N91-12409

10. PREDICTION AND RECONSTRUCTION OF ON-ORBIT ACCELERATION

Edward Bergmann, C. S. Draper Laboratory

ABSTRACT

As the number of acceleration sensitive experiments to be carried on each Shuttle or Space Station mission increases, the requirement for either low-g environment or for accelerometry at each experiment location also increases. Preflight planning of such experiments in the past has not always included detailed analyses of the acceleration environment at the experiment location that had a serious impact on the experiment. Careful modeling of the mission activities and their effect on the experiment in many cases would have been beneficial to these experiments. In some cases, the experiment was not compromised, but insufficient instrumentation was available onboard to directly measure accelerations at the experiment location. This paper describes the type of preflight modeling available to assist in experiment design and mission integration and the use of that tool postflight to enhance flight data when sensors are not ideally suited to experiment analysis. Examples of recent shuttle flight experiments are presented.

My presentation is going to appear different from those of my predecessors; they presented data actually measured on orbit with accelerometers. The specific subject I want to discuss is what to do in a situation where there is no appropriate instrumentation to support analysis of the experiments. The way that I got into this particular quandary was that during mission 61-B I met the principal investigator of the 3M experiment, who was very interested in precise, low g environment. When I started talking to the experimenter, it became apparent to me that there was no single source of g-levels at various locations on the Shuttle. As a result, we are expending a significant effort trying to reconstruct the accelerations that the Shuttle induced on the DMDS experiment during that mission. We are trying to see how we can either interpret what happened to the experiment as a result of these accelerations that were induced by the Orbiter or redesign the experiment and refly it to avoid these by taking advantage of operational considerations.

I don't think I need to go through the numbers except that I want to indicate to you that most of the effects that would influence an experiment in the milli-g or micro-g range have either been studied mathematically or calibrated by in-flight measurements and verified against simulations on the ground. What that leads to is that we have a fairly good ability to predict and model the kinds of effects that the various environmental disturbances would have on the vehicle, probably down to the micro-g range. I can't say that we have a good model of some of the effects of things like solar radiation pressure and cabin leakage but they are at or below this range. We also have a very good way of modeling the control disturbances that are induced on the experiment.

The DMDS experimenters were not aware of the fact that Mission 61-B included the flight test of a new control system, which would maneuver the vehicle considerably more than most of the other Shuttle flights had been maneuvered. So there was a great deal of jet activity on that mission and, as a result there were very large jet thrust-induced disturbances on the experiment. The disturbance-level numbers were generated specifically in support of the DMDS experiment, which was in a middeck locker.

In trying to piece together what happened on that mission we first went back to the kinds of data that are normally available from a Shuttle mission. There are two primary sources of information on what occurred during a mission in terms of the dynamic environment. First is the normal Shuttle telemetry of a large number of flight control, guidance, and navigation parameters to reconstruct the Shuttle state, trajectories, and the control activities. In addition, on the orbiter Columbia there is also the Aerodynamic Coefficient Identification Package/High Resolution Accelerometer Package (ACIP/HIRAP). This is a set of linear accelerometers, angular rate gyros, and angular accelerometers that were originally installed in support of entry aerodynamic studies. The ACIP has been available since STS-3 and the HIRAP has been available since STS-6. We have borrowed them for on-orbit measurements to calibrate RCS jets and to verify disturbance levels, as shown in Figure 1. Unfortunately, 61-B was flown on Atlantis, which does not have an ACIP/HIRAP. Direct accelerometer data were therefore not available from the instruments in support of the experiment.

One of the types of information that we did have available was in the telemetry; it is the state feedback through the flight control system and the navigation system. For flight control and navigation the orbiter relies on an inertial measurement unit, which is simply a four-axis set of gyros for measuring attitude, capable of about 20 arc seconds quantitization. There is also a set of accelerometers mounted on the stable member of the IMU that have a resolution on the order of 1 cm/sec^2.

Normally for on-orbit operation there are no other onboard state data available. There are ground tracking data available but the resolution of that data is somewhat less than needed for analysis of an experiment.

In the on-orbit flight control system there is no rate gyro in the loop. The angular rate information that is supplied by the flight control system on the orbiter is actually inferred from the attitude measurements and from the control supplied by the autopilot of the vehicle and is basically generated by a two-part filter. That filter is very similar to a Kalman filter, based on the difference of the estimated vehicle attitude and IMU. It generates an estimate of the vehicle angular rates and the undesired acceleration.

One interesting problem in using these data to analyze what happens at a particular location in the orbiter is that the navigation system is navigating the Orbiter center of gravity and the DMOS experiment was located in the orbiter middeck, which is 45 feet forward of the center of gravity. The result is that the acceleration at that location consists of the jet accelerations, centripetal, and Coriolis terms, which actually become quite significant when the Orbiter is maneuvering in attitude. There are also significant accelerations due to the gravity gradient, aerodynamic, and vibration. Most of these have been observed in the past and have been modeled mathematically. These models have been compared to measurements, so it is not unreasonable to build a simulation of these effects to infer what is going on at the middeck location of the orbiter from jet firing activity and flight control activity.

We have used the HIRAP to observe vehicle response to individual jet firings and also to validate the frequencies and some of the modal amplitudes of the structural model of the Orbiter. Figure 1 shows processed HIRAP linear accelerometer data. This is a time history of the response to a series of vernier jet firings and you can see a very strong jump in the acceleration when the vernier jets are fired. These are all very short firings and the oscillation is indeed the Orbiter structure. We have removed most of the known electrical and instrument noise and in doing the analysis of these data, we found frequencies that correspond very closely to the predicted structural frequency of the orbiter. This gave us a fair amount of confidence in the structural models of the orbiter that were generated by the standard finite element techniques. We also have flight data that can be used to model the structural response of the orbiter, at a given station, to individual jet firings.

The HIRAP is mounted very close to the orbiter center of gravity, close to the keel of the orbiter, about 10 feet below and 10 feet behind the center of gravity of the orbiter. So it is a very good measurement of what the Orbiter center of gravity is doing.

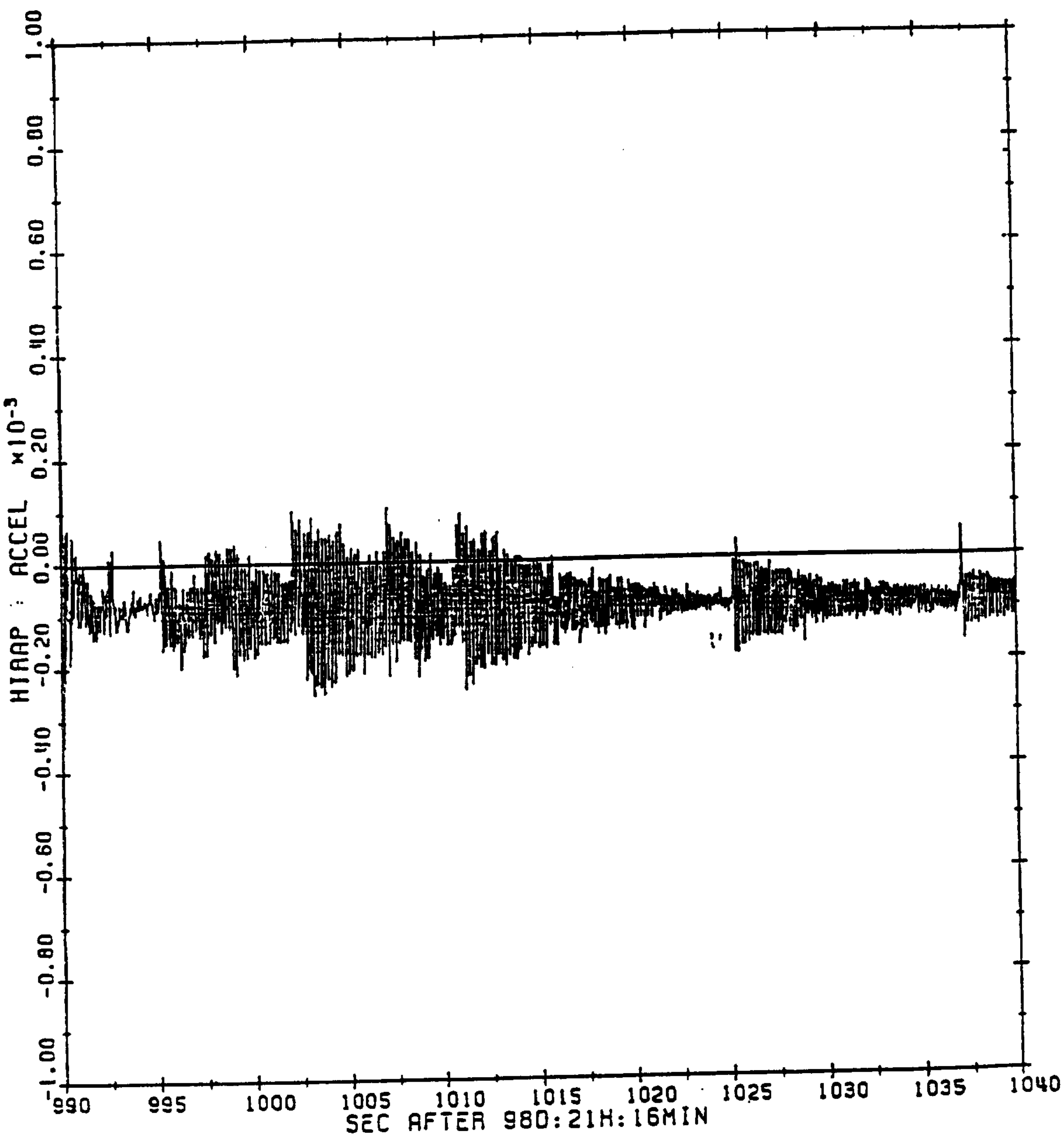

FIGURE 1. HIRAP (X) LINEAR ACCELEROMETER; TIME HISTORY, VRCS REGION, COMPENSATION (20 Hz BANDWIDTH) (G)

Data are generally telemetered at 1 Hz. The flight control system on the orbiter, however, operates at 12½ Hz. There is a sampling problem that can occur, if we were to plot the flight data represented by the circled points shown on Figure 2. There is a great temptation to simply connect the points and say this is what happened. You can miss significant events, in this case a pair of jet firings, that get you back to the same state, but produce some motion of the vehicle in between these points. So using 1 Hertz telemetry data and then doing things like sampling at high rate can actually be misleading. You can miss some disturbances acting on the vehicle. Fortunately, the jet firing activity is sent down at 12 Hz, and that means that we see all the jet firings that are being applied to the vehicle. So, we do know every time that a jet is fired on the orbiter and that's a highly reliable system. In fact, there are two separate indications each time a jet is fired. We can look at the data at 1 Hz then notice a jet firing in between these points. We then have to do some work to find out what happened to that measurement, as a result of those jet firings. That leads us into the kind of analysis that we are doing for DMOS.

The simulation we developed is a tool that will also be available for the space station. For analysis of flight control design on shuttle, we built a model of the shuttle flight control system which is now used in doing analysis in flight experiments. Going back to our math models of the environmental disturbances, reactions of the vehicle, jet torques, and so forth, we can build a model of the rigid motion of the orbiter that we use to predict performance. We have actually used this to design some of the in-flight control experiments.

We have compared that with the results of flight data after similar activities were performed and found that it is a highly accurate measure of what the vehicle would do in response to certain control inputs. In addition, we have a model of the flight control and guidance system and this model is directly traceable to the flight code and can be made to interact with the environment in exactly the same way that

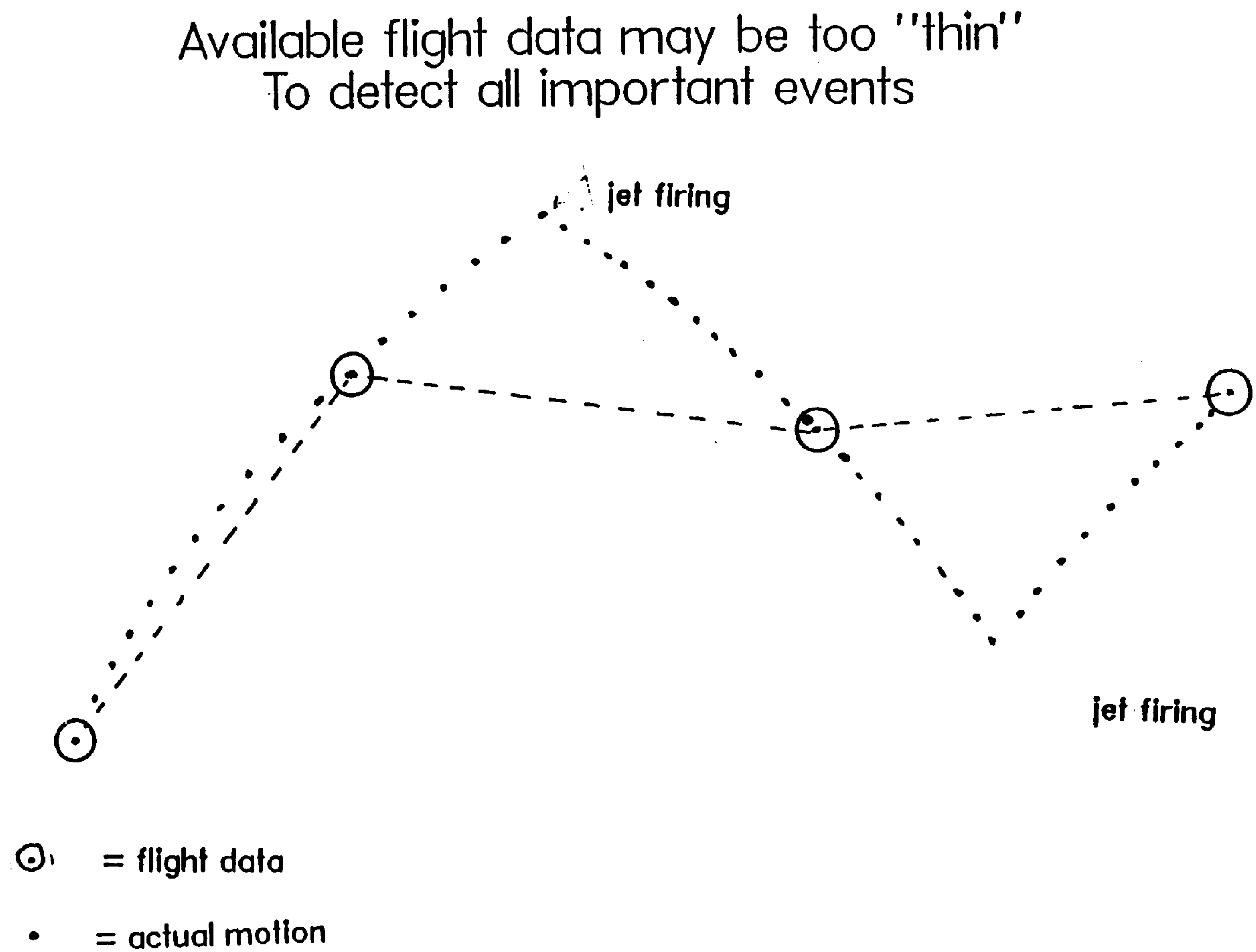

FIGURE 2. AVAILABLE FLIGHT DATA MAY BE TOO "THIN" TO DETECT ALL IMPORTANT EVENTS

the orbiter flight control system interacts with the orbiter. Jet firings act on the orbiter and the IMU data are fed back to the flight control system, which processes that data and acts upon it.

For the 61-B mission there were actually two ways we could reconstruct what happened. Using a tape from NASA of all the jet firings that occurred during a portion of the mission, we can turn off our avionics model and simply drive our environment model with the jet firing activity. We integrate the equations of motion to generate a history of the vehicle state. We can then apply the corrections that correspond to the difference in the motion of the vehicle at the cg, or in any particular location on the vehicle, accounting for the gravity gradient terms, the transverse and centripetal terms, the input flex terms, and then produce some representation of what motion occurred at that location.

In other situations, and fortunately 61-B was not one of them, where the telemetry drops out, we can get into this very dilemma of good data up to a point and have a gap because the telemetry was lost for an interval. However, we can take the last data point and use that as an initial condition in our simulation, and since our simulation mimics the flight control and dynamics of the vehicle, we can fill in the gap. We use the next data point as a check, that we have indeed arrived at a correct statement when the data are picked up again. So we have two positions and basically we are solving differential equations between those positions, so we can also use this to fill in intervals where data are not available.

One of the reasons that one can't simply take the accelerometer data from ACIP, HIRAP, and the navigation data at the center of gravity is that the orbiter does rotate. In fact, the normal mode of operation for the orbiter is to rotate at orbital rates to keep the payload bay pointing at the earth (about 0.06 degrees per second). There are also quite a number of attitude maneuvers that are performed as a part of the normal orbiter operations to align the IMU or to satisfy certain experimental requirements. Any time such a rotation happens, the orbiter naturally rotates about the center of gravity and an experiment in the middeck will be accelerated. If there is a particle suspended in a volume that particle would eventually collide with the side of the vessel.

This rotation could be from a control input for an attitude maneuver, or it could be the gravity gradient trying to position the Orbiter a certain way. The only message here is: the orbiter is going to rotate about the cg, and because the middeck is on a lever arm it will swing like the mast of a boat, and you had better take that into account. The navigation data is really telling you where the center of gravity is going, not where you're going, that's the motivation for the corrections that we apply to the results of this simulation. There are further corrections that you would have to apply to navigation data or any ACIP data to determine what happened in the middeck.

One of the things we did for the DMOS experimenter on Mission 61-B was to demonstrate some of the typical maneuvers that he would have seen during the mission. Figure 3 is a simulation of one of the vernier yaw maneuvers on the mission. You can see the vernier jets firing to accelerate the vehicle at about two tenths of a degree per second. The angular rates in the other axes are moving up and down due to the way the autopilot decouples the vernier jets. It will generally fire one or two jets continuously and cycle other jets to cancel the off-axis acceleration. After the rate is achieved, it will coast throughout the maneuver. Occasionally you'll see a firing in the middle of the maneuver and then jets fire to take out the angular rate. Most of the maneuvers are performed going from a local vertical track so you are starting at 0.06 degree per second and going to a vertical track. This maneuver had a great deal of jet coupling in it, and looking at what happened to the orbital center of gravity during that maneuver, you can see the acceleration level cycling as the jets cycle off and on. There is a constant level at the beginning of the maneuver. During the closing phases of the maneuver there is a near-zero level of acceleration because the angular rate is so small and you can see jet cycling again as the maneuver stops. Figure 4 shows what happens at the center of gravity.

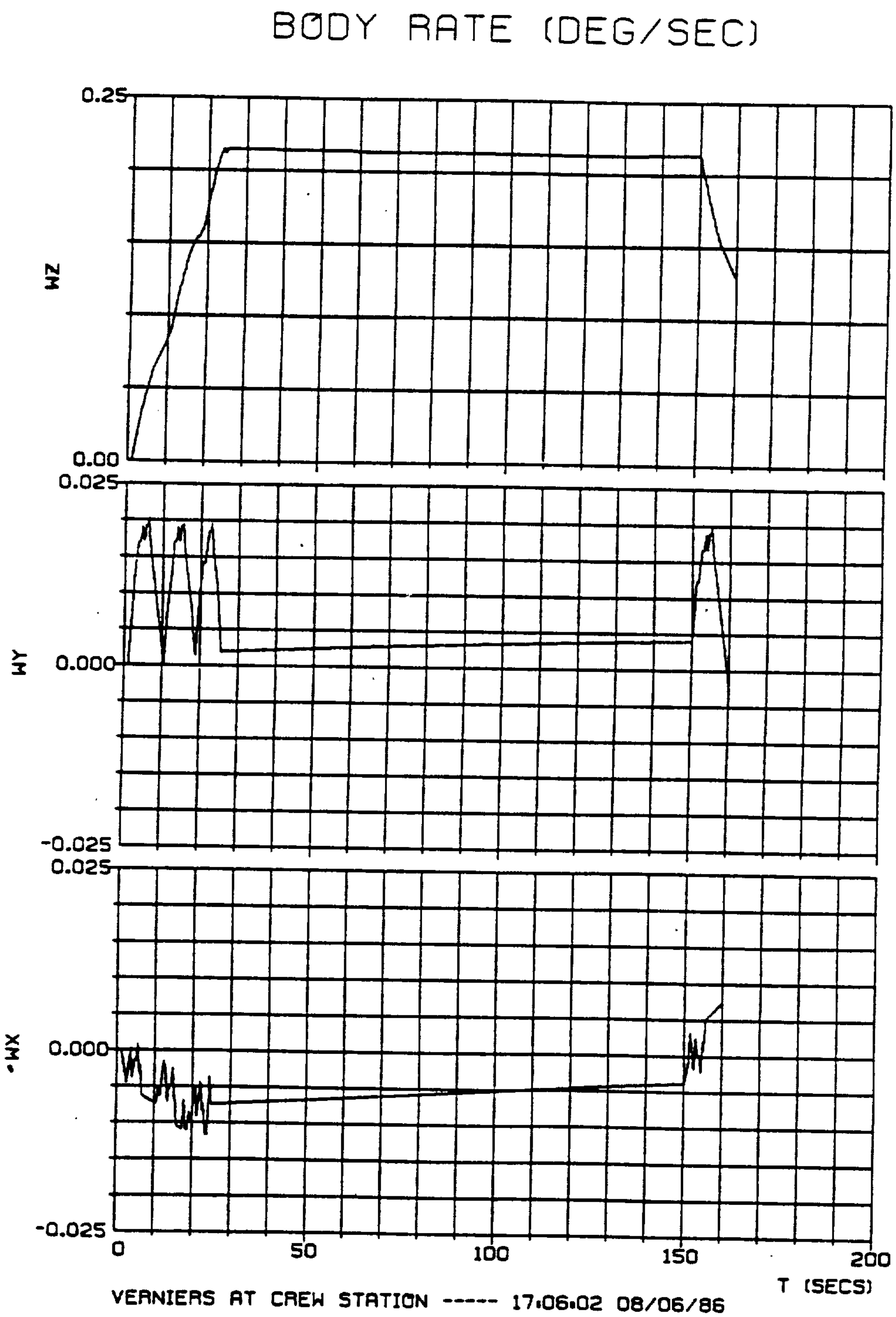
BØDY RATE (DEG/SEC)
0.25
0.00
WZ
0.025
0.000
WY
-0.025
0.025
0.000
-WX
-0.025
0
50
100
150
200
T (SECS)
VERNIERS AT CREW STATION ----- 17:06:02 08/06/86

FIGURE 3.

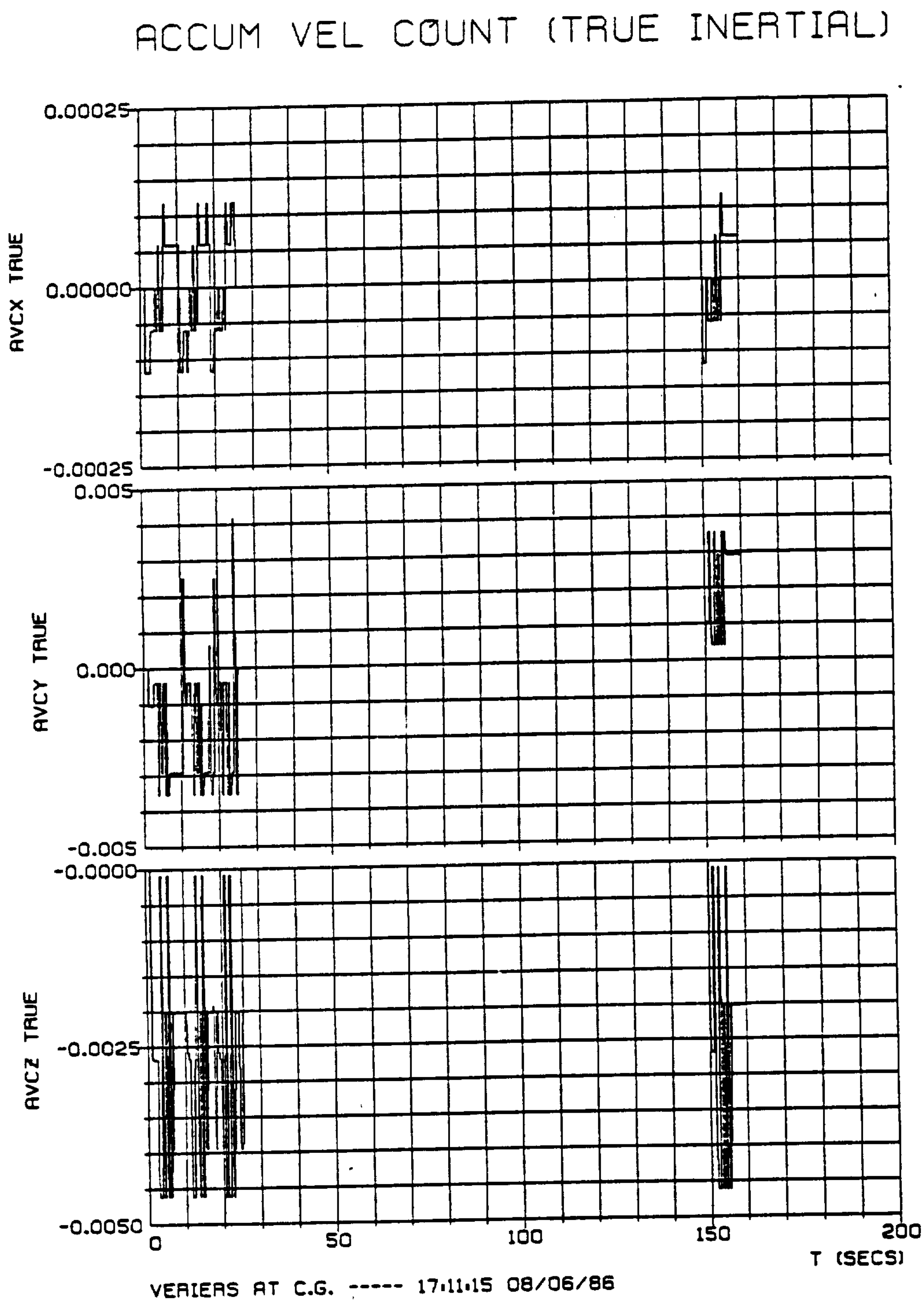
ACCUM VEL COUNT (TRUE INERTIAL)
AVCX TRUE
0.00025
0.00000
-0.00025
AVCY TRUE
0.005
0.000
-0.005
AVCZ TRUE
-0.0000
-0.0025
-0.0050
0
50
100
150
200
T (SECS)
VERIERS AT C.G. ----- 17:11:15 08/06/86

FIGURE 4.

When we consider that our experiment is not at the center of gravity we get a plot that looks very similar (Figure 5), you can see the jets cycling. You can see that this plot looks very similar except the scales differ by an order of magnitude approximately, and that ratio comes out to be about a 50-foot lever arm. Had the experimenter been supplied with ACIP/HIRAP data, or had he been supplied with navigation data to tell him what happened during his experiment, he would have gotten a very misleading impression of the acceleration that his experiment saw as a result of this maneuver.

The second thing that occurred on that mission showed us that the orbiter doesn't always rotate about the center of gravity, depending on what the control system is trying to accomplish. At one point in the mission we deployed a small radar reflector from the forward end of the payload bay. After the commander maneuvered the orbiter back about 35 feet from the payload, he practiced moving around relative to the reflector, to assess the ability to control the vehicle position using a different auto pilot than the one we have now. The commander had to rely primarily on visual cues to determine what motion occurred.

The control system was configured to control the center of gravity of the vehicle and we actually ran into a couple of interesting things that could have misled the commander during that experiment. When we asked him to perform this task the commander put the vehicle in a mode which held the attitude automatically so he didn't have to worry about the vehicle orientation. He used translation hand controller to change the velocity of the vehicle incrementally. Each deflection of the controller changes the vehicle velocity by approximately 0.1 ft/sec. At one point during this activity, he attempted to move the vehicle to the side in the Y direction. He told us the vehicle didn't move and we weren't sure why because the telemetry said the jet fired, the vehicle responded, and the center of gravity moved. The motion at his location, however, was an order of magnitude smaller than the spike at the center of gravity.

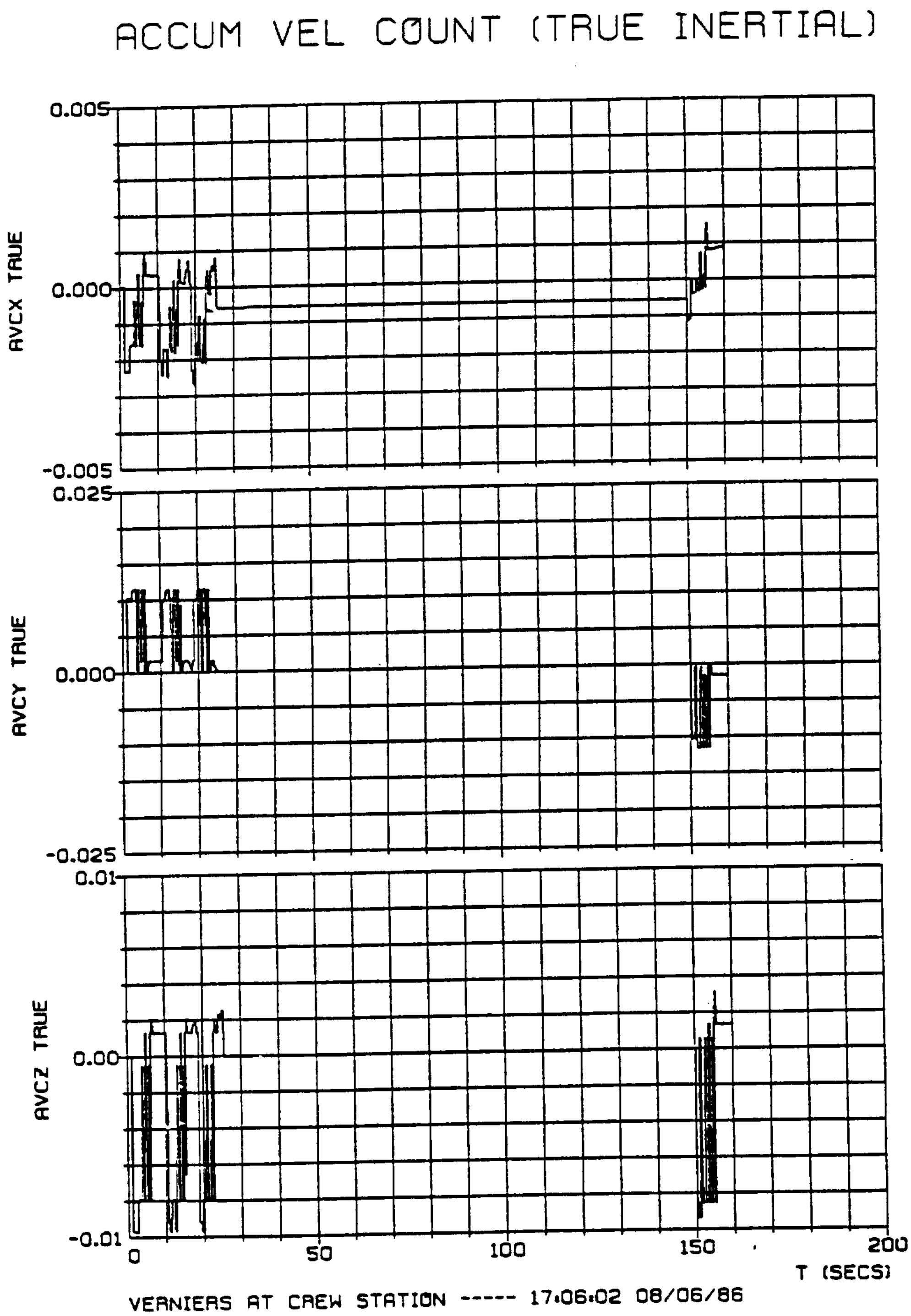
ACCUM VEL COUNT (TRUE INERTIAL)
0.005
0.000
-0.005
AVCX TRUE
0.025
0.000
-0.025
AVCY TRUE
0.01
0.00
-0.01
AVCZ TRUE
0
50
100
150
200
T (SECS)
VERNIERS AT CREW STATION ----- 17:06:02 08/06/86

FIGURE 5.

The vehicle had actually controlled attitude and translation at the same time. The control system was trying to find the optimal way to take out the attitude errors and to simultaneously satisfy the translation of the cg that the commander wanted. So instead of doing what the commander thought it was going to do, it actually rotated around him; the center of rotation was instantaneously moved to where the commander was. To satisfy the angular rate requirement and the translation requirement at the same time it fired one jet that resulted in an instantaneous center of rotation that was not the center of gravity because the CG was translating. Therefore, it is possible to make the vehicle rotate about any point you want.

It is important to try to plan to have accelerometers near your experiment and not rely upon the system. In the past you didn't always have them where you wanted them, and there are going to be times when they fail. What we are finding now is we can accurately fill in some of those gaps by reconstructing the vehicle motion based on the information that we have. In addition, we also want to warn you that when you're planning an experiment that requires micro g's, talk to the people planning the mission. Find out what they're doing and look very carefully at the kind of motion you're going to get. Perhaps if you do these kinds of simulations you can save yourselves a lot of trouble.

Ray Yoel, Boeing: This simulation work that you've done. It can be used to predict accelerations in future flights?

Ed Bergmann: The question was if this acceleration work could be done to predict accelerations on future flights?

In fact, one of the things that we have done with the simulation is to use it to support the development of crew procedures for certain experiments and one of the products is the center of gravity acceleration of the vehicle. In general, the procedures for a mision are laid out long in advance of the mission, and since the vehicle most of the time is operated in automatic mode, and we have a model of that mode, we can give you a pretty good prediction of what's going to happen. It's a little tougher when it's controlled manually because people fly the thing differently.

The same is true of the space station, except it's a little premature right now because the design is not firmly pinned down but in principle one can do the same thing for a space station.

Rudy Ruff, Marshall Space Flight Center: You mentioned knowing the structural frequencies of the orbiter. Do they correlate with what we heard this morning from Dr. Hamacher?

Bergmann: The structural frequencies that we found in looking at the flight data correspond well with the lowest structural frequencies that were predicted by the prime contractor of the orbiter. I think that most of the data that people have seen do confirm the correctness of the frequencies of the orbiter structural models. One has to be careful in using that data however, because those frequencies change dramatically when the payload bay doors open and close and they change dramatically based on the payload configurations. In addition, one thing I'd like to mention is there are a number of flexible payloads that are attached to the orbiter. One of our efforts, at Johnson Space Center, is to investigate how the addition of those flexible payloads interacts with the control system so that you can actually, depending on what your payload is, and if it's flexible, see other modes superimposed on the orbiter structural modes. It can be quite significant, enough to interact with the control system.

Bob Naumann, Marshall Space Flight Center: I may have misinterpreted what you said. You said that the orbiter is actually just flying and maintaining its local vertical or whatever, you put a centrifugal force in there due to the fact you've got a moment arm away from the center of mass. Is that what you mean to say?

Bergmann: The question was when the orbiter is tracking the local vertical there's centrifugal force because this point is away from the center of mass?

Naumann: This is what I'd like to point out because you are always in that mode where you are actually earth oriented. The centrifugal forces exactly balance the gravitational forces and you don't have any additional acceleration from that.

Bergmann: I guess you don't. That's true at the center of gravity of the vehicle.

Question: No, it's true anywhere along the flight path of the center of gravity.

Bergmann: As long as you are at the same altitude as the center of mass of the vehicle.

Ken Demel, Johnson Space Center: Have you looked at any of the Space Station rates on attitude maneuvering? When you do a desaturation of the gyros and that sort of thing, what I have seen is that you're talking about 0.02 degrees per second or less and $r\omega^2$ is less of a problem than gravity gradient.

Bergmann: The question has to do with the Space Station maneuvering rates during desaturation and so forth, and the answer is that the rates people typically think of are well below a tenth of a degree per second and you're right. In those cases those terms can be relatively small. But when you're talking microgravity or something like that, those are marginal on that scale. The other thing is it is physically possible to rotate the space station at a higher rate which could occur in some kind of accident or contingency, or where you have got to do something quickly, but I don't want to preclude that kind of capability because of my ability to model what the vehicle is doing.