A MINIATURE PARACHUTE-PROBE DYNAMICS TEST-BED

Jessica Dooley(1), **Ralph D. Lorenz**(2)

(1) *Lunar and Planetary Laboratory and Aerospace and Mechanical Engineering Department,*
University of Arizona, 85721, USA, dooleyj@u.arizona.edu
(2) *Lunar and Planetary Laboratory, University of Arizona, 85721-0092, USA, rlorenz@hindmost.lpl.Arizona.edu*

ABSTRACT

Small-scale sensor packages and parachutes manufactured for model rocket recovery were hand-dropped from within a building in order to gain familiarity with the descent kinematics of a planetary probe through an atmosphere. A number of parachute-probe systems ranging in size, shape, weight, riser length, and sensors were dropped while exterior video cameras and onboard sensor data were collected. Data extracted from the camera images were then compared with sensor data to gain familiarity with the data and corresponding motions of the system such as swing amplitude, rotation, descent rate, etc. These tests allowed for a more detailed look at parachute-probe dynamics and provided the starting point for the development of a simple parachute-probe model.

1. INTRODUCTION

Detailed kinematics of the descent of a planetary probe through an atmosphere may be important in several respects. First, the attitude motion and any associated translations may affect some scientific measurements, notably optical measurements. Secondly, and perhaps more importantly, the response of the probe-parachute system to wind shear allows such shears to be estimated [1,2].

A descent probe is at least a 6-degree of freedom system, and 12- or even 18- degree of freedom models are often used to study parachute-probe dynamics [2,3,4]. Instrumented, full-scale vehicles have been used to obtain performance data, but such tests are unavoidably costly. In order to build a dataset of attitude motion to gain familiarity with sensor data and corresponding motions, and to validate dynamic models, a need for a low-cost test-bed emerged. Cost and ease of use, rather than dynamic similarity, were the driving concerns. With this in mind, several small-scale parachute-sensor packages were constructed from off-the-shelf parts and hand-dropped from within a building. The low velocity permitted adequate descent durations from modest drop heights.

2. INSTRUMENTATION

A number of parachute-probe systems and techniques were used to get a wide variety of information about the general behaviour of a parachute descent dynamics.

2.1 Instrumentation on the Probes

The sensors used exploit the ready availability of new sensors developed for mobile robotics and home entertainment applications. Designed with digital interfacing in mind, the sensors are well suited for a compact package using inexpensive micro controllers.

Our initial experiments used the Basic Stamp 2 by Parallax Inc to collect sensor data during the parachute drops. The Basic Stamp executes around 4000 instructions per second and has 2K of EEPROM, which carries the program and permits the storage of about 10 seconds of data onboard without requiring additional memory. The Basic Stamp worked well but in future tests a Basic-X24 micro controller from NetMedia Inc. was used. The Basic-X is faster, has more memory and features a built-in analog to digital converter, at the same cost and package size.

The parachute-probe system utilized a variety of sensors for data collection. During preliminary tests, the probe consisted of an orthogonal triad of FGM-1 fluxgate magnetometers and three Analog Devices ADXL202 low-cost, low-power 2-axis accelerometers with a measurement range of ± 2g. Additional sensors implemented in later probe designs included three single-axis, PG2033 resonant piezo-electric rotation sensors, a Nutex wireless video camera, and a Daventech SRF-04 sonar module. These sensors helped conduct a detailed study of the parachute-probe descent dynamics.

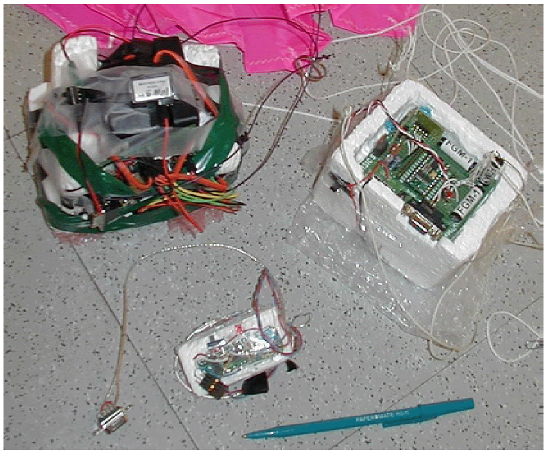

Fig. 1. Three versions of the parachute-probe dynamics test-beds with a pen near the bottom for size reference.

2.2 Parachutes

Parachutes manufactured for model rocket recovery proved ideal for indoor drop testing. The Apogee Rockets parachutes under study are listed in Table 1. Some heavier, military grade parachutes were also used, but with less success.

Table 1. Apogee Rockets parachutes used for testing.

Colour	Style	Diameter(cm)	Weight(g)	P/N
Pink	Hexagon	60.96	27.3	29202
Orange	Hexagon	91.44	64.5	29203
Yellow	Octagon	149.86	134.6	29205

Each Apogee Rockets parachute used in testing is made of 70-devier rip-stop nylon and the suspension lines are braided nylon.

3. TESTING AND SET-UP

While the specific sensors varied from probe to probe, the main testing technique remained fairly constant. The drop tests were conducted inside the Lunar and Planetary atrium at the Space Sciences building at the University of Arizona. The drop height from within the atrium was approximately 8 meters with durations of decent from 1 to 5 seconds. The air remained relatively calm with some gentle winds from air conditioning, although an updraft existed in the corner of the atrium where warm air welled up from the bottom floor. Some parachute-probe drop were documented with one or more video cameras in order to visualize descent dynamics such as swing amplitude, spin rate, and descent rate.

In general, each data collection with the Basic Stamp is initiated when the micro controller is activated with a momentary push switch. At this time, the onboard sensors are polled for 20 seconds. In contrast to real-time data transmission, the storage of data onboard during the descent avoids interruptions to the transmission due to multi-path effects or notches in the antenna radiation pattern and allows for more samples per second to be collected. After the switch is activated the controller reads out the EEPROM data for archiving and analysis. Data is collected in a similar fashion when the Basic-X micro controller is used.

3.1 Preliminary Pendulum Testing

A set of preliminary tests helped identify common relationships between onboard sensor data and typical parachute-probe kinematics such as swinging and spinning. The preliminary probe, consisting of 3 accelerometers and 3 magnetometers, was hung vertically and set into simple, pendulum-like motions while recording sensor data. Plots of acceleration and magnetometer time histories provided a starting point for picking out key patterns in the sensor data.

It was believed that the magnetometers would provide an insight into the orientation of the probe and an indication of spinning at certain locations in the preliminary pendulum tests and future drop tests. In addition to the time histories of all 3-axis magnetometers, the angles of magnetic field relative to probe axis were plotted. Unfortunately, the magnetometer outputs, while interesting to study, proved more difficult to associate to probe orientation due to the non-intuitive reference to the earths magnetic field and possible interference by nearby fields.

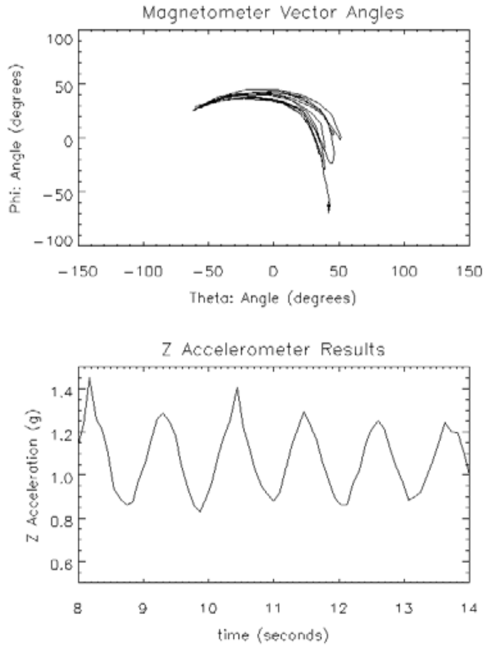

Fig. 2. Preliminary pendulum tests reflecting the angles of magnetic field relative to the probe axis and the z-accelerometer history during pendulum swinging from North to South with no observable rotation about the z-axis.

3.2 Preliminary Parachute Drop Testing

Preliminary drop test began with the same sensor set-up utilized in the simple pendulum tests (the Basic Stamp micro controller, 3 accelerometers and 3 magnetometers). A camcorder positioned mid-way between the probe-parachute release and touch-down heights captured the majority of each drop test. However, using only one off-board camera to record the drops fails to capture the swings and motions that take place in the plane perpendicular to the camera view, as if the probe was swinging towards and away from the camera itself. Thus, comparing the probe swing amplitude obtained from the camera data to the onboard sensor data could be giving false impressions, unless the length of the vector between the probe and parachute apex was somehow used to indicate a swing towards and away from the camera.

3.3 Compact Probe Drop Testing

Additional descent tests were conducted with a variety of parachutes and a smaller sensor package weighing 22g. The compact probe was equipped with a Basic Stamp micro controller and a single accelerometer sampling the z-axis 50 times per second. While the single accelerometer set-up allowed for faster data updates and storage, the lighter probe was almost too lightweight for some the parachutes under study, causing weak inflation of the larger, yellow parachute. Moreover, the accelerometer data was difficult to interpret due to lack of supporting data. Despite these concerns, the compact probe tests revealed interesting accelerometer patterns, raising questions about probe spinning during descent. It was speculated that the different patterns were due to the probe rotating and this inspired the addition of an onboard camera to future drop tests.

In an attempt to capture the parachute-probe movement along the camera boresight, a second camcorder was installed for the compact probe drop tests. Positioned at different angles, the camcorders recorded the compact probe drops in attempts of capturing more of the parachute-probe movements that might be missed by a single camera. However, due to geometric constraints in the atrium it was not possible to set up the camcorders in the ideal, perpendicular configuration and some of the parachute-probe movements in the line-of-sight of the cameras remained undocumented. In most cases, the addition of a second camera data did little in terms of capturing a different perspective of the parachute-probe drop.

3.4 Probe Drop Testing with On-board Camera

The use of the secondary off-board camera was exchanged in favour of an on-board, wireless video camera mounted perpendicular to the bottom of a new probe structure. Images transmitted to a laptop via a 2.4GHz wireless link into a USB frame grabber acquiring 320x240 pixel colour images at about 10 frames per second while z-axis accelerometer data was collected on the EEPROM and then downloaded to the laptop after each run. While the onboard camera data proved useful, the high-speed sampling of the BasicX24 often corrupted the video signal.

3.5 Multi-Sensor Drop Testing

Testing and analysis is ongoing. Additional probe arrangements including a multi-sensor unit with the 2-axis accelerometer, onboard video camera, gyro, and a sonic altimeter are planned for future tests. One goal for future testing is to capture sonar waveform, not just range, during descent. The new sensor arrangements rely on two microprocessors and clever programming to obtain the most information from all the onboard sensors.

4. DATA ANALYSIS

A variety of computer programs were constructed using Interactive Data Language to compute, display and compare sensor data and off-board camera footage. These programs evolved over the course of the pendulum and drop tests and helped compare data collected from the camera images to sensor data in order to gain familiarity with the data and corresponding motions of the system.

4.1 General Visualization with Camcorder Data

The camcorder documentation provided an excellent reference to the general behaviour of the probe and parachute during drop tests. However, this media proved insufficient for detailed analysis of each drop. To quantitatively exploit the camcorder data a computer program was written to input the individual frames from the camcorder recordings, display them on a user interface, and allow the recording of pixel locations from the click of a mouse. The program user interface allowed the position of the parachute apex and the centre of the probe to be identified and recorded for each frame captured by the camcorder. Each pair of parachute apex and probe positions collected from the individual frames was then plotted as a vector; revealing a visual representation of the parachute-probe position, swing amplitude, descent rate, etc. When only the probe or only the parachute was visible in the camera frame, the vector is represented as a single point as shown in Fig. 3.

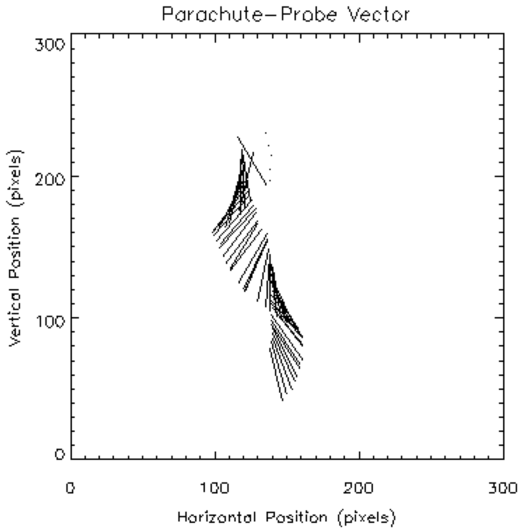

Fig. 3. Parachute-Probe vector plot calculated from drop 0423_10W camcorder data. This drop utilized the pink Apogee parachute with 179 cm between the chute and the probe (179 cm is the total including the length of the riser and suspension lines). Swing amplitude did not decrease in all drops.

4.2 Horizontal and Vertical Velocity

The camcorder recordings also proved useful in extracting probe horizontal and vertical velocity data during the drop. Another computer program calculated the horizontal and vertical velocities of the probe using the camcorder frame rate of 0.065 frames per second, the change in pixel location of the probe in consecutive frames, and a pixel-to-real-world conversion factor. An object of known dimensions, and approximately the same distance from the camera as the dropping parachute-probe assembly, was used to determine the conversion factor between image pixels and real-world distances. In the case of a two-camcorder-set-up (when one camera recorded from one angle and a separate camera from a different angle) a separate conversion factor was used to for each camera calculate the velocity of the probe.

The horizontal and vertical velocity plots reveal a number of general patterns associated with simple, pendulum-like motion. First, a sinusoidal pattern is evident in both vertical and horizontal plots. More importantly, the horizontal velocity plots indicate a period double that of the vertical velocity plots. This is due to the oscillatory nature of a pendulum in which the horizontal velocity only reaches zero at the apex of the swing but the vertical velocity, in addition to having zero velocity at the apex, is also zero at the trough or bottom of the swing. Fig. 4 and Fig. 5 illustrate these patterns with camcorder data from the 10th parachute-probe drop recorded on April 23rd of 2003.

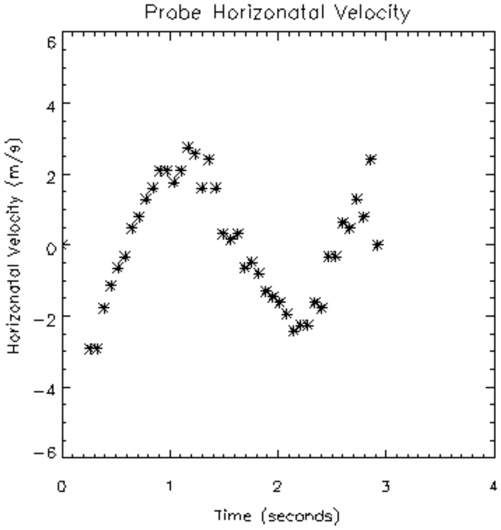

Fig. 4. Probe horizontal velocity profile calculated from camcorder data of the 10th drop on April 23rd.

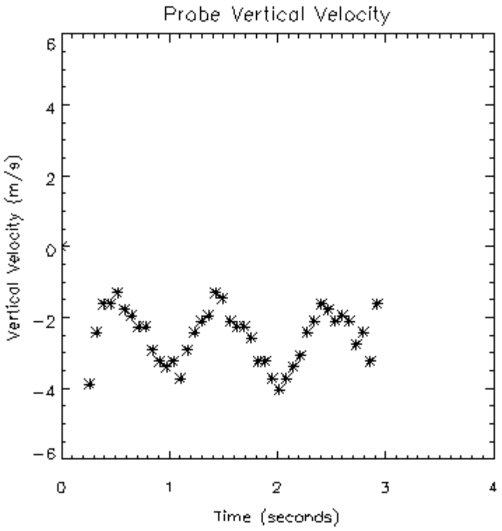

Fig 5. Probe vertical velocity profile calculated from camcorder data of the 10th drop on April 23rd.

The general pendulum-like motion of the parachute-probe system indicated in the horizontal and vertical velocity plots further inspired the creation of a simple pendulum mathematical model as discussed in section 5.

4.3 On-board Sensor Data

Acceleration data was collected in the preliminary pendulum tests and drop tests that followed. In fact, data of this type is likely to be the only data available on many planetary probes.

A striking and consistent feature of the acceleration record is that the Z-axis acceleration record (or near-equivalently, the total acceleration) is asymmetric, not sinusoidal. Specifically there are broad troughs and narrow peaks, often with spikes superimposed, as shown in Fig. 6.

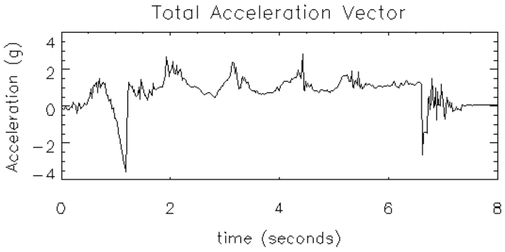

Fig. 6. Accelerometer history during the second compact probe drop of April 23rd . This drop utilized the pink parachute and a riser plus stabilizer length of 0.9 meters. Note the release of the probe near 1 second after data collection was initiated, the oscillating pattern with jagged tops and smooth troughs during the probe descent, and the touch-down around 7 seconds.

An on-board camera was added to the sensor package to investigate the conjecture that the jagged patterns in the acceleration results were caused by rotation at specific points in the pendulum swings. Before the next set of drop tests with the onboard camera data were conducted we returned to the preliminary pendulum results for "hand-guided" pendulum with rotations at key areas in the swing.

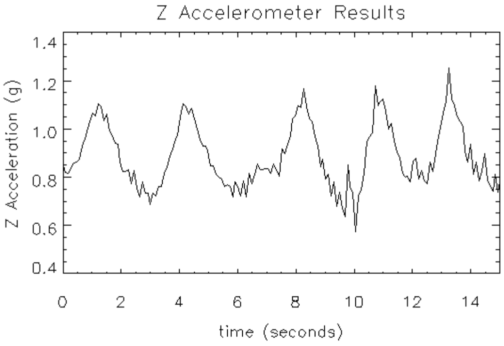

Fig. 7. The z-axis accelerometer plots for a "hand-guided" pendulum tests with 180-degree rotation at the ends of the pendulum swings.

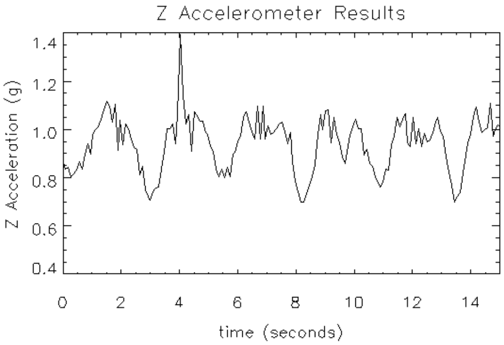

Fig. 8. The z-axis accelerometer plots for a "hand-guided" pendulum tests with 180-degree rotation at the midpoints of the pendulum swings.

The accelerometer data with rotations at the endpoints of the pendulum swing exhibit rough features in the troughs of the oscillating accelerometer patterns. In contrast, pendulum tests with rotations at midpoint of the swing exhibit smooth troughs and jagged tops in the accelerometer data. These preliminary plots helped identify the places of rotation during the real parachute-probe drops.

4.4 On-board Camera Data

The on-board camera provided an interesting perspective on parachute-probe dynamics, highlighting instances of translation, swinging and rotation, similar to the descent imagers featured on the Huygens probe and on Mars landers (e.g. Mars Polar Lander, Phoenix, etc) [6]. To fully understand the on-board camera footage data, the drop environment must be described. The drop tests were conducted inside the Lunar and Planetary atrium at the Space Sciences building at the University of Arizona. The floor of the atrium is covered with grey tile containing a large black cross pattern. This pattern proved useful for tracking the movements of the probe during the drop tests. In addition, the West wall of the atrium has a large, white pillar that is highly contrasted by the dark walls. The East side of the Atrium features a white wall with black lettering that also helped in deciphering general probe movements such as translation and rotation rate and when in the descent they occurred.

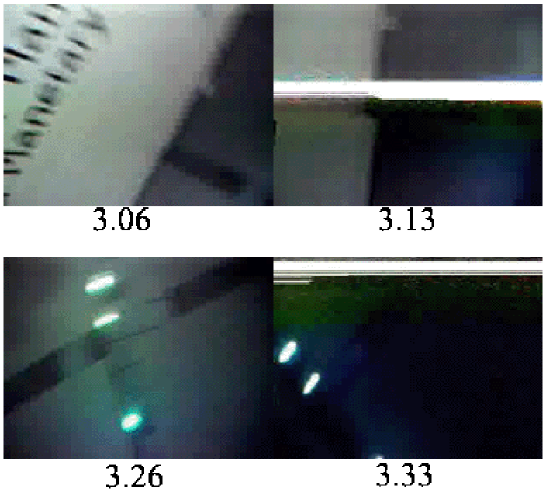

Fig. 9. Part 1. A sequence of frames captured from the on-board camera from the 6th drop conducted on June 10th. This sequence includes the frames captured 3.06 seconds to 3.33 seconds after collection of data was initialised.

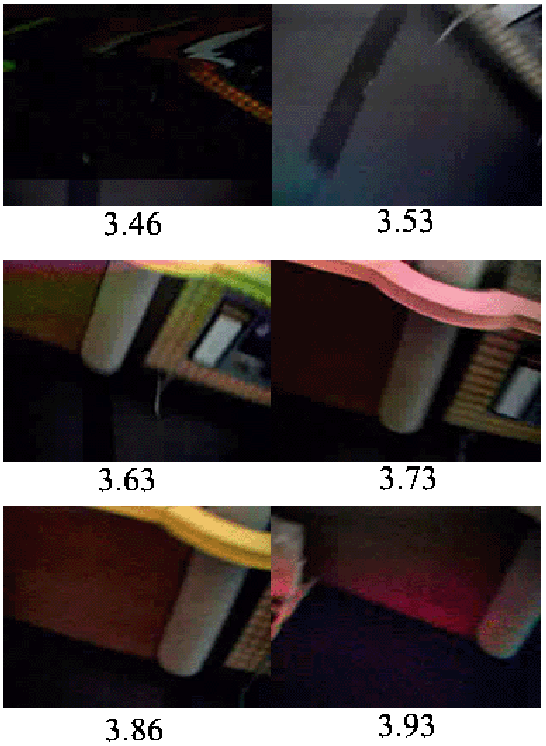

Fig. 9. Part2. A sequence of frames captured from the on-board camera from the 6th drop conducted on June 10th. This sequence includes the frames captured 3.46 seconds to 3.93 seconds after collection of data was initialised.

In addition to providing a qualitative, first look at the amount of rotation during parachute drops, the onboard camera frames containing high contrast objects and straight edges, like those in Fig. 10, provided quantitative rate of rotation data before the implementation of gyros. The rate of rotation at a given instant was calculated by measuring the change in orientation of a stationary object found in successive data frames during a known change in time. However, the accelerometers and the video camera data began sampling data at different times, resulting in different timescales. Luckily, the touch-down time for the probe was clearly visible in both the onboard sensors and onboard camera data. Comparing these touch-down times allows for the creation of a common time scale, permitting direct comparison of the rate of rotation and acceleration plots such as Fig. 10 and Fig. 11.

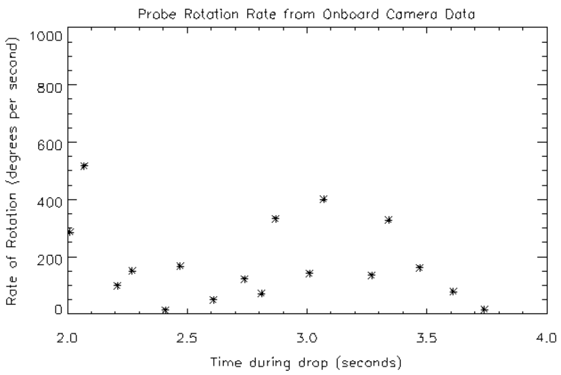

Fig. 10. This plot displays the measured rotation rate from onboard camera data for the 6^{th} drop on June 10^{th}, 2003. We can see instances of relatively high rates of rotation around 3 seconds into the data collection and the decrease in rotation rate near 3.7 seconds. The probe total acceleration data for this drop is plotted in Fig. 11. Note the superimposed spike near 3 seconds and the smooth trough near 3.6 seconds. This corresponds to the high and low rotation displayed in this figure at those times.

5. SIMPLE PENDULUM MODEL

A simple pendulum model was created to represent the parachute-probe system. The model assumes the probe-parachute system to be a rigid pendulum with length l between the parachute and probe and an initial angular displacement, θ_0. The model also assumes that drag acts in the plane of pendulum motion, thereby damping the system. A number of parameters are included so that the model may be adjusted to fit the accelerometer data as accurately as possible. These include a phase, bias and drag term. A computer code was written using Interactive Data Language with a for-loop to produce time histories of

$$\theta,\ \dot{\theta},\ \ddot{\theta},$$

which are needed to calculate the radial acceleration given by,

$$l\dot{\theta}^2 + \text{bias}$$

of the pendulum model which can be compared directly with our measured acceleration. The input parameters are altered until a best fit is found for the descent portions of the accelerometer data. The model included an initial angular displacement term, *theta0*, and a drag term that damped the pendulum motion over time. Phase and bias terms were also used to sync the model oscillations as best as possible with the acceleration data.

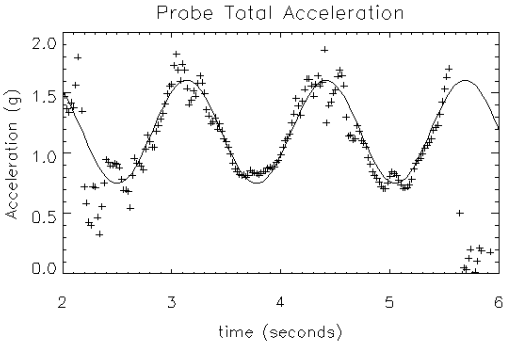

Fig. 11. This plot displays accelerometer history for the 6^{th} drop on June 10th with the simple pendulum model superimposed. The riser was shortened slightly for this drop. However, the effective length, l, needed to match the model to the accelerometer data was slightly larger than the actual distance between the parachute and probe.

Fig. 11 depicts one of the few cases in which the simple pendulum model fit well to more than one cycle of the acceleration data using approximately the same parameters measured from the drop tests used as the parameters in the model. This drop actually employed a shorter riser than others performed during the same sequence of drops. However, this shorter value was used as the effective length, l, in the math model and the drag term was not needed to match the model to the accelerometer data. In most drop plots the period of the acceleration data was increased greatly in the troughs of the cycle, offsetting the pendulum model from matching the following acceleration peak.

Surprisingly, many of the mathematical models that used the measured distance between the parachute and the probe as the parameter l, were less accurate than those that used a much larger value for l. For instance, when the third drop on March 5th used the measured value of 2.10 meters for the length l the mathematical model could only match one of the oscillations of the accelerometer data (Fig. 12). However, when the effective length l was increased to 2.80 meters and the drag term was also increased (Fig. 13), the mathematical model fit the sensor data for more than just one oscillation. One interpretation of this result is that the pendulum is pivoting not at the end but at some point displaced inwards from the parachute.

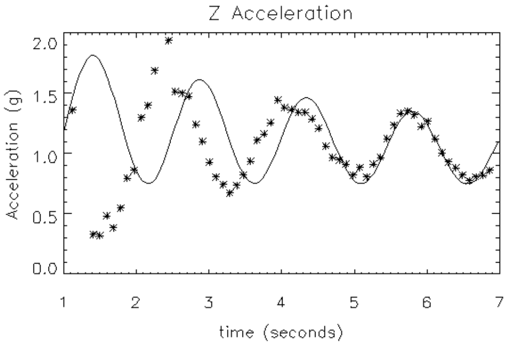

Fig. 12. In this plot the simple pendulum model uses the measured 2.10 meters for length l and a drag term of 0.25 for data collected during the third drop from March 5th. Using these parameters, only the last oscillation can be replicated with the pendulum model.

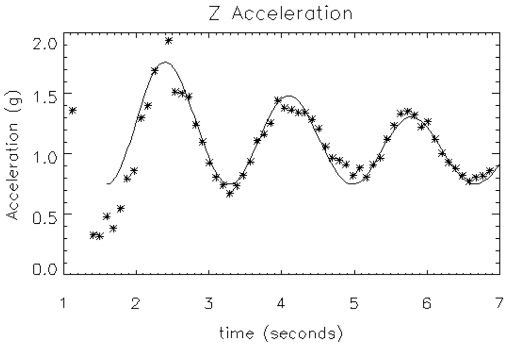

Fig. 13. When the effective length l between the parachute and probe is increased from the measured length of 2.10 meters to 2.80 meters and the drag term is increased to a value of 0.40 more of the oscillations in the accelerometer data can be represented with the model.

The simple pendulum model was able to produce at least one oscillation in the accelerometer patterns for most of the data collected and for a series of oscillations in drops that were dominated by large amplitude swinging motion. Results have shown that the parachute-probe system behaves as a compound pendulum rather than a simple pendulum. Clearly longer drops would provide more convenient datasets.

6. SUMMARY

Small-scale sensor packages and parachutes manufactured for model rocket recovery were hand-dropped from within a building in order to gain familiarity with the descent kinematics of a planetary probe through an atmosphere and to explore interactions of the parachute system with in-situ measurements (e.g. [5]). Testing and analysis techniques used to explore the parachute-probe system have been reviewed as well as the introduction of a simple pendulum model.

Two salient results so far are the correlation of spin with the bottom (fastest part) of the swing, and the apparent need for an effective pendulum length that is larger than the physical length of the parachute-probe distance.

These experiments have obvious visual appeal and are relatively inexpensive to perform. Additionally, the data acquisition equipment is in fact quite easy to assemble: plans and programs may be made available for download in due course. The relevance of the dynamics to syllabi in physics and mechanics may make such experiments useful in an educational setting (e.g. [6]).

7. REFERENCES

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