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A WIND–TUNNEL FLIGHT CORRELATION OF APOLLO 15 SONIC BOOM

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ABSTRACT

A correlation of sonic boom pressure signatures recorded during reentry of the Apollo 15 command module with wind-tunnel signatures extrapolated to flight distances has been made for Mach numbers of 1.16 and 4.57. The flight pressure signatures were recorded by pressure sensors located onboard ships positioned near the ground track while the wind-tunnel signatures were measured during tests of a 0.016-scale model of the command module. The agreement between estimates based on wind-tunnel data and flight measurements was better at Mach 4.57 than at Mach 1.16.

SYMBOLS

h	flight altitude, meters
l	length of model or full-scale vehicle, meters
M	Mach number
p	reference pressure, N/m^2
γ	flight path angle, degrees, positive above horizon
Δp	sonic boom overpressure, N/m^2
ϕ	ray path angle, degrees; the 0 ray direction is down; positive is left looking forward on aircraft
ψ	heading angle, degrees, north = 0 degrees; positive toward east
$\cdot$	$\frac{d(\ )}{dt}$

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SUMMARY

A correlation of sonic boom pressure signatures recorded during reentry of the Apollo 15 command module with wind-tunnel signatures extrapolated to flight distances has been made for Mach numbers of 1.16 and 4.57. The flight pressure signatures were recorded by pressure sensors located onboard ships positioned near the ground track while the wind tunnel signatures were obtained from tests of a 0.016-scale model of the command module. The flight and extrapolated wind tunnel peak overpressures differed by .96 N/m^2 (.02 psf) at Mach 4.57 while the difference was 7.66 N/m^2 (.16 psf) at Mach 1.16. The flight signatures exhibited multiple shock waves while the extrapolated wind-tunnel signatures were N-waves. This difference in signature shape is not understood at this time but may be due to reflected waves from the ship superstructure.

INTRODUCTION

No theoretical methods are available for calculating the sonic boom overpressures produced on the ground by blunt vehicles with detached shock waves maneuvering at high Mach numbers. Therefore, estimates for these types of vehicles such as the space shuttle must be based on one of the currently available semi-empirical techniques (refs. 1 and 2) by which near-field pressure signatures measured in wind tunnels are extrapolated to the far field (ground). In order to extend the range of conditions for which these techniques have been validated, an experiment was conducted using the Apollo 15 command module as the test vehicle. Personnel of the Langley Research Center employed microphones placed onboard ships located along the ground track of the command module to obtain measurements of sonic boom overpressure generated during reentry into the Earth's atmosphere. These overpressures were compared with estimates based on the wind-tunnel data of reference 3 and the extrapolation procedure of reference 1. The results of these comparisons are reported herein.

TEST CONDITIONS

A photograph of the full-scale command module is shown in fig. 1(a). A report giving a complete description of the technique used to record the pressure signatures generated by the command module during reentry and the resulting measurements is being prepared by Langley Research Center and will be published at a later date.

A 0.016-scale model of the Apollo 15 command module (fig. 1(b)) was tested at Mach numbers of from 1.5 to 10 in the Jet Propulsion Laboratory supersonic and hypersonic wind tunnels. A complete description of the test conditions along with the wind tunnel pressure signatures are presented in ref. 3.

RESULTS AND DISCUSSION

The reentry trajectory data for Apollo 15 are given in fig. 2. The ground track along with the locations of the three ships with onboard pressure sensors used to record the sonic boom overpressures generated during reentry are shown in fig. 3. No attempt was made to estimate the overpressure (10.67 N/m^2 (.223 psf)) measured by the sensors onboard the USS Genesee since the measurement corresponded to a flight Mach number of 15.65 and the highest Mach number for which a complete set of wind tunnel data was available at all necessary bank angles was 7.75. Extrapolation of the tunnel data from Mach 7.75 to 15.65 probably would be unreliable since both the bow shock strength and signature length are still increasing rapidly at Mach 7.75.

The flight data (figure 2) and the pressure signatures measured in the wind-tunnel (figure 4) were used to calculate the ground overpressures generated by the command module during reentry into the Earth's atmosphere. The tunnel signature for Mach 1.16 was obtained by extrapolating the data of reference 3 from Mach 1.5. This extrapolation is justified because the signature parameters have been found to change very little between these Mach numbers. It was also necessary to interpolate between the bank angles for which data are presented in ref. 3 to obtain the signatures shown in fig. 4.

The first step in the calculation of the ground overpressures was to determine the point of origin on the flight path of the pressure signal received by the onboard sensor for each ship. This was accomplished by choosing a point on the flight trajectory and then calculating the ground-ray intersection for the rays eminating from that point. If the intersection was different from the coordinates of the ship another point on the flight path was chosen and the procedure was repeated. This procedure was repeated until the difference between the ground-ray intersection and the ship's coordinates was less than 100 meters (further iteration was found to have a negligible effect on the ground overpressure). The procedure was carried out for the location of the USS Kawishiwi and USS Okinawa. The results of the iteration showed that the pressure signal recorded onboard the Kawishiwi originated at Mach 4.57 and the signal received by the Okinawa originated at Mach 1.16.

The accelerations required in the extrapolation of the tunnel signatures to flight distances were obtained by measuring the appropriate local slopes of the curves shown in fig. 2. The atmosphere employed in the extrapolation was taken from the 1966 U. S. standard atmosphere supplements for 15 degrees north, annual. The wind velocity was assumed to be 0 at all altitudes. Rawin wind and temperature profiles measured at Barking Sands, Hawaii located approximately 275 statute miles south of the USS Kawishiwi showed that the temperature profile present during reentry was nearly standard and the winds were light to moderate at all altitudes of interest in the study. However, a separate calculation of surface overpressure was carried out using the Rawin data to determine the error involved in using a standard atmosphere with no winds. The effect of temperature was found to be small at both Mach numbers while the wind effect was negligible only at Mach 4.57 In spite of a somewhat larger effect of wind at Mach 1.16 it was considered preferable to use a wind velocity of 0 rather than to use wind conditions determined more than 300 miles from the site of the overpressure sensors since wind velocity and direction can change appreciably over short distances particularly if frontal zones are present.

Comparisons of extrapolated wind tunnel data with flight measurements are shown in figure 5. Only the positive portion of the wind tunnel signature has been shown at Mach 1.16 since shock-wave reflections from the floor of the wind tunnel prevented the recording of the full pressure signature at the lowest Mach number of the test described in reference 3. At Mach 1.16 the predicted overpressure based on wind tunnel data is 7.66 N/m^2 (.16 psf) below the value recorded at the ground (fig. 5(a)). This difference may be due to variations in the atmosphere from standard conditions at the location of the USS Okinawa as discussed above or to errors introduced by extrapolating available wind tunnel data to the lower flight Mach number. The former explanation for the small discrepancy at Mach 1.16 is most likely since the effect of wind gradients on surface overpressure is known to increase with decreasing Mach number. Headwinds with a large vertical gradient increase the overpressure while tailwinds cause a decrease in overpressure. If an accurate wind profile at the location of the Okinawa had been available a better correlation between wind tunnel and flight data might have been achieved. The wind tunnel-flight correlation for peak overpressure at Mach 4.57 was very good as shown in figure 5(b). At this Mach number a lack of knowledge of wind conditions would be less serious than for Mach 1.16.

The multiple shock waves exhibited by the flight pressure signatures have not been satisfactorily explained. However, some differences in signature shape might be expected for the following reasons: First, the flow conditions in the tunnel were different in some respects from the conditions present in the atmosphere during reentry (e.g. temperature, Reynold's number, etc.); second, the model wake was different from the wake behind the full-scale vehicle due to sting effects; third, the rearward facing step at the aft end of the full-scale vehicle (see fig. 1(a)) may have produced additional shock waves; and fourth, shock reflections from the ship superstructure may have produced the multiple shock character of the flight signatures (see fig. 6). However, the parameter of primary interest is the peak overpressure and the agreement between estimates and measurements for this parameter is certainly acceptable as shown in figure 7.

CONCLUDING REMARKS

A wind tunnel-flight correlation of the sonic boom characteristics of the Apollo 15 command module has been made. The results indicate that the maximum overpressure generated by a blunt, maneuvering vehicle with strong detached shock waves can be satisfactorily predicted using currently available sonic boom extrapolation methods.

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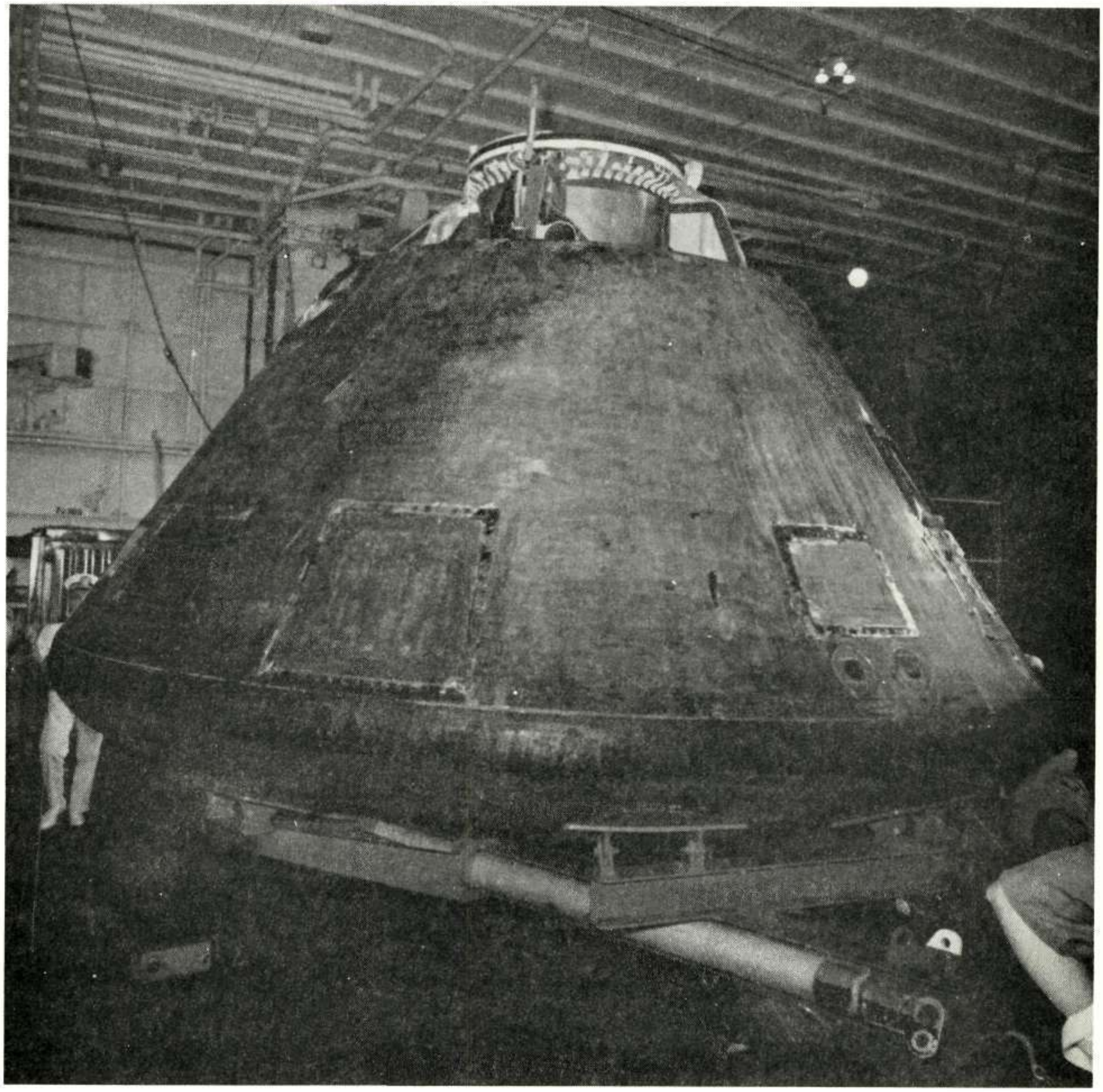
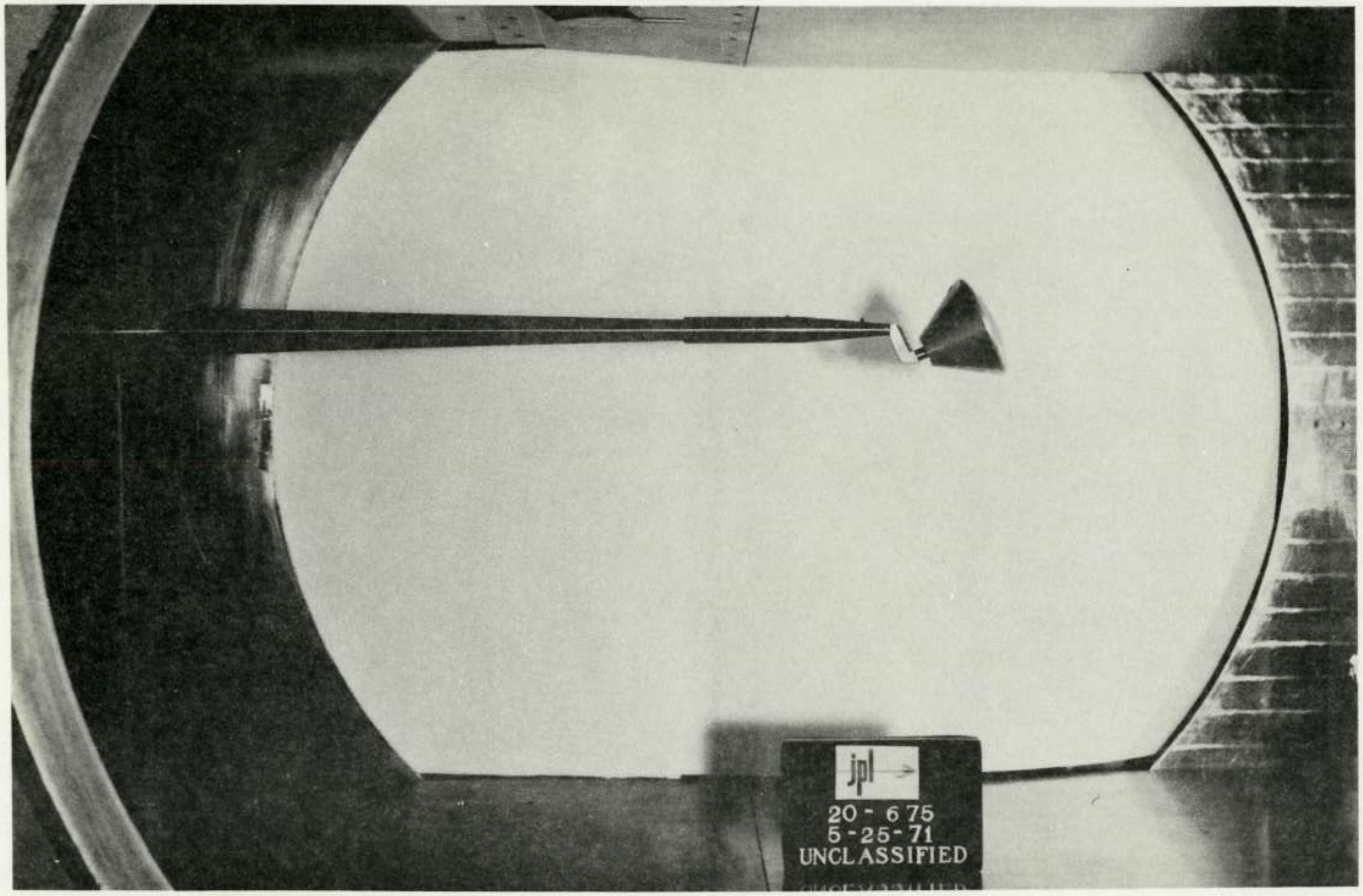
2. Hayes, W. D.; Haefeli, R. C.; and Kulsrud, H. E.: Sonic Boom Propagation in a Stratified Atmosphere, with Computer Program. Rept. No. 116, Aeronautical Research Associates of Princeton, Inc., Dec. 1968.

3. Mendoza, Joel P., and Hicks, Raymond M.: Wind Tunnel Pressure Signatures for a .016-Scale Model of the Apollo Command Module. NASA TM X-62,047, July 14, 1971.



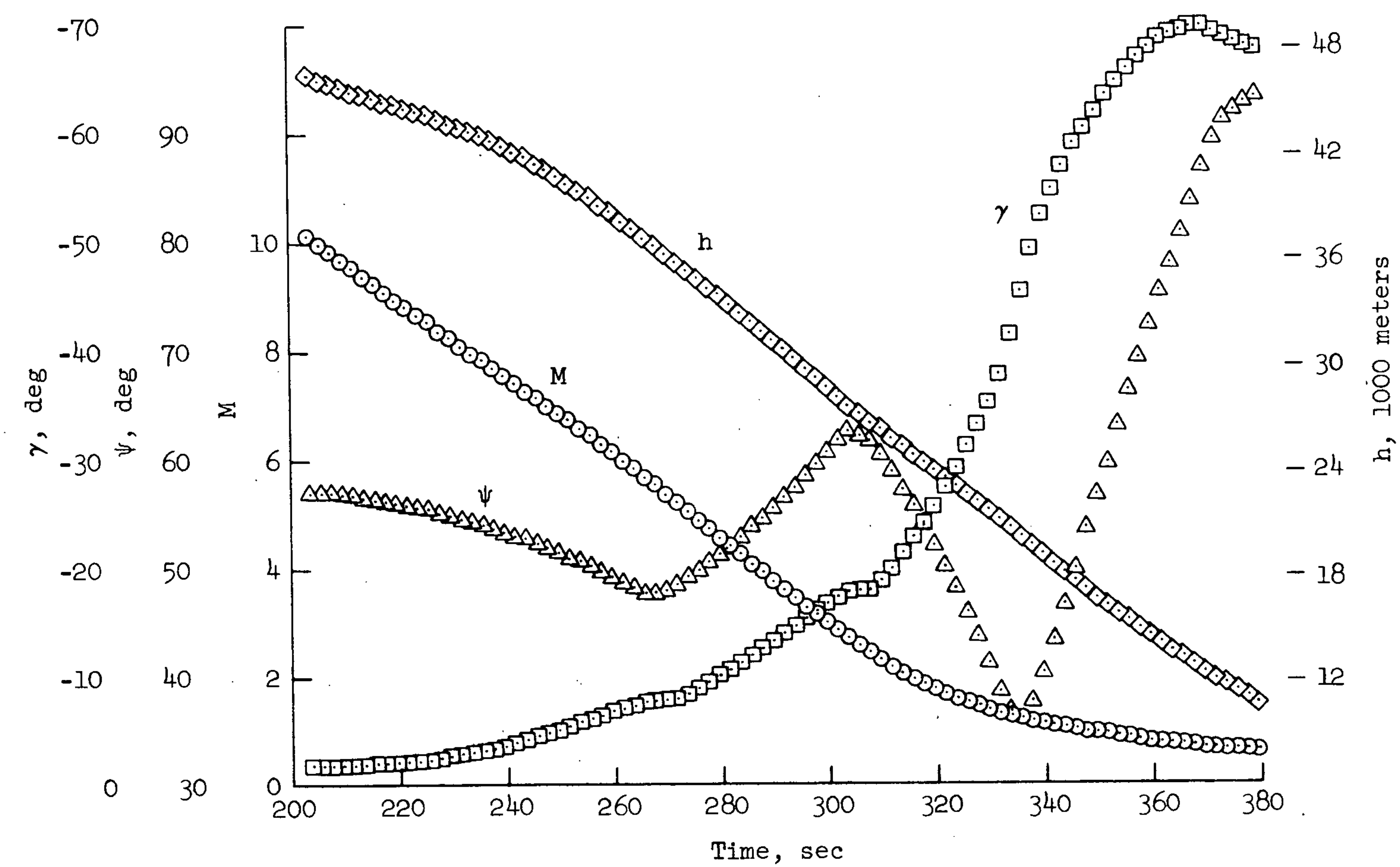
(a) Full scale vehicle

Figure 1.- Photograph of the Apollo 15 Command Module.



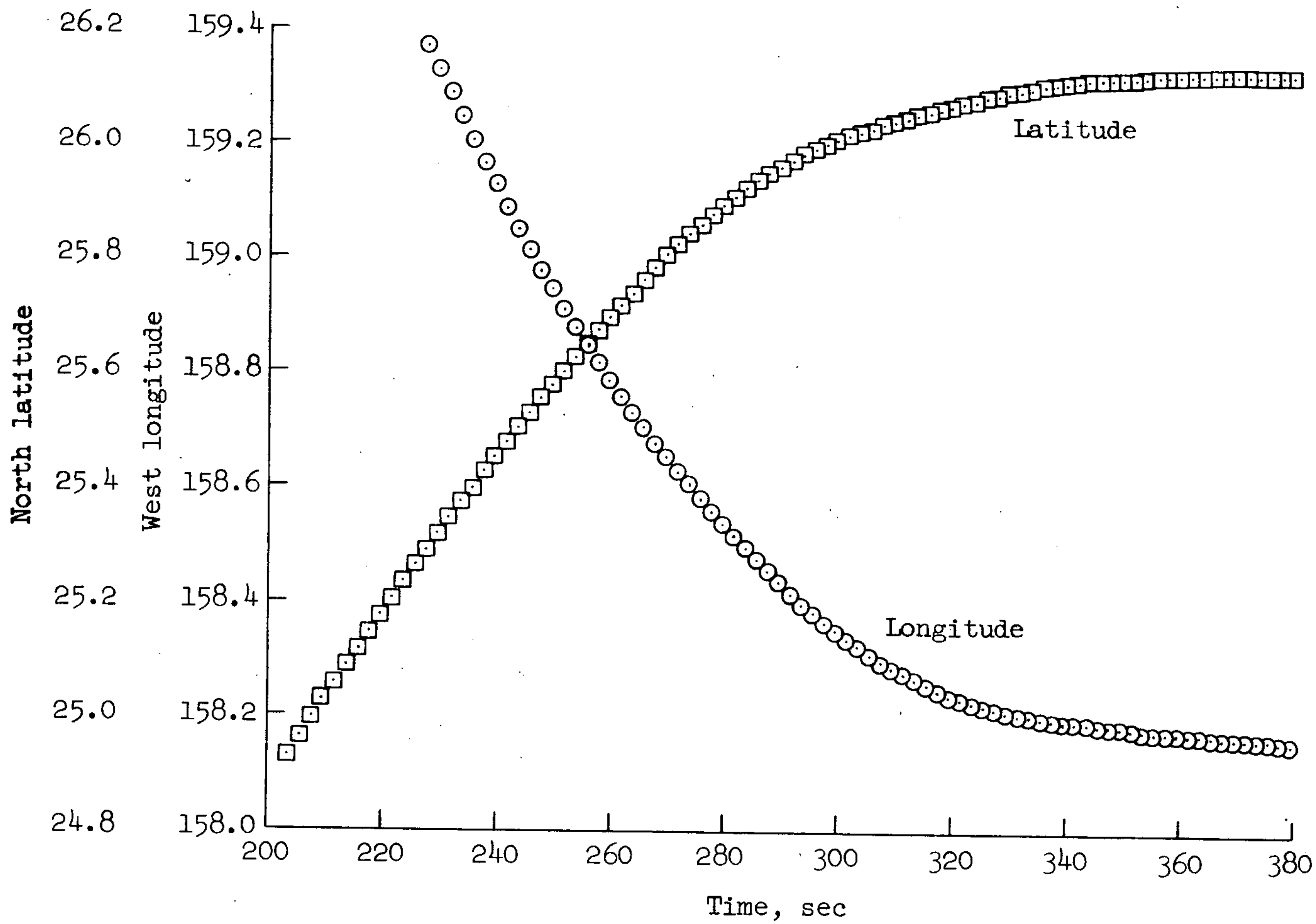
(b) Installation photograph showing model in 20-inch Supersonic Wind Tunnel at the Jet Propulsion Laboratory

Figure 1.- Concluded.



(a) Flight path angle, heading angle, Mach number and attitude

Figure 2.- Apollo 15 reentry flight data.



(b) Longitude and latitude

Figure 2.- Concluded.

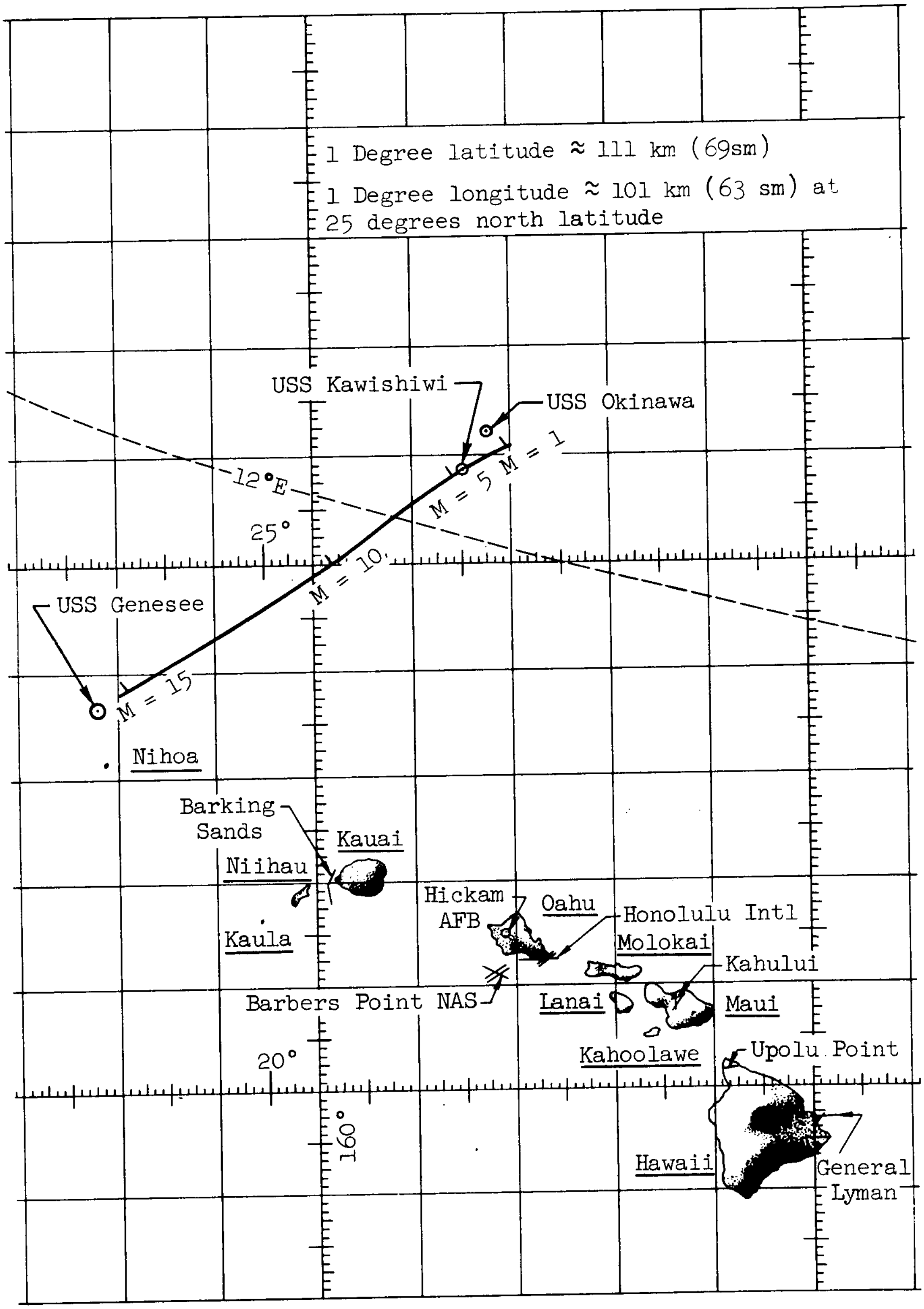


Figure 3.- Reentry ground track of Apollo 15.

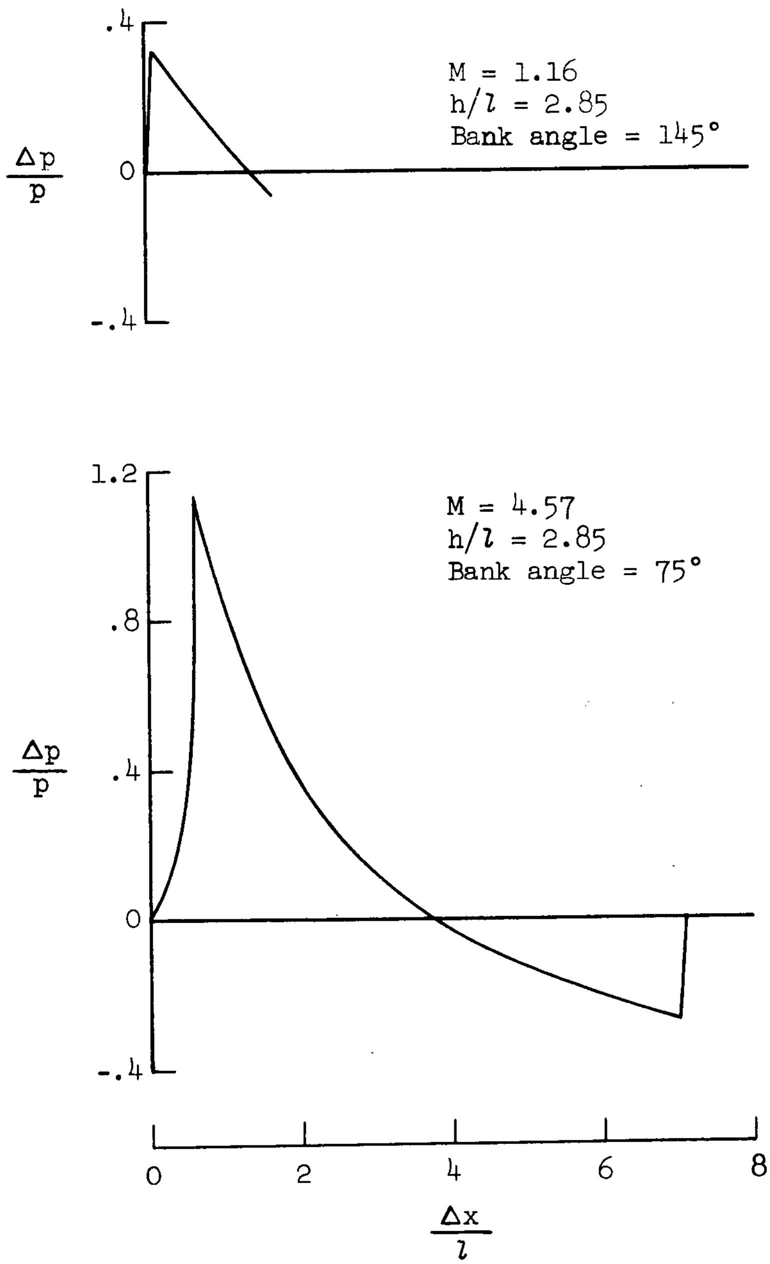
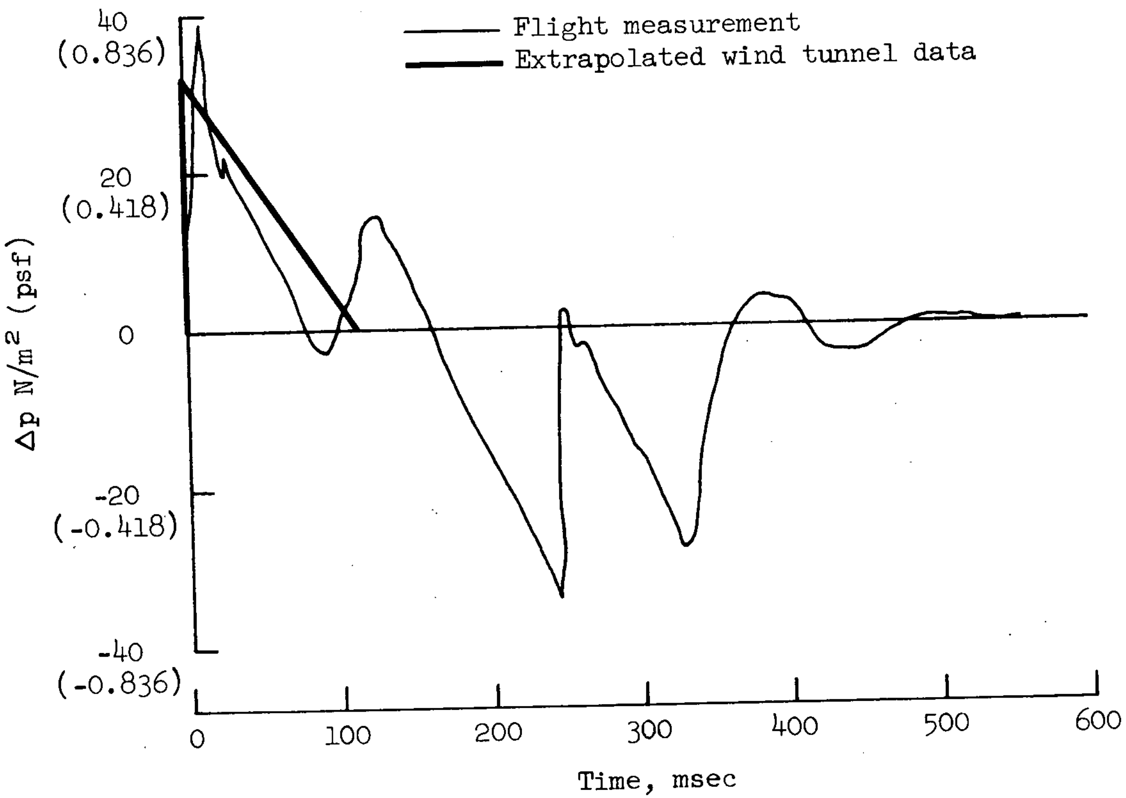
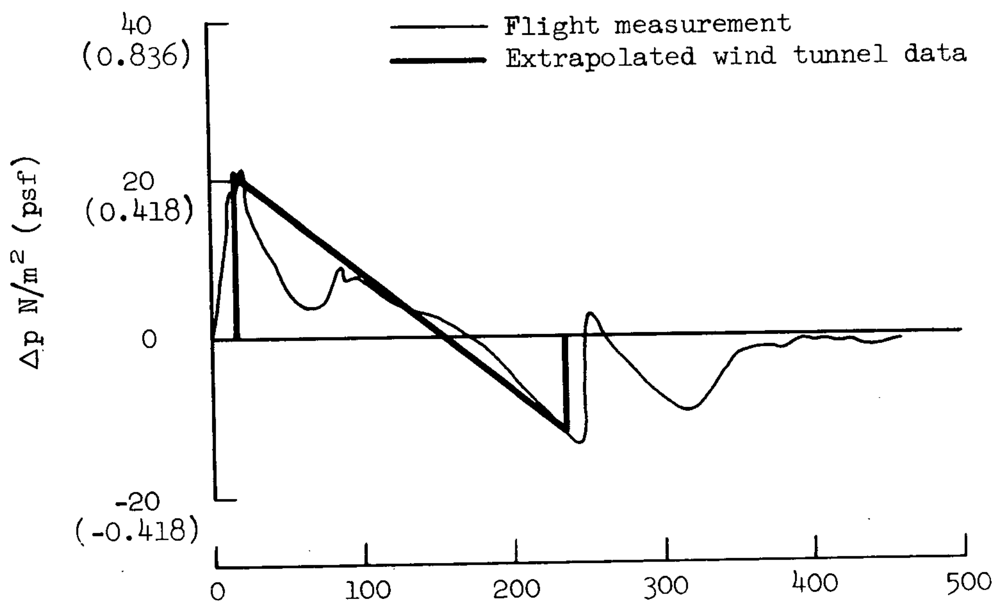


Figure 4.- Wind tunnel pressure signatures.



(a) $M = 1.16$, $h = 19{,}580$ m (64,253 ft), $\psi = 37.6°$, $\gamma = -49.36°$, $\dot{M} = -0.0213$/sec, $\dot{\psi} = 0.94°$/sec, $\dot{\gamma} = -1.75°$/sec, bank angle = $-145°$, $\varphi = 50°$

Figure 5.- Apollo 15 command module wind tunnel-flight correlation.



(b) $M = 4.57$, $h = 34{,}450$ m (110,304 ft), $\psi = 51.3°$, $\gamma = -10.1°$, $\dot{M} = -0.0812/\text{sec}$, $\dot{\psi} = 0.4°/\text{sec}$, $\dot{\gamma} = -0.3°/\text{sec}$, bank angle = 75°, $\varphi = 0°$

Figure 5.- Concluded.

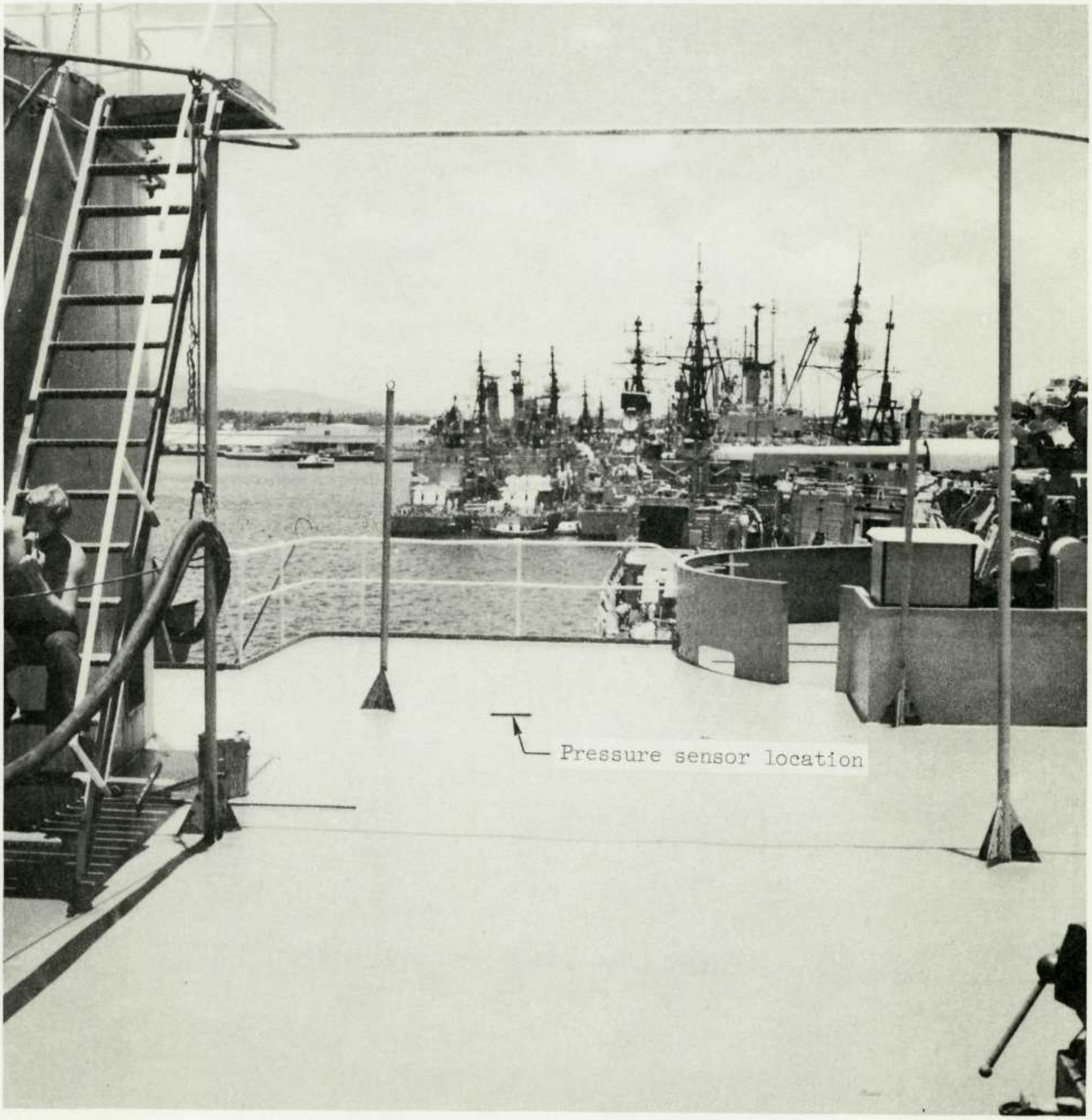


Figure 6.- USS Kawishiwi looking to port.

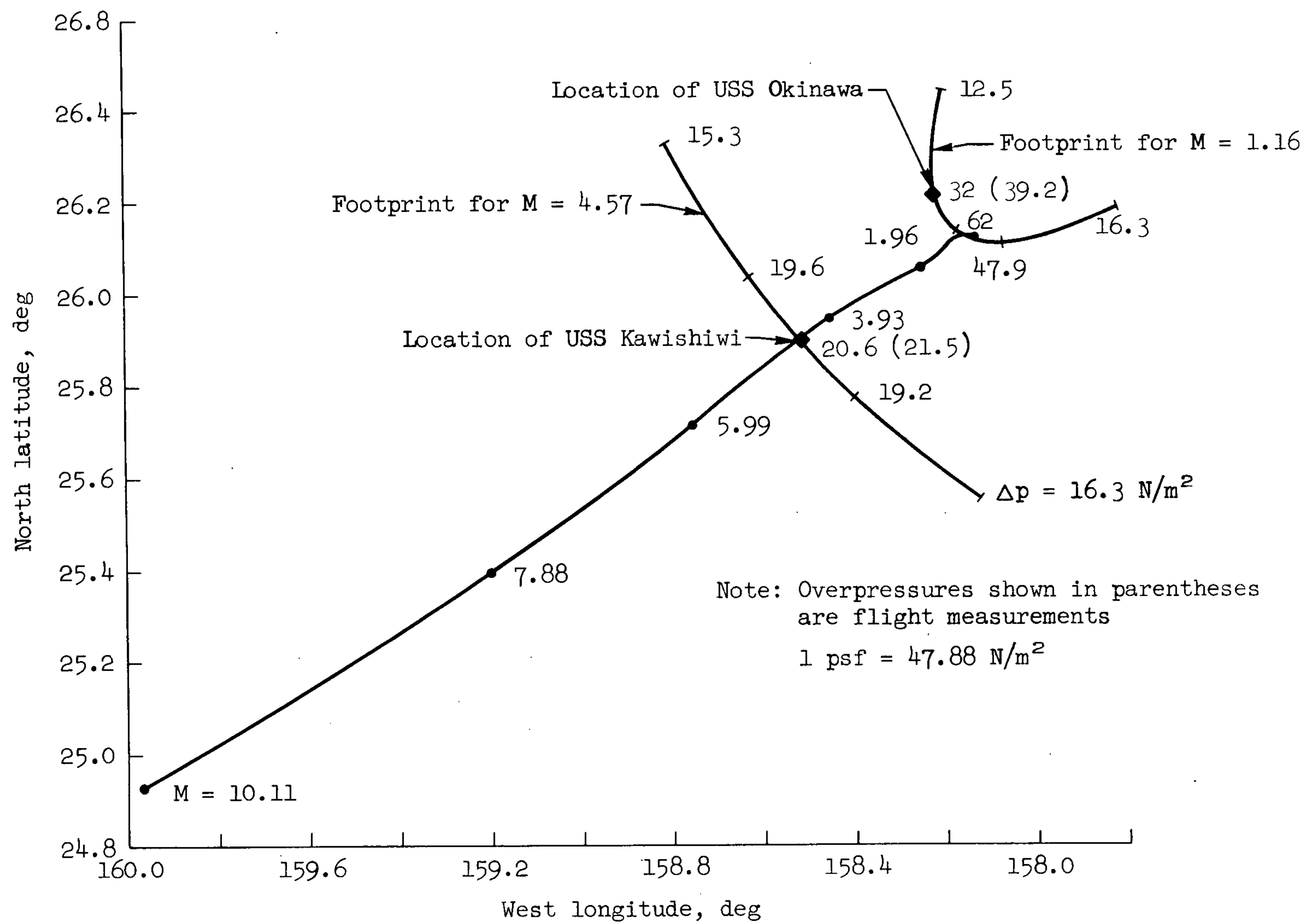


Figure 7.- Apollo 15 ground track with overpressures.