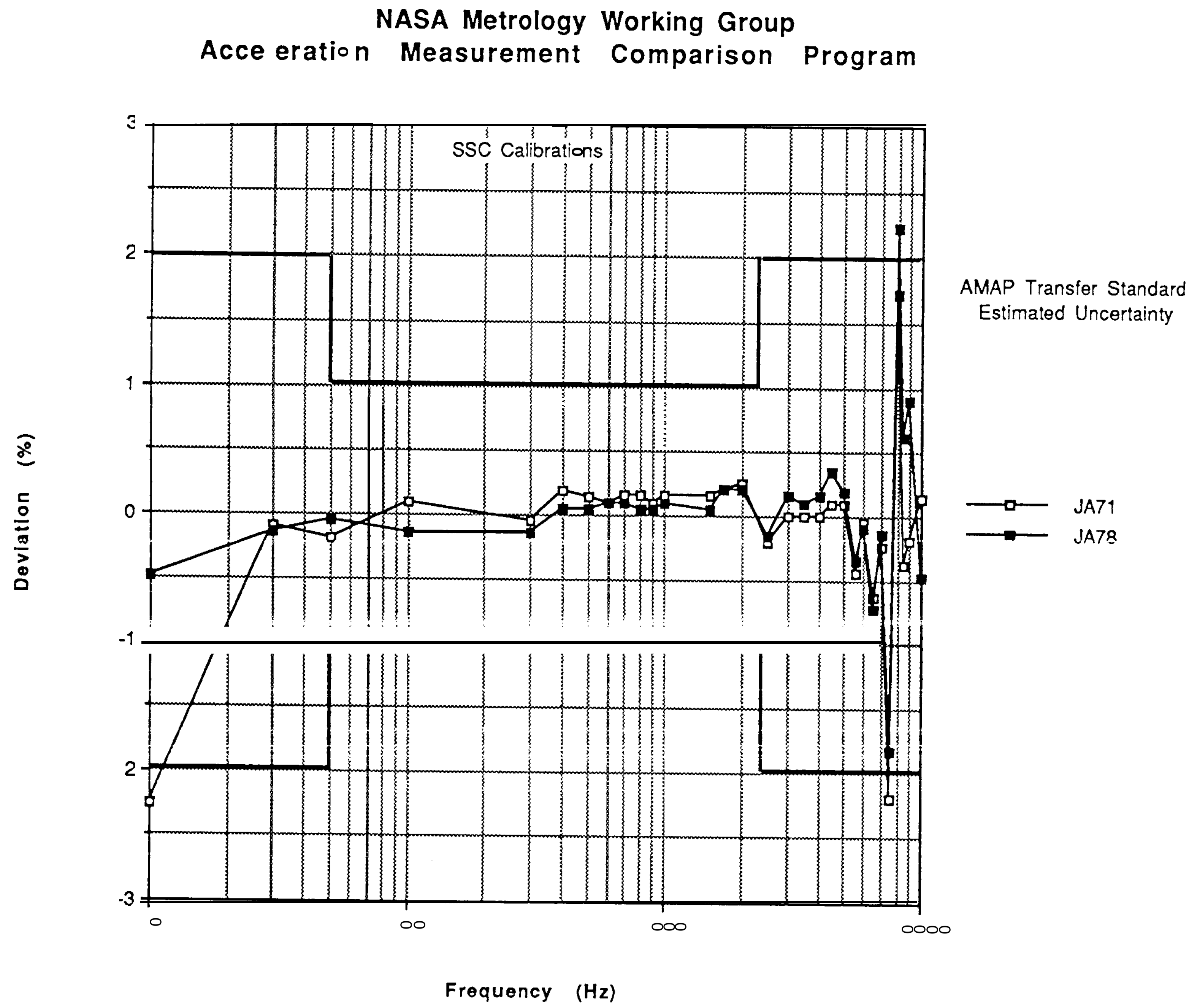
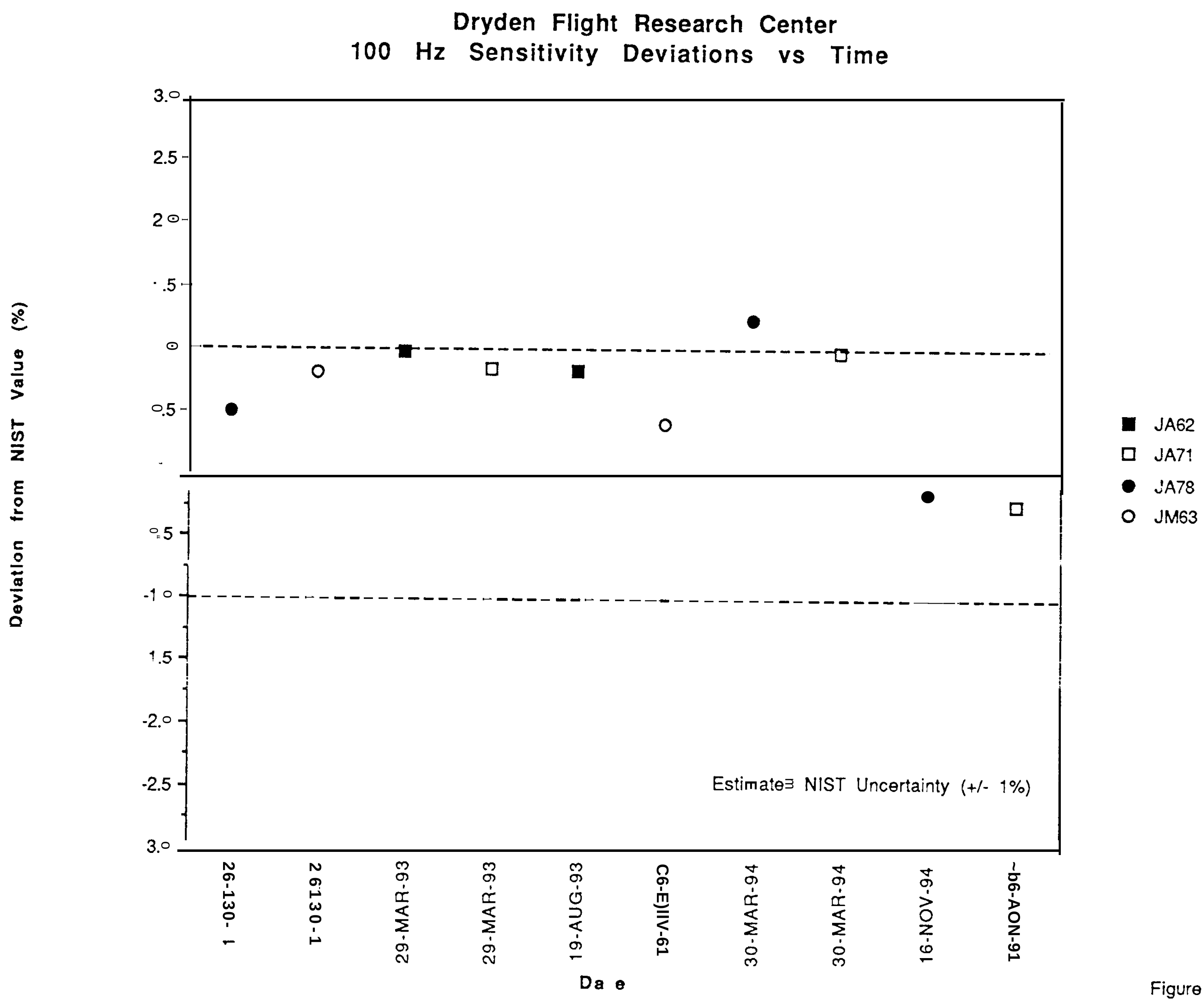


Figure ≤



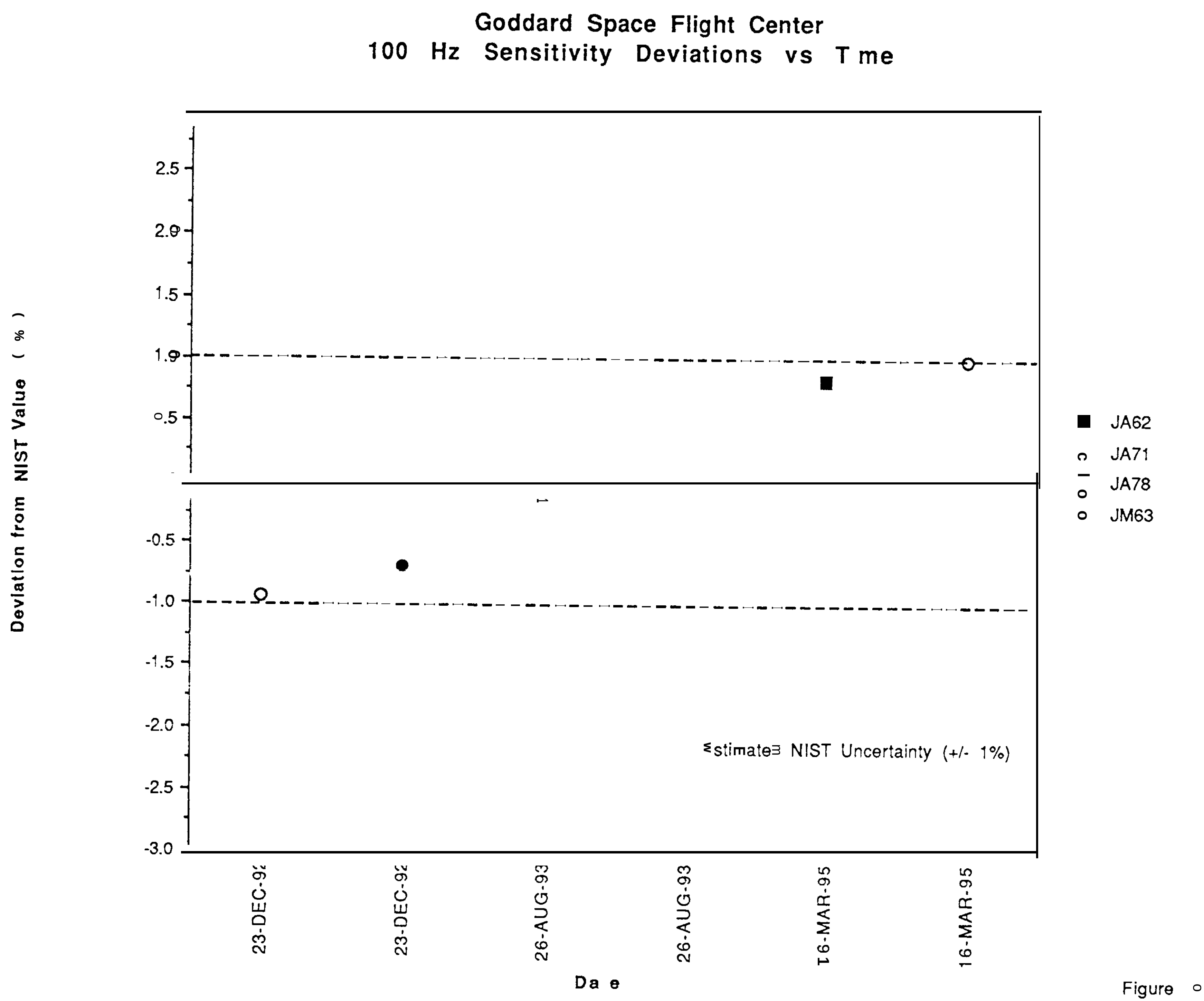
NASA Metrology Working Group
Acceleration Measurement Comparison Program
SSC Calibrations
AMAP Transfer Standard
Estimated Uncertainty
JA71
JA78
Deviation (%)
Frequency (Hz)

Figure 7



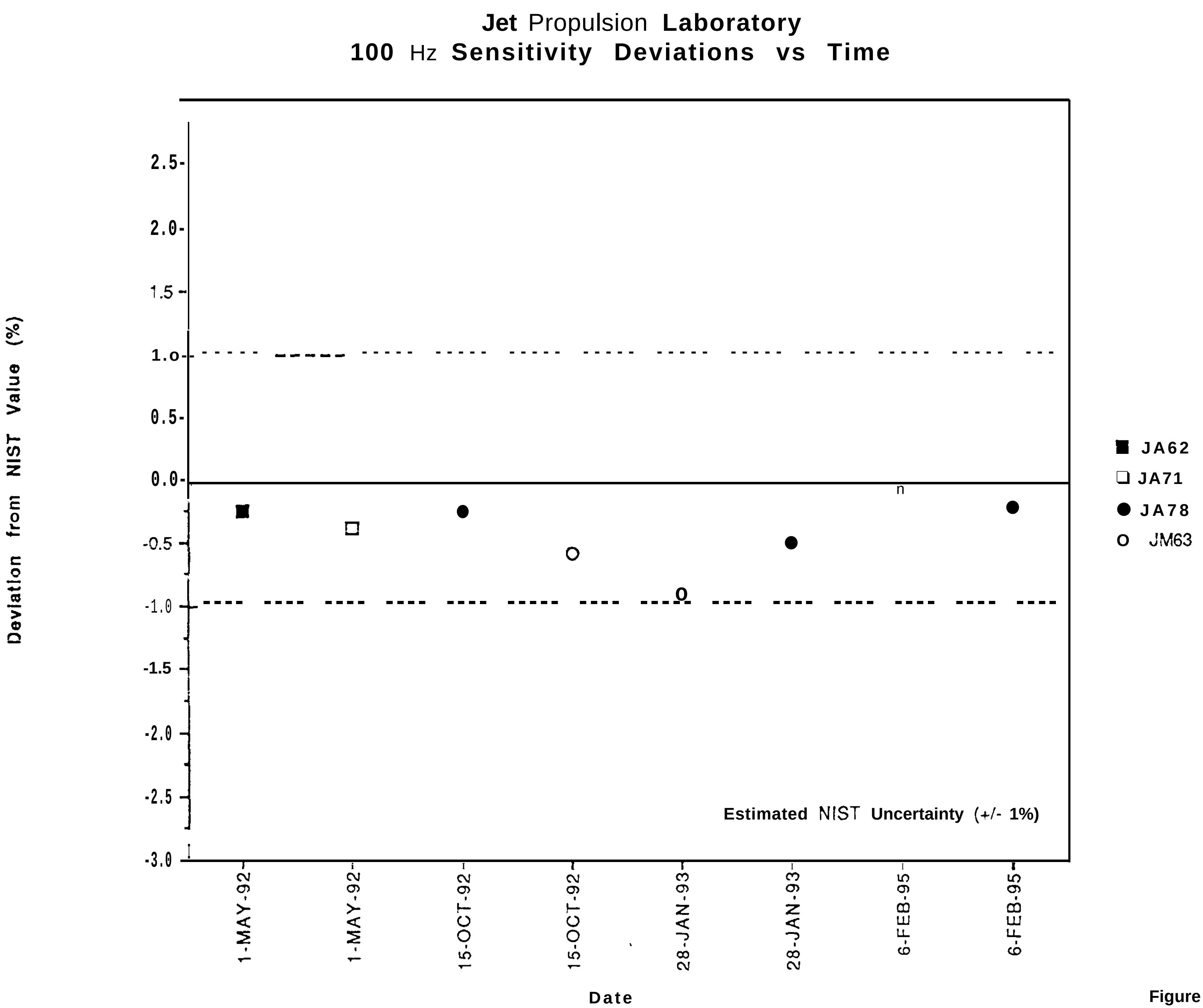
Dryden Flight Research Center
100 Hz Sensitivity Deviations vs Time
Deviation from NIST Value (%)
3.0
2.5
2.0
.5
0
0.5
0.5
-1.0
1.5
-2.0
-2.5
3.0
Estimate NIST Uncertainty (+/- 1%)
26-130-1
26130-1
29-MAR-93
29-MAR-93
19-AUG-93
C6-E)IIV-61
30-MAR-94
30-MAR-94
16-NOV-94
~b6-AON-91
Da e
JA62
JA71
JA78
JM63

Figure 9



Goddard Space Flight Center
100 Hz Sensitivity Deviations vs T me
Deviation from NIST Value (%)
2.5
2.0
1.5
1.0
0.5
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
JA62
JA71
JA78
JM63
Estimated NIST Uncertainty (+/- 1%)
23-DEC-92
23-DEC-92
26-AUG-93
26-AUG-93
16-MAR-95
16-MAR-95
Da e

Figure o



Jet Propulsion Laboratory
100 Hz Sensitivity Deviations vs Time
Deviation from NIST Value (%)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
JA62
JA71
JA78
JM63
Estimated NIST Uncertainty (+/- 1%)
1-MAY-92
1-MAY-92
15-OCT-92
15-OCT-92
28-JAN-93
28-JAN-93
6-FEB-95
6-FEB-95
Date

Figure 11

Johnson Space Center
100 Hz Sensitivity Deviation vs Time

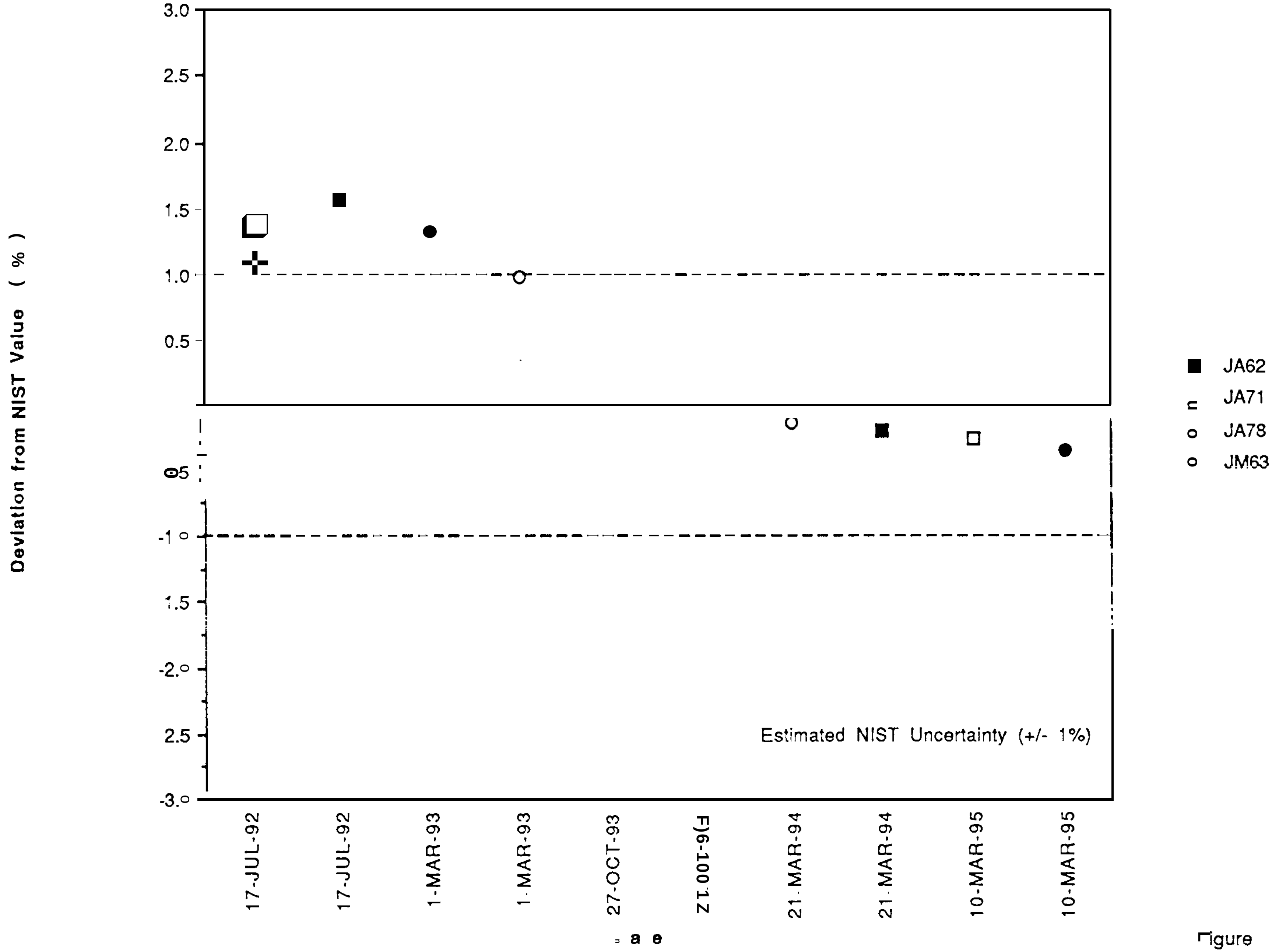


Figure 2

Kennedy Space Center
100 Hz Sensitivity Deviation vs Time

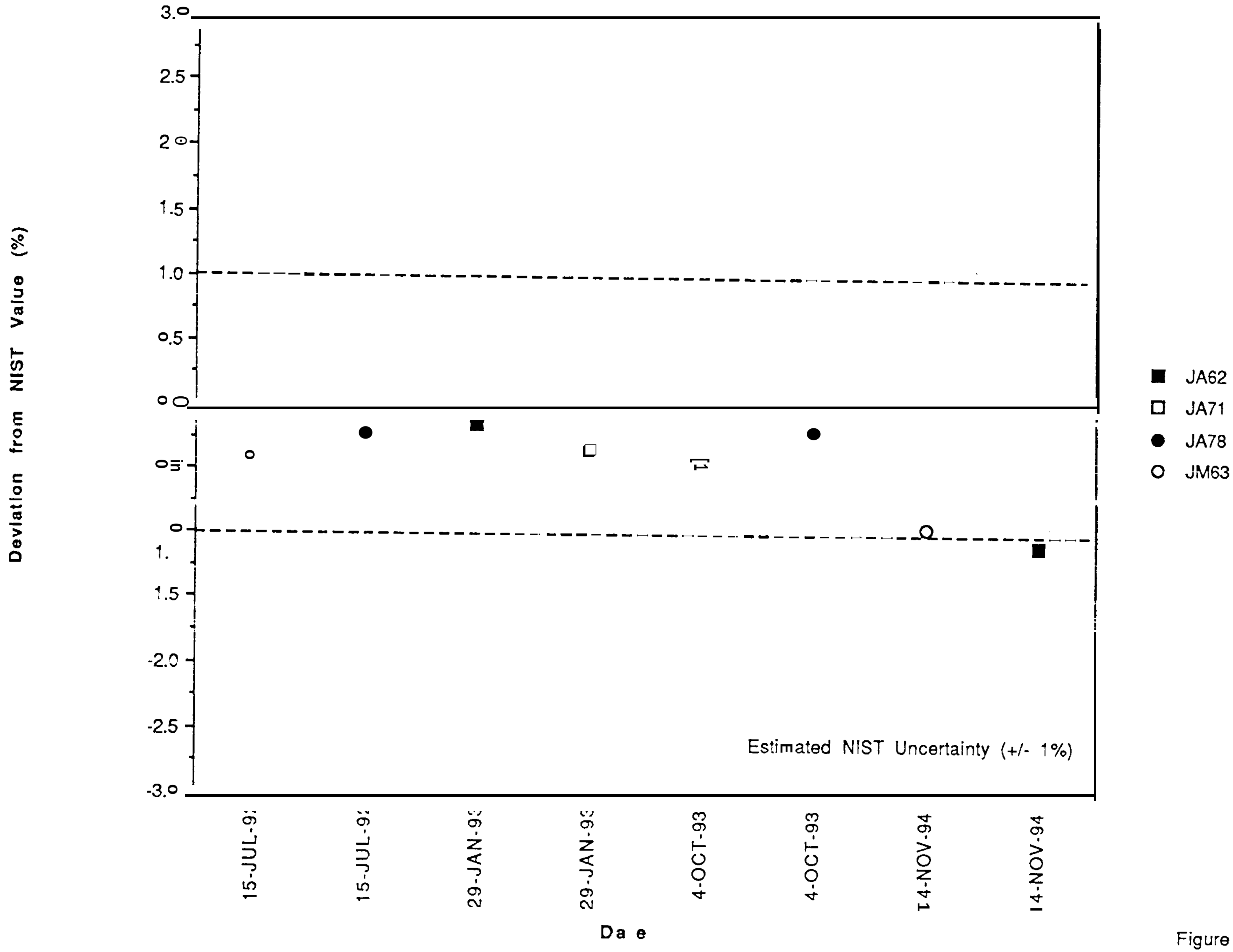


Figure 3

Langley Research Center
100 Hz Sensitivity Deviation vs Time

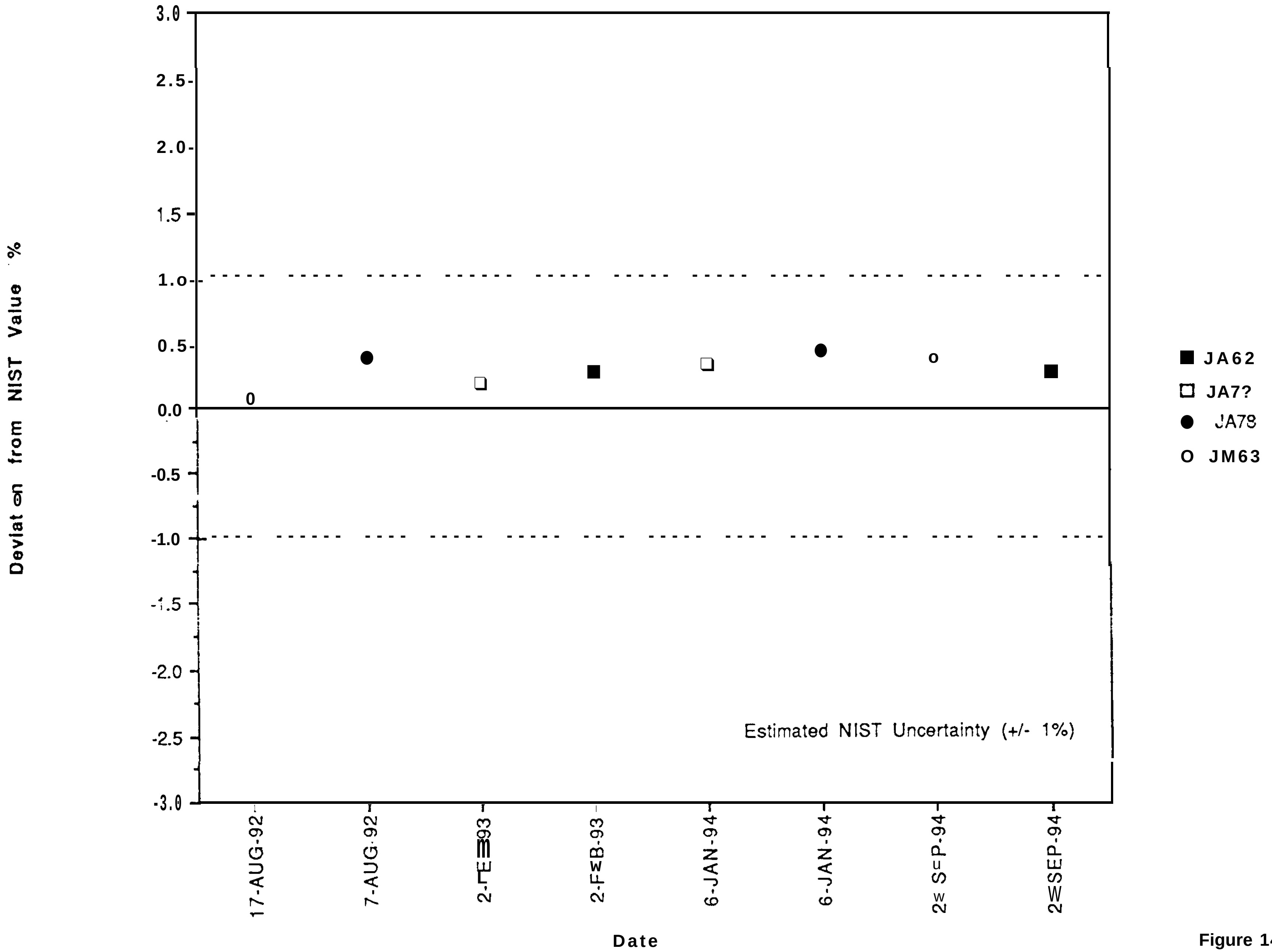


Figure 14

Lewis Research Center
100 Hz Sensitivity Deviation vs Time

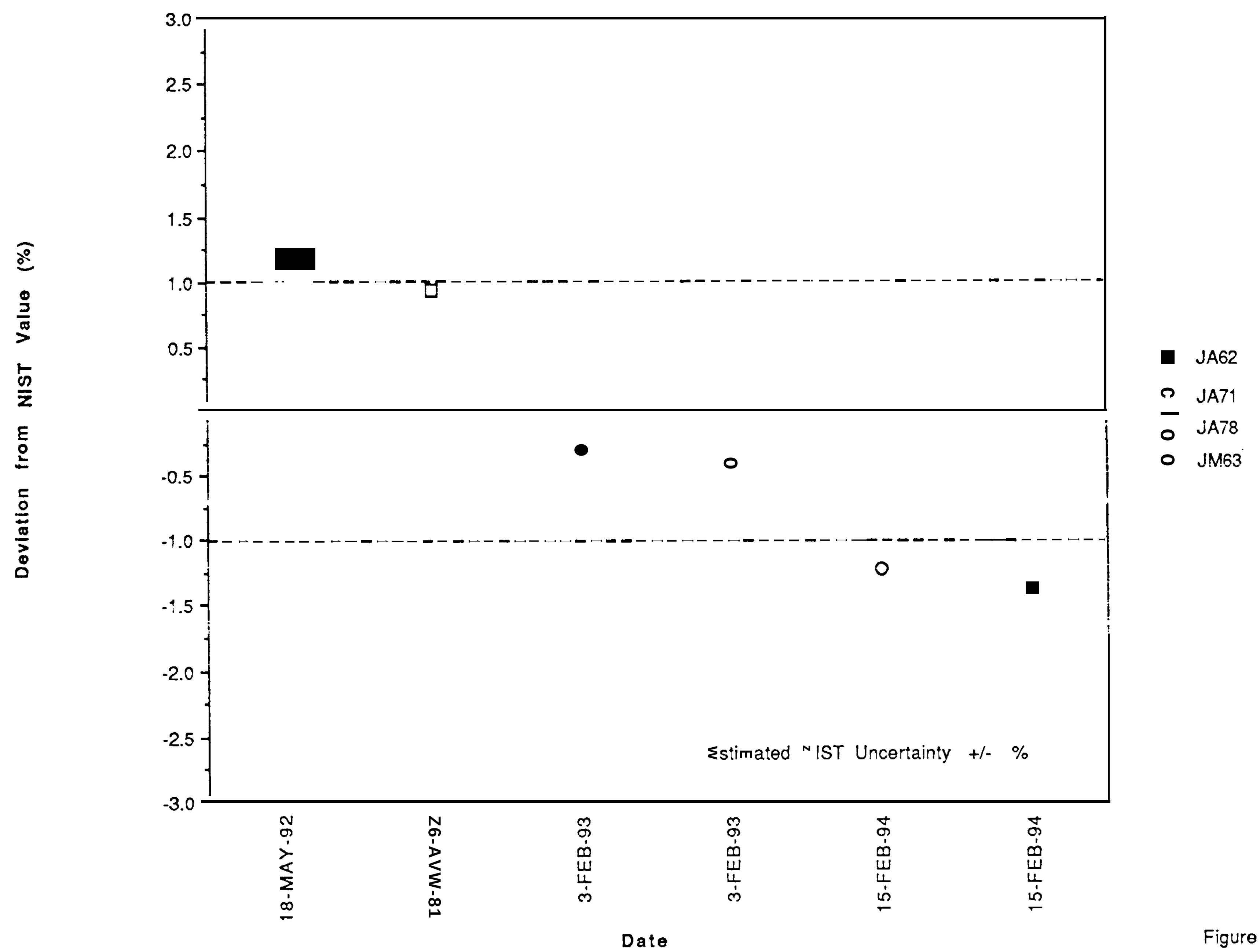
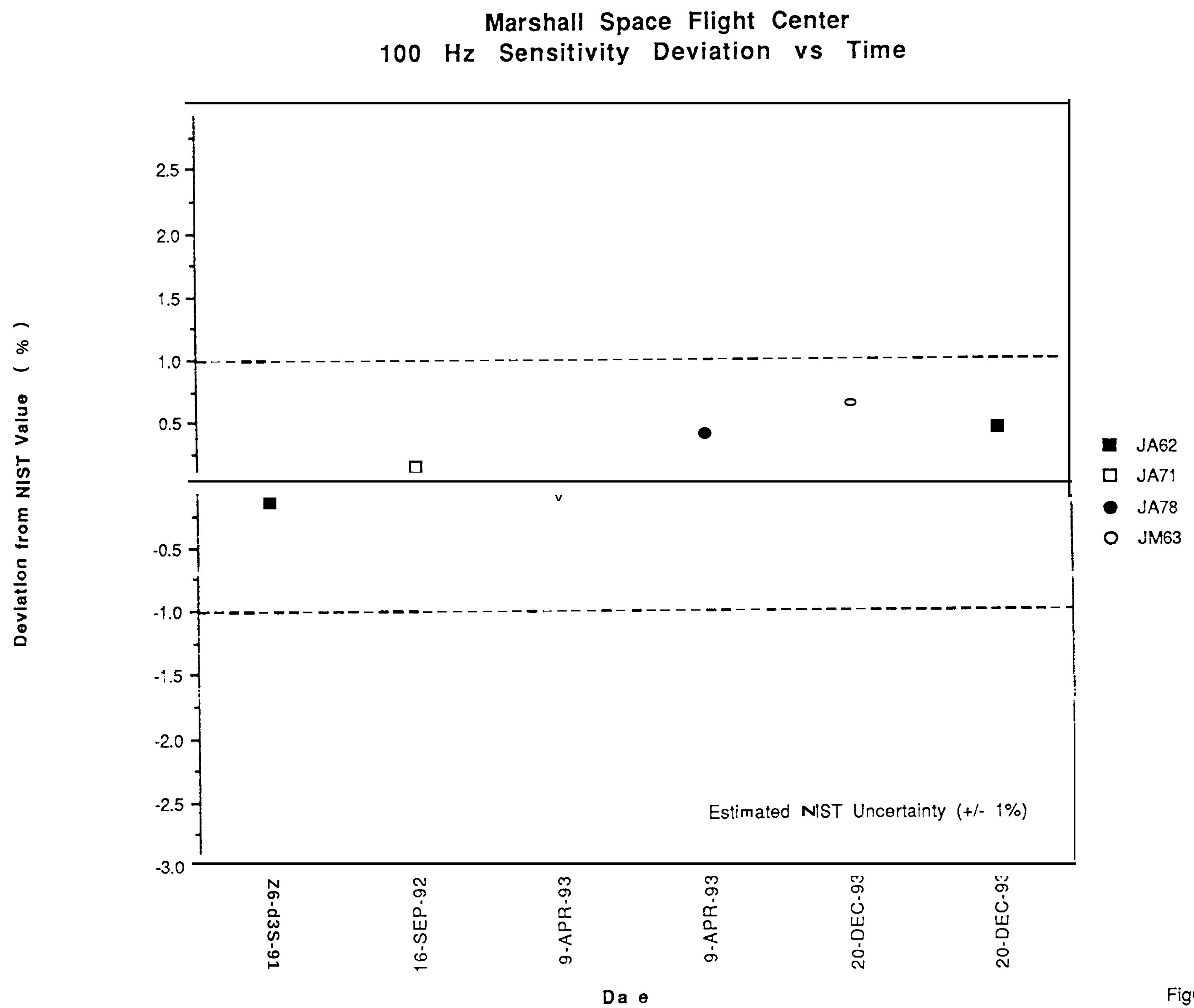


Figure 5



Marshall Space Flight Center
100 Hz Sensitivity Deviation vs Time
Deviation from NIST Value (%)
2.5
2.0
1.5
1.0
0.5
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
JA62
JA71
JA78
JM63
Estimated NIST Uncertainty (+/- 1%)
16-SEP-92
9-APR-93
9-APR-93
20-DEC-93

Figure 6

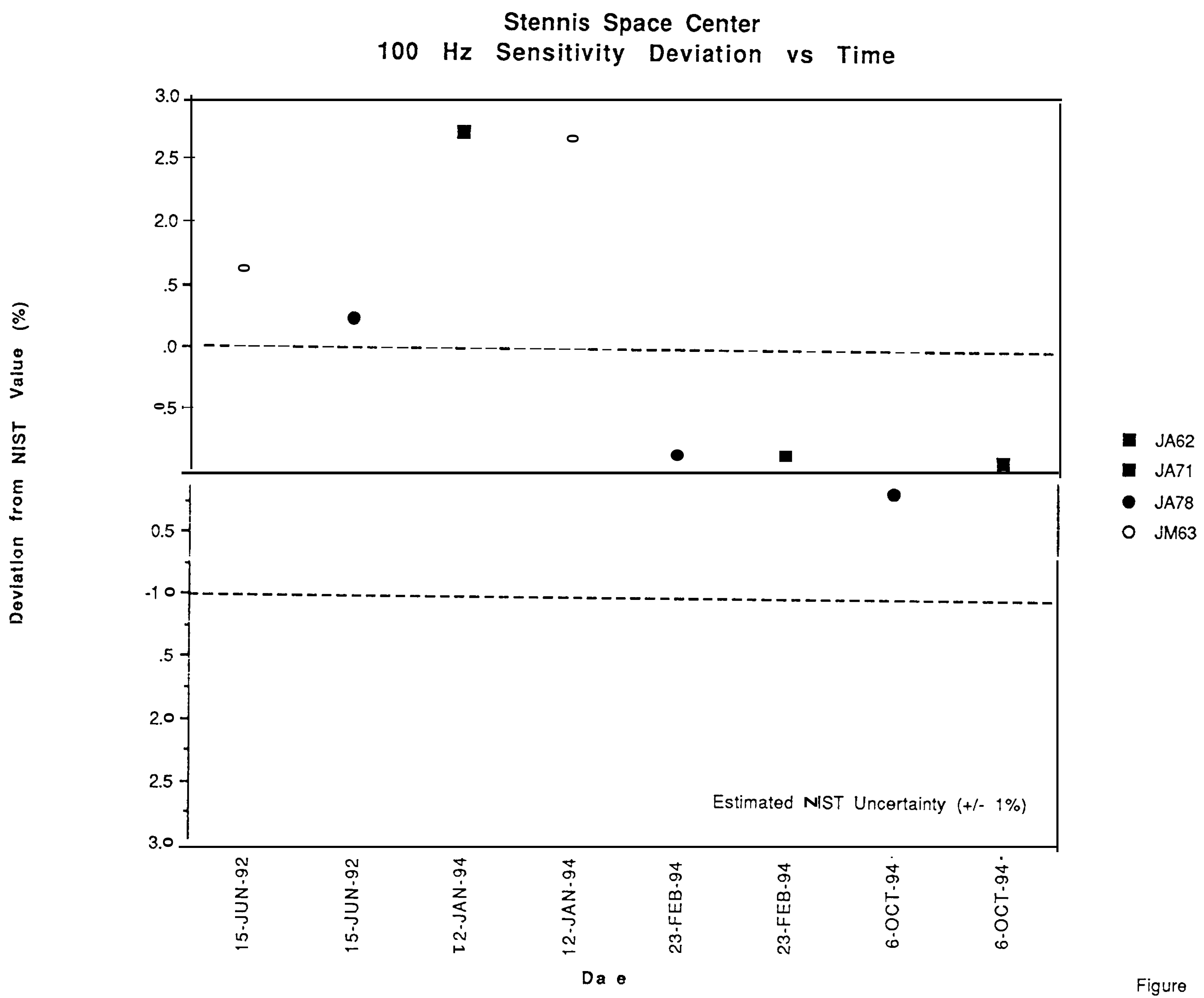

Stennis Space Center
100 Hz Sensitivity Deviation vs Time
Deviation from NIST Value (%)
3.0
2.5
2.0
.5
.0
0.5
-1 0
Estimated NIST Uncertainty (+/- 1%)
15-JUN-92
15-JUN-92
12-JAN-94
12-JAN-94
23-FEB-94
23-FEB-94
6-OCT-94
6-OCT-94
JA62
JA71
JA78
JM63

Figure 7