SMC-TR-03-03

AEROSPACE REPORT NO.
TR-2002(8506)-3

Sonic Boom Generated by Reentry of Mir

10 September 2002

Prepared by

D. M. MOODY
Vehicle Systems Division
Engineering and Technology Group

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE SPACE COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

Systems Planning & Engineering Group

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

THE AEROSPACE CORPORATION
El Segundo, California

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-00-C-0009 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Los Angeles Air Force Base, CA 90245. It was reviewed and approved for The Aerospace Corporation by Harlan F. Bittner, Principal Director, Systems Acquisition Support. John R. Edwards was the project officer for the program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

John R. Edwards
SMC/AXF

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (*DD-MM-YYYY*) 20-09-2002	**2. REPORT TYPE**	**3. DATES COVERED *(From - To)***
4. TITLE AND SUBTITLE Sonic Boom Generated by Reentry of Mir		**5a. CONTRACT NUMBER** F04701-00-C-0009
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) D. M. Moody		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Aerospace Corporation Engineering and Technology Group El Segundo, CA 90245-4691		**8. PERFORMING ORGANIZATION REPORT NUMBER NUMBER** TR-2002(8506)-3
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Space and Missile Systems Center Air Force Space Command 2450 E. El Segundo Blvd. Los Angeles Air Force Base, CA 90245		**10. SPONSOR/MONITOR'S ACRONYM(S)** SMC
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) SMC-TR-03-03

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Russian space station, Mir, was actively deorbited to impact in the South Pacific on 23 March 2001. Mir was the largest body in Earth orbit ever to be deorbited in a controlled fashion. As such, it provided a unique opportunity to observe, at a known time and location, what happens to such a large object as it re-enters the earth's atmosphere. The reentry and breakup were videotaped from the Fiji Sheraton hotel by a CNN cameraman. About four to five minutes after the streaking Mir debris left his view, he described hearing a number of sonic booms which were generated by pieces of the wreckage. This report contains the cameraman's description of what he heard and a calculation of the sonic boom amplitude and duration which would have been generated by a single Mir module on its reentry trajectory. Results of the calculation are consistent with the reported estimated time of boom arrival past visual sighting. However, no actual measurements were made at the hotel of the boom strength (sound level.) Thus the code results for boom amplitude cannot be quantitatively verified.

15. SUBJECT TERMS

Sonic boom, reentry, Mir, Range safety

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Douglas Moody
a. REPORT UNCLASSIFIED	**b. ABSTRACT** UNCLASSIFIED	**c. THIS PAGE** UNCLASSIFIED		19	**19b. TELEPHONE NUMBER *(include area code)*** (310)336-5892

Acknowledgments

This work was supported by the Air Force SMC/AXFV program office and The Aerospace Corporation Center for Orbital and Reentry Debris Studies (CORDS).

Contents

Figures

1. Introduction

The Russian space station, Mir, was actively deorbited to impact in the South Pacific on 23 March 2001 at approximately 06:00 GMT. Mir was the largest body in Earth orbit ever to be deorbited in a controlled fashion. As such, it provided a unique opportunity to observe, at a known time and location, what happens to such a large object as it re-enters the earth's atmosphere.

Mir was deorbited with three separate retro-burns. As originally planned, these impulses would have caused Mir to crash into the Pacific (as it headed north to south) in an area centered roughly at (37°S, 163°W.) However, the third and final burn delivered significantly more impulse than originally planned. This resulted in an impact zone centered roughly at (22°S, 180°E), some 1260 nmi (2330 km) uprange of the planned location. As a consequence of this change, airplanes which were positioned close to the original drop zone, were not able to observe this event. However, an excellent point of view for the reentry and breakup turned out to be the west side of Viti Levu in the Fiji Islands. It was from this vantage point that CNN cameraman Hugh Williams fortuitously videotaped the reentry and breakup, and subsequently heard the sonic booms generated by pieces of the wreckage.

In the following section, Mr. Williams' description of this event (Ref. 1) is recounted – both the description of what he saw and his description of the subsequent noise (sonic booms) which he heard. Following this is a section describing Aerospace's calculation of the sonic boom (amplitude and duration) which would result from a single piece of Mir debris on its north-to-south flyby off the west coast of Viti Levu. Results of the calculation are consistent with Williams' estimated time of boom arrival past visual sighting.

2. Visual and Auditory Description of Mir Reentry

The Mir reentry was videotaped by CNN cameraman Hugh Williams at the Sheraton Hotel on the west side of Viti Levu in the Fiji Islands. The approximate location of the hotel (Ref. 2) is (17°46'S, 177°22'E.) Local time was approximately 18:00 on 23 March 2001. According to Mr. Williams (see Ref. 1):

> "It was a collection of four or five or six very bright glowing lights that started low on the horizon. It streaked overhead at about a 30 or 40 degree angle, moving at incredible speed but without any sound. . . . It took only about a minute before it left my view, and it seemed to be traveling very low, and as I observed it, it was breaking apart. After about four or five minutes I noticed very distinct sonic booms, probably eight or nine sonic booms that would correspond to the eight or nine pieces of wreckage that were flying overhead."

A common misconception should be corrected in the above description. The sonic boom from a single body consists of two shocks (N-wave.) Therefore, hearing eight separate "bangs" would indicate four N-waves (four sonic booms), corresponding to at least four separate pieces of debris (not eight pieces.) At least four, because even if only eight separate shocks were heard, there may have been more than four separate pieces in the debris cluster which swept by the hotel. This is because all the shocks from all the pieces may not have been audible as separate events. Depending on the ray paths to the observer, the booms from separate pieces could have coalesced into the same wave.

Thus the "data" for this acoustic event are descriptive, but not quantitative.

A calculation of the boom waveform and arrival time is now presented.

3. Calculation of Mir Sonic Boom

The sonic boom received at the Fiji Sheraton from the supersonic flyby of Mir was calculated via REBOOM, a code developed at Aerospace in 2001. REBOOM is a special-purpose tool for computing booms from bodies reentering Earth's atmosphere. In common with other sonic boom codes, REBOOM is an implementation of acoustic ray tracing through a non-uniform atmosphere. The heart of the algorithm is essentially equivalent to that presented by C. L. Thomas (Ref. 3).

Inputs required by REBOOM are: 1. meteorological data (atmospheric temperature and wind components as functions of altitude), 2. trajectory (flight state) data for the supersonic body generating the boom, and 3. the near-field pressure signature (NFPS), i.e., the pressure distribution relatively close to the body. (The default NFPS algorithm in REBOOM is for a spherical body.) Each of these inputs is discussed below.

The essential output from the code is the boom overpressure time-history (waveform) at a desired point on the ground, and also the boom time of arrival (subsequent to the time at which the disturbance was produced.)

The time at which the boom was generated which eventually reached the Fiji Sheraton will be denoted by t_0. (This will also be referred to as the initiation time.) The time of arrival of the boom at the hotel will be denoted by t_A. The propagation time, i.e., the sound arrival delay time, is the difference in these two times, $\Delta t_{delay} = t_A - t_0$.

3.1 Meteorological Data for Mir Reentry

The atmospheric temperature profile used in the present calculations is shown in Figure 1. The east and north components of wind velocity used are shown in Figures 2 and 3. These data were provided by the Acquisition Meteorology Branch of the Air Force Space and Missile Center (Ref. 4.) Model atmospheric temperatures were available up to and above Mir's altitude at initiation time (231,000 ft), but wind data (see Figures 2 and 3) essentially ended at 100,000 ft.

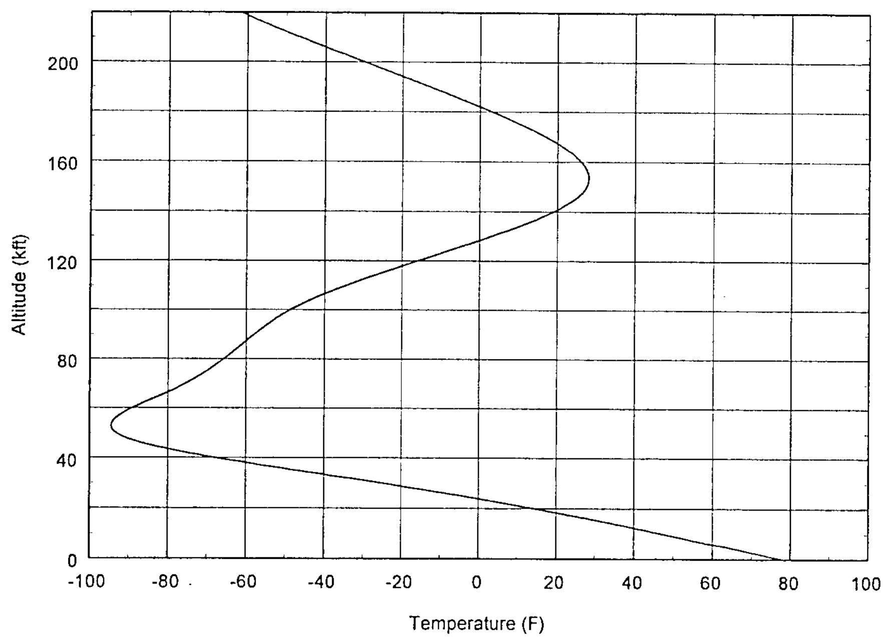

Figure 1. Temperature profile.

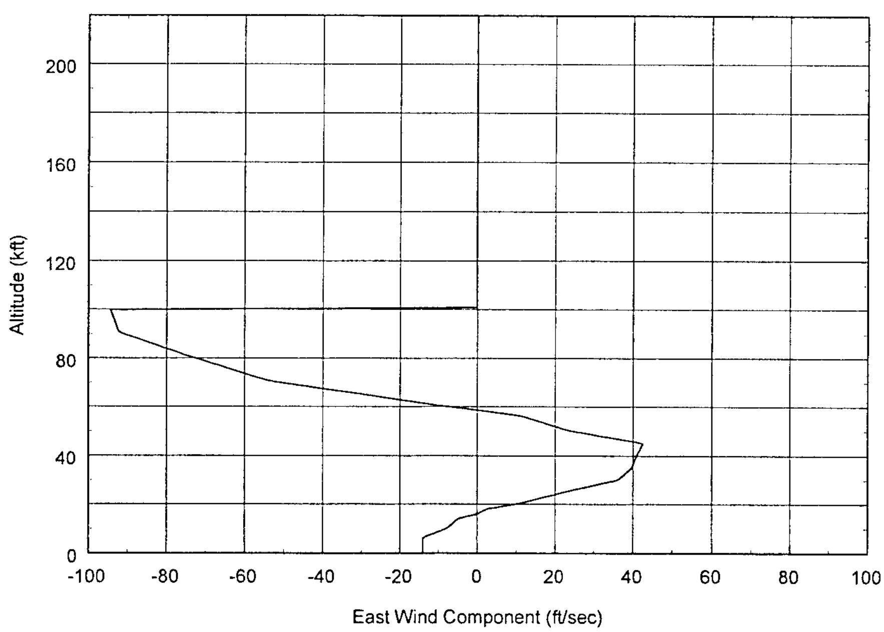

Figure 2. East wind component profile.

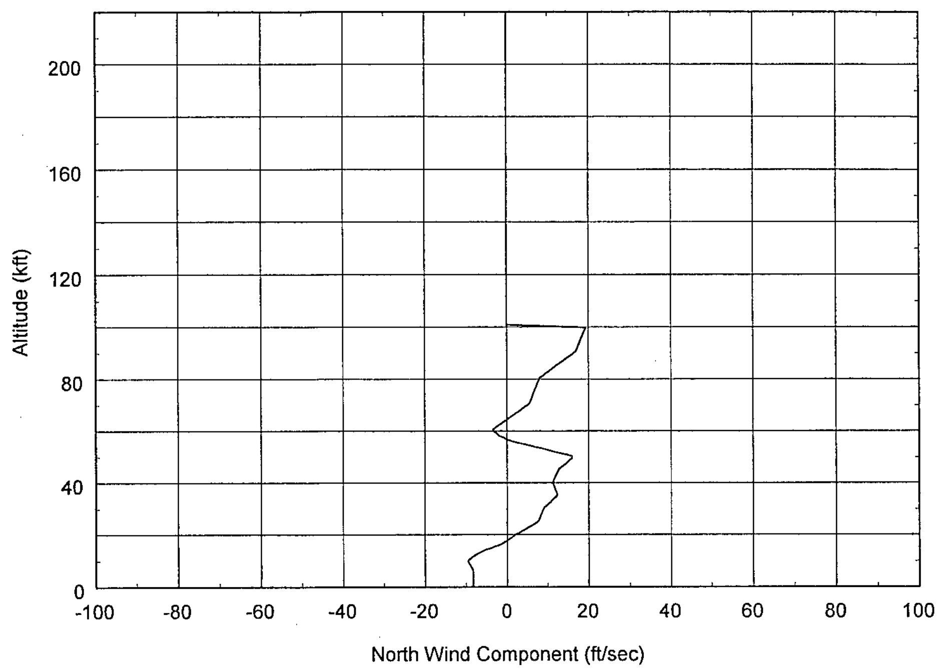

Figure 3. North wind component profile.

3.2 Flight State Data

The flight state (position, velocity, and acceleration) of a single Mir module as a function of time during reentry was provided via a trajectory reconstructed by Hallman (Ref. 5.) At time t_0, the best estimate of the state, in Earth-centered Cartesian Inertial (ECI) coordinates, is:

$$\vec{r}_{eci} = \begin{bmatrix} 1967046.11035 \\ 20016457.14386 \\ \text{-}6540085.48182 \end{bmatrix} \text{ ft}$$

$$\vec{v}_{eci} = \begin{bmatrix} \text{-}16709.25108 \\ \text{-}4545.77291 \\ \text{-}17671.27190 \end{bmatrix} \text{ ft/sec}$$

$$\vec{a}_{eci} = \begin{bmatrix} 6.42310 \\ \text{-}26.93342 \\ 20.60815 \end{bmatrix} \text{ ft/sec}^2$$

The corresponding Earth-relative position (altitude, latitude, longitude) is:

$$h = 230{,}577 \text{ ft}$$
$$\phi = -18.125^\circ$$
$$\lambda = 176.897^\circ$$

The corresponding air-relative velocity (Mach number, flight path elevation, azimuth) is:

$$M = 24.790$$
$$\gamma_{rel} = -0.9457^\circ$$
$$\psi_{rel} = 141.089^\circ$$

The acceleration is transformed within REBOOM into the following set of quantities which are required to start the ray tracing algorithm.

$$\dot{M} = -0.02939 \text{ sec}^{-1}$$
$$\dot{\gamma}_{rel} = -0.00617 \text{ deg/sec}$$
$$\dot{\psi}_{rel} = -0.01574 \text{ deg/sec}$$

3.3 Near-Field Pressure Signature (NFPS)

The REBOOM code approximates a reentering, tumbling blunt body as a sphere. This section describes the algorithm used in REBOOM to compute the NFPS for a sphere. Application of this method to the Mir case is addressed in the next section.

The algorithm returns the NFPS, $p(x)$, for a specified flight Mach number, M, and "data" radius, r_{dat}. Here, x denotes the stream-wise direction, i.e., the direction opposite to the velocity vector. The x-axis is assumed to pass through the center of the sphere and r denotes the perpendicular distance (radial coordinate) from this axis. The location and hyperbolic shape of the detached bow shock are found via the method described by Shapiro (Ref. 6). The wave angle, σ_{dat}, at the desired radius, r_{dat}, is thereby determined. From this angle and the free-stream Mach number, the bow shock strength at the data radius is determined.

$$P_0 \equiv \left(\frac{\Delta p_0}{p_\infty}\right) = \frac{7}{6}\left(M^2 \sin^2 \sigma_{dat} - 1\right) \tag{1}$$

Here, p_∞ denotes the free-stream static pressure at the flight altitude, and Δp_0 is the pressure jump across the shock at the data radius.

The origin of the x-axis is defined to lie at the intersection of the bow shock asymptote with this axis. (See Figure 4 for an example.) Values of x are measured positive stream-wise from this point. The total signature length, L, is assumed to be

$$L = L_C + 4R_0 + \Delta L_T - x_{BS} \tag{2}$$

where L_C is the x-coordinate of the sphere center, R_0 is the sphere radius, x_{BS} is the x-coordinate of the bow shock at the data radius, and

$$\Delta L_T = r_{dat} \cot \mu \tag{3}$$

where μ is the free-stream Mach angle, i.e.,

$$\mu = \sin^{-1}\left(\frac{1}{M}\right) \tag{4}$$

Now to specify the NFPS, first define a stream-wise coordinate which is non-dimensionalized with sphere radius as follows.

$$\tilde{x} = (x - x_{BS}) / R_0 \tag{5}$$

Similarly, define a non-dimensional signature length.

$$\tilde{L} = L / R_0 \tag{6}$$

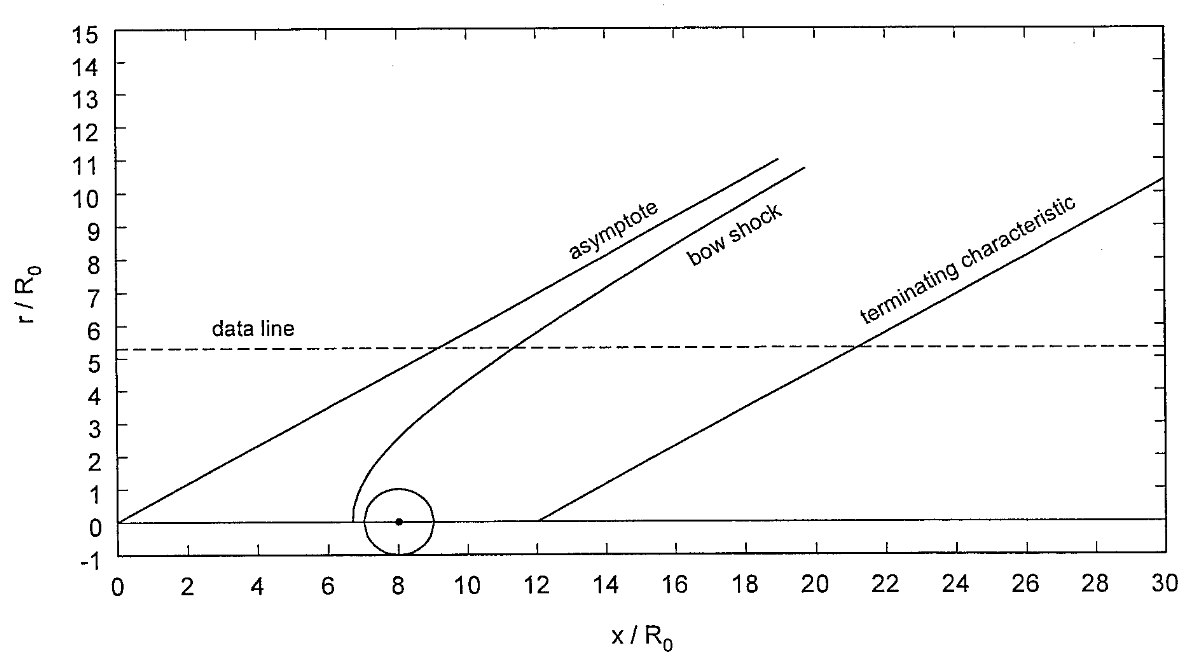

Figure 4. Bow shock shape for $M = 2$.

Now with $\xi = \tilde{x} / \tilde{L}$ denoting the stream-wise coordinate in units of signature length (with origin at the shock), the NFPS is assumed to have the following scaled waveform (shape function.)

$$y(\xi) = \begin{cases} 1 - 6\xi + 9\xi^2 - 4\xi^3 & \text{for } 0 \le \xi \le 1 \\ 0 & \text{for } \xi < 0 \text{ or } \xi > 1 \end{cases} \tag{7}$$

This function satisfies the following four conditions.

$$y(0) = 1 \tag{8}$$
$$y(1) = 0 \tag{9}$$
$$y'(1) = 0 \tag{10}$$
$$\int_0^1 y \, d\xi = 0 \tag{11}$$

The first condition provides for a unit pressure jump at the bow shock. The second condition requires the static pressure to return to the ambient value at the terminus of the signature. The third specifies that the pressure recover to ambient with zero gradient. The final condition ensures that the NFPS is "area-balanced," i.e., that the positive and negative phases of the signature be of equal area.

With the shape function so defined, it is discretized at a number of points:

$$y_i = y(\xi_i) \quad i = 1, 2, ..., N \tag{12}$$

where $\xi_1 = 0$ and $\xi_N = 1$ are the endpoints of the signature. The output of the algorithm is then a set of normalized overpressures:

$$P_i = P_0 \, y_i \tag{13}$$

corresponding to a set of stream-wise locations measured in units of sphere radius.

$$\tilde{x}_i = \tilde{L} \xi_i \tag{14}$$

3.4 NFPS for Mir

Using the above method, the NFPS for Mir, traveling at $M = 24.79$, is now computed at a data radius of $r_{dat} = 5.3 \ R_0$. In order to clarify the wave geometry used in the NFPS model, Figure 4 shows the bow shock shape, terminating characteristic, and data line for a sphere traveling at $M = 2$. Figure 5 shows the same geometry, but for Mir traveling hypersonically at $M = 24.79$. The computed NFPS for Mir is shown in Figure 6.

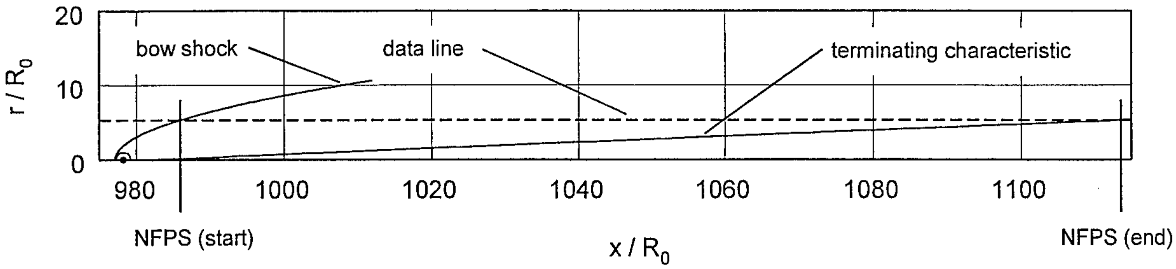

Figure 5. Bow shock shape for Mir at $M = 24.79$.

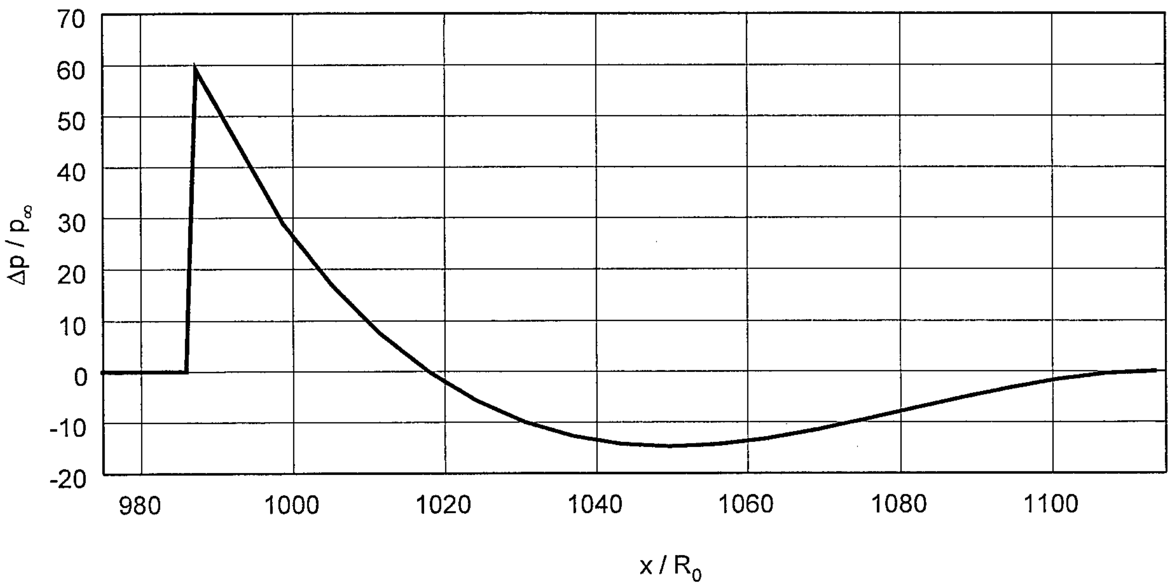

Figure 6. Near-field pressure signature for Mir at $M = 24.79$ and $r_{dat} = 5.3\ R_0$.

The ambient pressure at the initiation altitude of 230,577 ft is $p_\infty = 0.1105$ psf. Thus the non-dimensional pressure jump of 59.2 across the bow shock (see Figure 6 at $x / R_0 = 986$) corresponds to a dimensional pressure jump of

$$\Delta p_0 = 6.54 \text{ psf} \tag{15}$$

The length of the NFPS in Figure 6 is approximately 128 sphere radii. Of course, in order to execute the ray tracing, an actual sphere radius (in feet) must be specified in order to give the NFPS a physical meaning. This is the subject of the following section.

3.5 Choice of an Equivalent Sphere Radius

As the videotape clearly shows, the five modules which comprised Mir were breaking apart as the assembly streaked by Viti Levu. Each of these modules was a cylinder. The diameters ranged from 4.15 to 4.35 m. The average radius was 2.175 m (7.136 ft.) The lengths of the cylinders ranged from 13.00 to 13.73 m. The average volume of a single cylinder is equal to that of a sphere with radius 11.79 ft. Therefore the sonic boom was calculated with these two values of equivalent radius: 7.136 ft and 11.79 ft. These choices should yield boom amplitudes which bound the value generated by a single module. However, since the modules were "flying in formation" at t_0, the booms from two (or more) individual modules could have coalesced to produce a stronger boom. Unfortunately, no measurements exist of the overpressure time-history received at the Fiji Sheraton, which means that the code results for amplitude cannot be quantitatively verified.

3.6 Results

The ground track of the final portion of Mir's reentry trajectory is shown in Figure 7. The flight path heading is roughly southeast. The figure also shows the location of the Fiji Sheraton (17°46' S, 177°22' E) and Mir's position at signal initiation time, t_0, and at signal arrival time, t_A. This final point represents the position of a Mir module at the boom arrival time, assuming no secondary breakup of the structure.

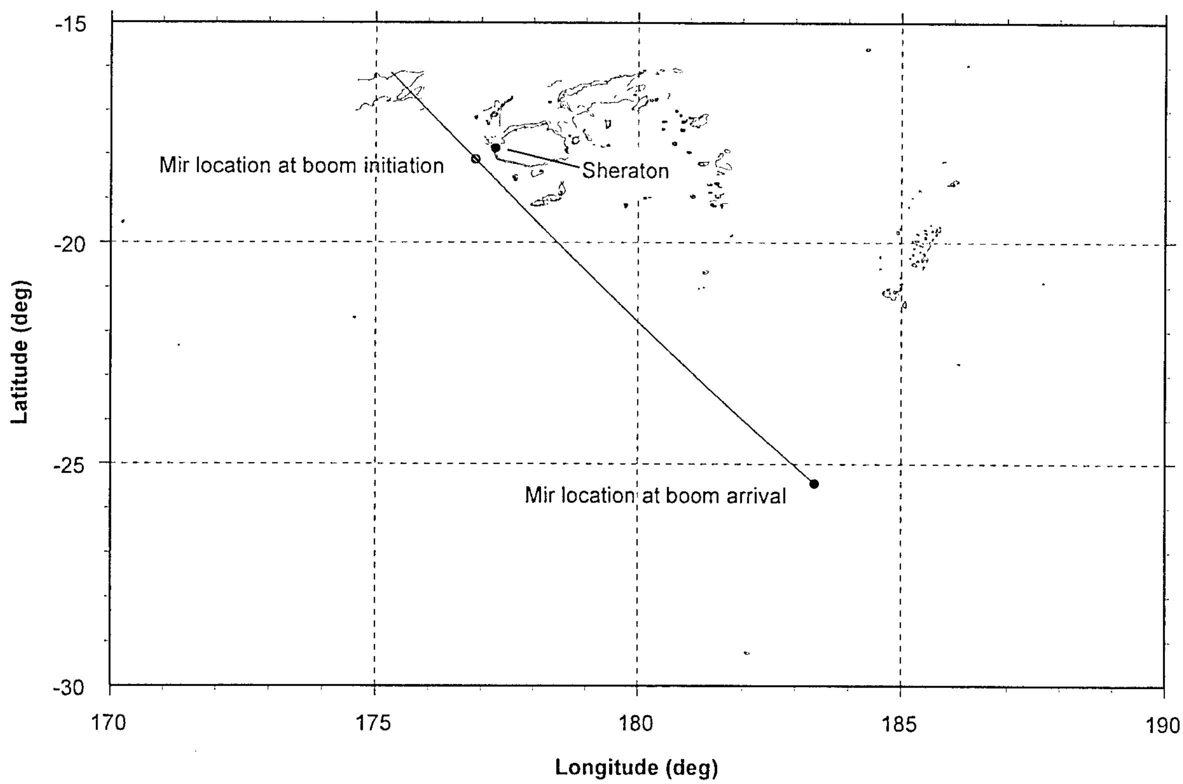

Figure 7. Ground track of final portion of Mir trajectory.

At t_0, the Sheraton was 26.2 nmi cross-track (to the northeast) and 0.99 nmi down-track of Mir. These lengths and the t_0 altitude of 37.95 nmi imply that the slant range between the hotel and Mir at this instant was 46 nmi. The atmosphere and flight state did not conspire to produce a focused boom in this case. It is therefore remarkable that the booms were heard so clearly from a source at such a great distance from the hotel. The clearly audible reception after this long path length was obviously due to the large size and high Mach number of the objects which generated the disturbance. As a point of comparison, a sonic boom was heard in South Africa in April of 2000 which was generated by debris from a reentering U.S. Delta II launch vehicle (Ref. 7). For this event, the slant range was only about 16 nmi. At time of initiation, the generating body (a fuel tank) was traveling at only Mach 1.2, and its equivalent (volumetric) sphere radius was only 3.8 ft.

Figures 8 and 9 show the calculated waveform at the Sheraton for the larger (11.79 ft radius) and smaller (7.136 ft radius) sphere, respectively. For both sizes of equivalent sphere, the calculation showed that ray arrival at the Sheraton occurred 275 seconds past initiation. That is

$$\Delta t_{delay} = t_A - t_0 = 275 \text{ sec } = 4.6 \text{ min} \qquad (16)$$

This is consistent with CNN cameraman Hugh Williams' estimate of "about four or five minutes."

The computed boom strength (peak overpressure at the Earth's surface) for the larger sphere is 0.183 psf. For the smaller sphere, it is 0.125 psf. That is,

$$p'_{\max} = 0.125 \text{ to } 0.183 \text{ psf} \qquad (17)$$

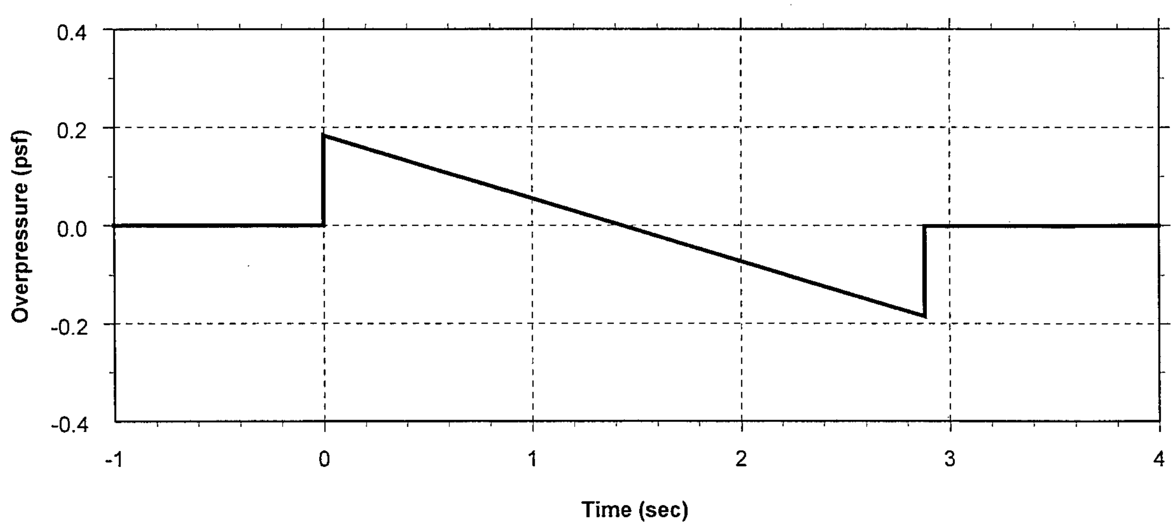

Figure 8. Predicted sonic boom waveform from a single Mir Module, $R_0 = 11.79$ ft.

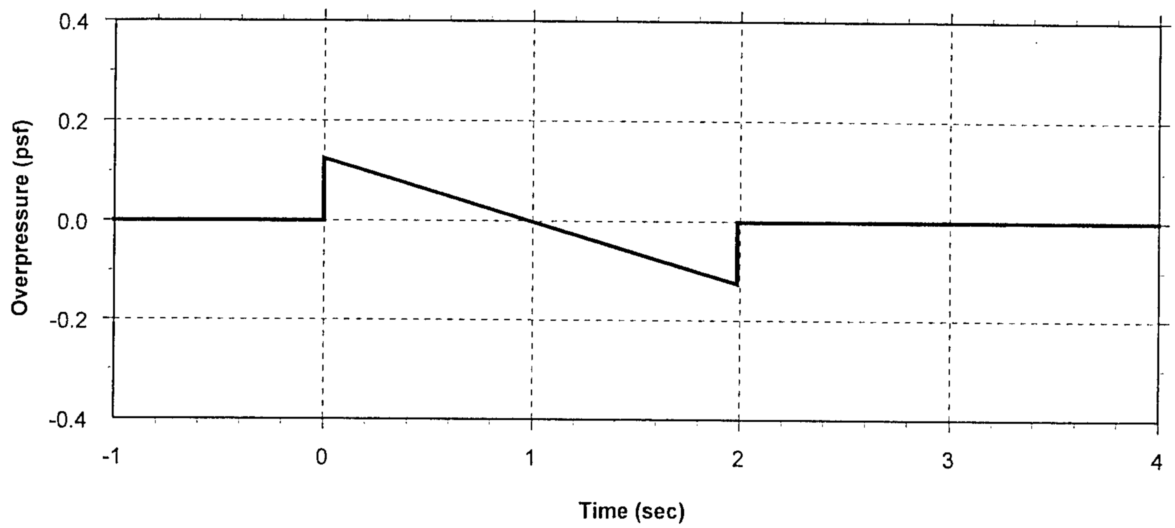

Figure 9. Predicted sonic boom waveform from a single Mir Module, $R_0 = 7.136$ ft.

The computed N-wave durations are 2.9 and 2.0 seconds for the larger and smaller spheres, respectively. That is,

$$\Delta t_N = 2.0 \text{ to } 2.9 \text{ sec} \tag{18}$$

For N-waves of this duration, the two shocks from a single module would definitely be heard as two separate and distinct reports.

4. Conclusions

The sonic boom which was generated by the Mir reentry and struck the Fiji Sheraton has been calculated using REBOOM – a sonic boom code developed at Aerospace. The computed boom arrival time at 4.6 minutes past initiation is consistent with an eyewitness description. The computed boom strength from a single Mir module is 0.125 to 0.183 psf, depending on the assumption used for an equivalent sphere radius. Unfortunately, no measurements exist of the overpressure time-history at the hotel. There is therefore no basis for quantitative comparison of this computed amplitude with the actual sound level received. The booms were simply described as "distinct."

References

1. CNN News Archive, http://www.cnn.com/2001/TECH/space/03/23/ williams.debrief/index.html.

2. Microsoft Encarta Interactive World Atlas 2000.

3. C. L. Thomas, "Extrapolation of Sonic Boom Pressure Signatures by the Waveform Parameter Method," NASA TN D-6832, June 1972.

4. Capt. L. M. Hagerman, Chief, Acquisition Meteorology Branch, SMC/AXEW, April 2001.

5. W. P. Hallman, private communication, November 2001.

6. A. H. Shapiro, The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. II, Ronald Press, New York 1954.

7. J. Tooley, private communication, July 2000.