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Sonic Boom Propagation Codes Validated by Flight Test

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Foreword

The verification of sonic boom propagation codes has long been the desire of George T. Haglund. Working on supersonic transports virtually from their conception, he developed many of the sonic boom analysis tools used at Boeing. He spearheaded initial assessment of sonic boom characteristics of low–boom concepts at Boeing and originally proposed the idea of flying two aircraft in tandem to generate a shaped, long duration sonic boom source. Such a signature would require a very long propagation distance to completely evolve into an N–wave and thus provide the ideal source to test propagation codes for their resolution of fine detail in the sonic boom waveform. Recent near–field pressure signature measurement of a single supersonic aircraft using a novel probing technique lays a foundation for such propagation code verification and ultimate demonstration of the viability of low–boom supersonic transport design.

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Summary

Propagation Codes

A major thrust of recent developments to sonic boom propagation codes has been to more properly incorporate air absorption effects. This effort has been made practical by the general availability of improved computing power since absorption effects are based on inclusion of "higher order" terms in the basic thermodynamic equations. These terms were previously discarded in order to focus on the basic phenomena of non–linear wave steepening, formation of shocks, and shock propagation according to the equal–area rule. The higher order terms render a closed–form solution impossible and the equations are thus solved using an iterative technique over small steps along the wave propagation.

The sonic boom propagation codes reviewed in this study, SHOCKN and ZEPHYRUS, implement current theory on air absorption using different computational concepts. Review of the codes with a realistic atmosphere model confirm the agreement of propagation results reported by others for simplified propagation conditions. ZEPHYRUS offers greater flexibility in propagation conditions and is thus preferred for practical aircraft analysis.

Comparison to Measurement

The ZEPHYRUS code was used to propagate sonic boom waveforms measured approximately 1000 feet away from an SR–71 aircraft flying at Mach 1.25 to 5000 feet away. These extrapolated signatures were compared to measurements at 5000 feet. Pressure values of the significant shocks (bow, canopy, inlet and tail) in the waveforms are consistent between extrapolation and measurement. Of particular interest is that four (independent) measurements taken under the aircraft centerline converge to the same extrapolated result despite differences in measurement conditions. Extrapolated and measured signature durations disagree because the measured duration of the 5000 foot signatures is either much longer or shorter than would be expected. The measured durations are 0.07 seconds, 0.21 seconds and 0.15 seconds where a value of 0.1 might be expected.

These duration anomalies may have been introduced by the simplified method of converting the measured pressure at a position relative to the SR–71 to a time history at a fixed point in space. A more refined procedure has been suggested that accounts for changes in SR–71 speed and position of the probe aircraft during pressure measurement. Implementation of this procedure by others indicates a much better resolution of near and far measurements.

Introduction

Absorption

Absorption of sound in air is primarily composed of five mechanisms: viscosity, thermal conduction, bulk viscosity and vibrational relaxation of oxygen and nitrogen. Viscosity and thermal conduction dissipate sound pressure into heat through vorticity and thermal conduction. Bulk viscosity summarizes the exchange of energy between rotational and translational modes of molecular motion (primarily of oxygen and nitrogen molecules) as the air strives for thermal equilibrium after passage of the pressure signature. Vibrational relaxation is another process whereby sound pressure is converted to heat by increasing the vibrational energy of the (primarily oxygen and nitrogen) molecules.

In addition to air absorption effects, shock discontinuities introduce pressure losses. Non–linear steepening of the waveform also redistributes energy from low frequencies to high frequencies, which are more effectively attenuated in air.

Reference 1 is recommended as excellent background information on sonic boom propagation phenomenon, including absorption effects.

Code Development

During the last 25 years, the effects of molecular relaxation on sound propagation have been developed in the acoustic community. More recently, this knowledge has been applied to sonic boom propagation through NASA High Speed Research funding of university studies at University of Mississippi, Pennsylvania State University and the University of Texas. Methods are now available for predicting the important effect of molecular absorption on sonic boom propagation.

These methods trace their genesis to the 1973 doctoral dissertation by Pestorius[2]. The Pestorius algorithm was developed for the case of plane waves propagating in a tube, accounting for nonlinear distortion, dispersion and absorption. Nonlinear distortion as the wave propagates without losses leads to multivalueness in the waveform, which is resolved using weak–shock theory. Weak–shock theory uses the assumption of simple wave flow on either side of a shock to allow calculation of shock location and strength. It allows dispersion of wave pressure to heat through thermal conduction, supplementing the tube boundary dispersion (and absorption) explicitly included by the geometry of the Pestorius' problem. In his code, non–linear distortion, shock strength and shock location are calculated in the time domain and dispersion and absorption in the frequency domain with Fast Fourier Transforms to switch back and forth between the two domains.

The Pestorius code became the basis for two approaches to more fully account for absorption effects as other researchers adapted the code to their (more general) problems. One approach was implemented by Anderson[3], who dropped the weak–shock theory and modeled air as a thermoviscous fluid (that is, added the effect of energy dissipation due to thermal conduction and viscosity). This application depends on a large number of points to properly model shocks in the waveform and small propagation step sizes to keep the waveform single–valued. The Anderson code was later extended to include molecular relaxation effects[4] and atmospheric stratification with the resulting computer code named SHOCKN[5]. Since SHOCKN was used to analyze stronger shocks and longer duration waveforms than Anderson was concerned with, SHOCKN has a special absorption routine[6] to ensure single–valueness of the waveform. If shock amplitude is sufficiently strong, the viscosity of the air is artificially increased such that at least ten points are always used to describe the shock. This normally only occurs away from the ground so that normal absorption smooths out any unrealism in the waveform.

The other significant approach was taken by Robinson[7] in his computer code ZEPHYRUS[8]. The air is modeled as a thermoviscus fluid with stratified inhomogeneities, as in SHOCKN, but non–uniform, stratified winds are also allowed. Molecular relaxation effects are included. A three–dimensional ray theory is used to generate ray paths associated with the sonic boom shock front. Propagation through reflections and weak (line–like) caustics is allowed. Waveform propagation along these raypaths starts with the basic Pestorius marching algorithm, including weak–shock theory, with the updated absorption model for attenuation and dispersion effects. Shocks that are too strong to be modeled by the number of points in the waveform are handled by weak–shock theory and carried as discontinuities.

These methods have been authoritatively compared by Cleveland[5] on the basis of theory using idealized propagation conditions to focus on absorption effects and shock modeling. The current work validates these propagation methods through a more realistic atmosphere.

Flight testing of NASA's SR–71 in 1995 provides data for evaluating the accuracy in predicting detailed sonic boom characteristics. However, data available for this study provide only a short range (1000 feet to 5000 feet from the aircraft) of extrapolation so the absorption effects are minimal. Nevertheless, pressures are predicted reasonably well. Inconsistencies with measured duration inhibit accuracy of predicted duration, but a proposed refined method of data reduction promises to resolve most of these effects.

SHOCKN Code

Summary

SHOCKN calculates nonlinear distortion in the time domain and all other effects in the frequency domain. The Fast Fourier Transform is used to transfer between the time and frequency domains. For strong shocks, such as near the source, shocks are artificially thickened by extra viscous attenuation that is amplitude dependent. When the shock is weak enough, standard air absorption effects are modeled.

Since SHOCKN was basically written to verify certain absorption concepts, it is limited to propagation along the ray directly below the aircraft through the atmosphere coded into the program. The atmosphere does not include wind. Propagation halts at the ground so that ray reflection leading to secondary booms is not allowed. The program allows signatures at intermediate altitudes to be calculated.

A copy of the SHOCKN code was obtained from Jim Chambers of the University of Mississippi and incorporated into the Boeing Sonic Boom Toolbox. To run the code, the user supplies the following parameters:

Aircraft (source) altitude – feet
Aircraft body length – feet
Distance from aircraft to input waveform – feet
Aircraft Mach number
(any intermediate altitudes for output)
(special value for number of points in signature)
(special value for waveform sample rate)

In addition, the input waveform is supplied as a list of coordinates, time (seconds) and pressure (psf).

Atmosphere Model

SHOCKN uses an atmosphere profile generated by a function within the code. The code given to Boeing was set up with an isothermal atmosphere where, although temperature is constant, gravity effects cause pressure and density to decrease exponentially with altitude. The atmosphere function was rewritten to additionally allow use of the standard atmosphere[9]. The relative humidity is constant at 20%. A copy of the revised atmosphere function is presented as follows:

```
Subroutine Atmos(Al,t,p,r,hum)
C
C   Altitude(Al)     in meters      (input)
C   Temperature(t)   in K           (output)
C   Pressure(p)      in atm.        (output)
C   Density(r)       in kg/m**3     (output)
C   relative humidity(hum) in %.    (output)
C
      INCLUDE '/acct/hwp2093/etc/boom/shockn/code/parameters'

c       Standard atmosphere model included by Hugh Poling, March 6, 1996
c       Equations are from Anderson's book "Introduction to Flight" (pp.56-61)
c       We start with given altitude in meters, Al.
c       GRADIENT TROPOPAUSE
        if ( Al .lt. 11000.0 ) then
c          temperature in Kelvin
           t=T0std-(0.0065*Al)
c          pressure in atm
           p=p0std*exp(ATM_CONST*alog(t/T0std))
c          density in kg/m^3
           r=r0std*exp((ATM_CONST-1.0)*alog(t/T0std))
c       ISOTHERMAL STRATOSPHERE
        elseif (Al .lt. 25000.0 ) then
c          establish parameters at base of layer
C          (repeat of Tropopause equations)
           h1=11000.0
           t1=T0std-(0.0065*h1)
           p1=p0std*exp(ATM_CONST*alog(t1/T0std))
           r1=r0std*exp((ATM_CONST-1.0)*alog(t1/T0std))

c          next, calculate parameters at altitude, Al
           t=t1
           p=p1*exp( G0*(h1-Al)/(GAS_CONST*t1) )
           r=r1*(p/p1)
        else
           stop ' ERROR - standard atmosphere not defined above 25000 m'
        endif

      hum=20.

      write (15,*) Al,'  ',t,'  ',p,'  ',r,'  ',hum
      return
      end
```

Sample Case

The sample case used to demonstrate operation of the SHOCKN and ZEPHYRUS codes is based on the numerical exercise reported by Cleveland[5], for reasons explained in the section comparing the two codes. This section is only concerned with setting up inputs to SHOCKN and running the program.

The input pressure signature is a “ramp” waveform at a distance of 183m (600 ft) directly below the source. The format used in SHOCKN is an uncommented file with two columns of data. The columns are the waveform time (seconds) and pressure (psf). Note that the beginning and end of the waveform must be set to zero pressure, as shown following.

The flight altitude of the source is specified to be 14,630m (48,000 ft) and the Mach number is 1.8.

-0.0045268	0.00000000	0.0971371	2.55672956
-0.0037723	0.77863348	0.0998264	2.59542346
-0.0023389	1.55726409	0.1025157	2.63411736
-0.0022634	2.33589768	0.1052050	2.67281437
0.0021843	1.99676502	0.1078943	2.71150827
0.0066321	1.65763271	0.1105835	2.75020218
0.0110798	1.31850016	0.1132729	2.78889608
0.0137691	1.35719407	0.1159621	2.82759309
0.0164584	1.39589095	0.1186514	2.86628699
0.0191477	1.43458498	0.1213407	2.90498090
0.0218370	1.47327888	0.1240300	2.94367480
0.0245263	1.51197278	0.1523103	-2.51619887
0.0272155	1.55066967	0.1549996	-2.47750497
0.0299048	1.58936357	0.1576889	-2.43881106
0.0325941	1.62805748	0.1603782	-2.40011406
0.0352834	1.66675138	0.1630675	-2.36142039
0.0379727	1.70544529	0.1657568	-2.32272625
0.0406620	1.74414217	0.1684461	-2.28403234
0.0433513	1.78283620	0.1711353	-2.24533558
0.0460406	1.82153010	0.1738246	-2.20664167
0.0487299	1.86022413	0.1765139	-2.16794753
0.0514192	1.89892077	0.1792032	-2.12925386
0.0541085	1.93761492	0.1818925	-2.09055686
0.0567977	1.97630870	0.1850000	-5.09709215
0.0594870	2.01500273	0.1887631	-1.71722066
0.0621763	2.05369973	0.1907429	-1.52609026
0.0648656	2.09239340	0.1929323	-1.37998676
0.0675549	2.13108754	0.1952548	-1.26247084
0.0702442	2.16978145	0.1976698	-1.16484416
0.0729335	2.20847821	0.2001530	-1.08188438
0.0756228	2.24717236	0.2026888	-1.01019764
0.0783121	2.28586602	0.2052661	-0.94744158
0.0810014	2.32456017	0.2078771	-0.89192647
0.0836907	2.36325717	0.2105160	-0.84239167
0.0863799	2.40195084	0.2131781	-0.79787028
0.0890692	2.44064474	0.2158601	-0.75760704
0.0917585	2.47933888	0.3000000	0.00000000
0.0944478	2.51803565		

Outputs

SHOCKN provides files to plot up the signature at the specified distances from the aircraft. As the code runs, it supplies the following commentary:

```
  SHOCKN run with inputs: -a 48000 -b 300 -d 600 -dx 4800 24000 -m 1.8
ramp.wave

 INPUT:  Aircraft Altitude (m)          14630.40
                           (ft)         48000.00
 INPUT:  Aircraft Mach Number           1.800000
 INPUT:  Aircraft Body Length (m)       91.44000
                              (ft)      300.0000
 INPUT:  Input waveform distance (m)    182.8800
                                 (ft)   600.0000
 INPUT:  sample rate                    27600.00
 INPUT:  Points in spectra:   2 ^ 14 =   16384
```

```
   75 points read in with sample rate of  27600.0 Hz respaced to  8405 points
  read in initial time=    -0.004527 final time=    0.299953
 respaced initial time=    -0.004527 final time=    0.300000

1  The wave form at      182.9 meters (     600.0 feet)from airplane
              pmax= 2.9436 psf  imx=  7538
              pmin=-5.0886 psf  imn=  9221  RiseTime=0.107807 seconds
1  The wave form at     1463.0 meters (    4799.9 feet)from airplane
              pmax= 1.1261 psf  imx=  6825
              pmin=-1.1555 psf  imn=  9836  RiseTime=0.091190 seconds
  Switching from "FAIR" to "AIR" absorption at alt  13165.84 meters
1  The wave form at     7315.2 meters (   23999.7 feet)from airplane
              pmax= 0.7328 psf  imx=  5906
              pmin=-0.6061 psf  imn=  9733  RiseTime=0.069129 seconds
1  The wave form at    14630.4 meters (   47999.4 feet)from airplane
              pmax= 0.7793 psf  imx=  5690
              pmin=-0.6432 psf  imn= 10181  RiseTime=0.059572 seconds

Case description: DIST00183 SHOCKN wave with 2.944 psf max and 0.107807 sec
risetime
            OVERALL LEVEL OASPL =   127.191 dB
         A-WEIGHTED LEVEL SPLAW =    92.522 dB
         C-WEIGHTED LEVEL SPLCW =   112.770 dB
          PERCEIVED LEVEL SPLPL =   110.472 dB
Case description: DIST01463 SHOCKN wave with 1.126 psf max and 0.091190 sec
risetime
            OVERALL LEVEL OASPL =   118.813 dB
         A-WEIGHTED LEVEL SPLAW =    81.286 dB
         C-WEIGHTED LEVEL SPLCW =   100.515 dB
          PERCEIVED LEVEL SPLPL =    95.090 dB
Case description: DIST07315 SHOCKN wave with 0.7328 psf max and 0.06913 sec
risetime
            OVERALL LEVEL OASPL =   114.814 dB
         A-WEIGHTED LEVEL SPLAW =    81.657 dB
         C-WEIGHTED LEVEL SPLCW =    94.088 dB
          PERCEIVED LEVEL SPLPL =    95.070 dB
Case description: DIST14630 SHOCKN wave with 0.7793 psf max and 0.05957 sec
risetime
            OVERALL LEVEL OASPL =   115.405 dB
         A-WEIGHTED LEVEL SPLAW =    72.527 dB
         C-WEIGHTED LEVEL SPLCW =    93.691 dB
          PERCEIVED LEVEL SPLPL =    86.281 dB

Case description: DIST14630 SHOCKN wave with 0.7793 psf max and 0.05957 sec
risetime
Ground Reflection Factor 1.9
            OVERALL LEVEL OASPL =   120.980 dB
         A-WEIGHTED LEVEL SPLAW =    78.102 dB
         C-WEIGHTED LEVEL SPLCW =    99.266 dB
          PERCEIVED LEVEL SPLPL =    92.209 dB
```

ZEPHYRUS Code

Summary

ZEPHYRUS propagates using weak shock theory in the time domain and applies absorption and dispersion effects in the frequency domain. Transfers between the two are done with the Fast Fourier Transform and occur when sufficient absorption has "accumulated" over the propagation distance. This happen over approximately twenty steps. The weak shock theory resolves shocks in the waveform between applications of absorption.

A copy of ZEPHYRUS was obtained from Dr. Leick Robinson, now at SAIC. The three modules, "TSPLINE" to develop continuous curvefits of the atmosphere, "RAYTRACE" to calculate the ray paths, and "RAYPROP" to propagate a waveform along a ray path were installed into the Boeing Sonic Boom Toolbox.

In addition to the atmosphere profile described following, parameters describing the ray paths and waveform are needed. Examples of these files are included in the sample case.

Atmosphere Model

Zephyrus uses an atmosphere supplied by the user. The standard atmosphere profile used in this sample case looks like the following:

```
**************************************************************************
**        ZEPHYRUS style air profile from ARAP .HAG output file        **
**************************************************************************
**   This file constructed under the assumptions:                       **
**                                                                      **
**        aircraft heading is 90 degrees compass,                       **
**        North = ZEPHYRUS Y-direction per air navigation convention.   **
**                                                                      **
**        wind direction read from ARAP is based on                     **
**        (0 degrees compass = ZEPHYRUS Y-direction) + 180 degrees,     **
**        but output ZEPHYRUS angle is measured from                    **
**        X-dir per Conventional Cartesian geometry.                    **
**                                                                      **
**        temperature and wind data are supplied at the same            **
**        list of altitude values                                       **
**                                                                      **
**************************************************************************
```

ATMOSPHERE FOR U.S. 1962 STANDARD ATMOSPHERE, NO WIND

@

Altitude (meters)	Sound Speed (m/s)	Wind Velocity along flight path (m/s)	Wind Velocity across flight path (m/s)	Air Density (kg/m3)
0.	340.3052	0.00	0.00	1.22500883
305.	339.1320	0.00	0.00	1.18957639
610.	337.9581	0.00	0.00	1.15491395
1219.	335.5945	0.00	0.00	1.08793441
1829.	333.2142	0.00	0.00	1.02398986
2438.	330.8167	0.00	0.00	0.96296967
3048.	328.4051	0.00	0.00	0.90476391
3658.	325.9723	0.00	0.00	0.84932744
4267.	323.5247	0.00	0.00	0.79652170
4877.	321.0583	0.00	0.00	0.74627066
5487.	318.5694	0.00	0.00	0.69851661
6096.	316.0679	0.00	0.00	0.65312170
7011.	312.2728	0.00	0.00	0.58932064
7925.	308.4346	0.00	0.00	0.53041804
8839.	304.5444	0.00	0.00	0.47615435
9754.	300.6113	0.00	0.00	0.42624143
11019.	295.0788	0.00	0.00	0.36388839
12192.	295.0788	0.00	0.00	0.30267217
13411.	295.0788	0.00	0.00	0.24993006
14326.	295.0788	0.00	0.00	0.21649992
15240.	295.0788	0.00	0.00	0.18755608
16764.	295.0788	0.00	0.00	0.14766182
18288.	295.0788	0.00	0.00	0.11627384
19812.	295.0788	0.00	0.00	0.09157509
21336.	295.9402	0.00	0.00	0.07174076

Sample Case

The sample case used to demonstrate operation of the SHOCKN and ZEPHYRUS codes is based on the numerical exercise reported by Cleveland[5], for reasons explained in the section comparing the two codes. This section is only concerned with setting up inputs to ZEPHYRUS and running the program.

****
This is a NASA shaped wave obtained with the SHOCKN Code as a test case.
It is for a conceptual "low-boom" airplane at Mach 1.8, 48000 ft alt.

This waveform is 600 ft below the airplane, or 721.6 ft along the direction of propagation. 721.6 ft is as long as 219.9 meters, by the way.
****

Time(sec)	Overpressure(Pascals)
---------	--------------------@
-0.00452680	0.00000
-0.00377230	37.2812
-0.00233890	74.5622
-0.00226340	111.843
0.00218430	95.6056
0.00663210	79.3679
0.0110798	63.1301
0.0137691	64.9828
0.0164584	66.8356
0.0191477	68.6883
0.0218370	70.5410
0.0245263	72.3936
0.0272155	74.2465
0.0299048	76.0991
0.0325941	77.9518
0.0352834	79.8045
0.0379727	81.6572
0.0406620	83.5100
0.0433513	85.3627
0.0460406	87.2153
0.0487299	89.0680
0.0514192	90.9208
0.0541085	92.7735
0.0567977	94.6262
0.0594870	96.4789
0.0621763	98.3317
0.0648656	100.184
0.0675549	102.037
0.0702442	103.890
0.0729335	105.743
0.0756228	107.595
0.0783121	109.448
0.0810014	111.301
0.0836907	113.153
0.0863799	115.006
0.0890692	116.859
0.0917585	118.711
0.0944478	120.564
0.0971371	122.417
0.0998264	124.270
0.102516	126.122
0.105205	127.975
0.107894	129.828
0.110583	131.680
0.113273	133.533
0.115962	135.386
0.118651	137.239
0.121341	139.091
0.124030	140.944
0.152310	-120.476
0.155000	-118.624
0.157689	-116.771

0.160378	-114.918
0.163068	-113.065
0.165757	-111.213
0.168446	-109.360
0.171135	-107.507
0.173825	-105.655
0.176514	-103.802
0.179203	-101.949
0.181893	-100.096
0.185000	-244.050
0.188763	-82.2210
0.190743	-73.0696
0.192932	-66.0741
0.195255	-60.4474
0.197670	-55.7730
0.200153	-51.8009
0.202689	-48.3685
0.205266	-45.3637
0.207877	-42.7057
0.210516	-40.3339
0.213178	-38.2022
0.215860	-36.2744
0.300000	0.00000

This is the file for parameters used to set up the ray path calculation in RAYTRACE. In this example, only the single ray directly under the aircraft is calculated. The value of errortol sets the distance between points and usually needs to be optimized for accuracy and running time for wave propagation. For the short extrapolations in this report the value is not critical.

```
/****************************************************************************/
This is for a NASA shaped wave obtained with the SHOCKN Code as a test case.
It is for a conceptual "low-boom" airplane at Mach 1.8, 48000 ft alt.

sourcdir is the source direction in degrees ( zero = to East, not compass),
sourcez0 is the source altitude of 48000.0 feet cast in meters,

    sourcedir   sourcez0   sourcex0   sourcey0   sourcev
    (degrees)   (meters)   (meters)   (meters)   (Mach)
    ---------   --------   --------   --------   -------@
     0.0        14630.0     0.         0.         1.800

      rayt0       raytf      rayti
    (seconds)   (seconds)  (seconds)
      -----       -----      ----- @
       0           0          1

       rayphi0        rayphif        rayphii
      (degrees)      (degrees)      (degrees)
       -------        -------        ------@
        0.00           0.00           1.0

      Errortol    stepstart
                  (seconds)
      --------    --------@
      0.0001        2.0

     xcritical    ycritical    zcritical
     (meters)     (meters)     (meters)
     ---------    ---------     ---------@
       -1.0         -1.0         -1.0

      zreceiver
      (meters)
     ----------@
        7315.
```

The wave propagation along a ray is set by this set of parameters. Frequently, the power of 2, resampratio and attensampm are adjusted for best performance for an individual propagation.

```
/******************************************************************************/
This is the primary boom test case using a NASA shaped wave.
It is for a conceptual "low-boom" airplane at Mach 1.8, 48000 ft alt.

The airplane-waveform geometry is:
  vertical distance from aircraft to waveform: 600.0  feet (182.9 meters)
  with Mach number = 1.8, Co-Mach angle: 56.25 degrees
  rest frame path length from airplane to signature: 721.6 feet (219.9
meters).

     start distance (meters)       characteristic time of waveform (sec)
     -----------------------       -------------------------------------@
           219.9                                 0.401427

        rel hum (%)     power of 2     padding ratio  attenuation threshold
        -----------     ----------     -------------  ---------------------@
            20              14             0.50                 9

       nonlinear      absorption     dispersion
       ---------      ----------     ----------@
           1              1              1

       resampratio     stepratio
       -----------     ---------@
           30             5

     ground impedance     ground flow resistivity
     ----------------     -----------------------@
         6.0e06                 270.0

      reflectcoeff
      -----------@
           1

        attenerrorthresh     attensampm
        ----------------     ---------@
            0.00001              11
```

Outputs

The following is a typical commentary produced by the code when it is run. Other files are constructed to plot the pressure wave, risetime and other wave parameters.

After the ZEPHYRUS propagation is concluded, the waveforms are automatically processed through the Sonic Boom Toolbox module, LOUDBOOM, which performs acoustic analysis of the waveforms. Frequency spectra are generated and metrics which estimate loudness are calculated. The meaning of the acoustic analysis is discussed in the following section discussing ZEPHYRUS propagation compared to measurement.

```
#########################     getparams     #########################
Enter name of input file containing propagation parameters: primary.propin
Enter name of input file containing ray data:               primary.fan
Enter ray numbers (m [source time],n [ray angle]): 0 0
                   Total ray path length is   43904.0 meters with 77 points.
Enter name of input file containing the starting waveform:  nasa/wave
#########################  computeparams  #########################
Enter name of output file for new ray parameters:           primary.ray
#########################     propagate     #########################
Enter name of output file for waveforms along ray:          primary_wave.ggp
Enter name of output file for rise-time function:           primary.rtp
Enter name of LoudBoom style file for pressure signatures:  primary.lbin

Path Length=  220 Time=  0.75 S_00000219 *** Starting signature ***(76 points)
Path Length= 1277 Time=  4.33 S_00001276 Ordinary Pt, Alt=13568 m (120 points)
Path Length= 3333 Time= 11.30 S_00003333 Ordinary Pt, Alt=11859 m (180 points)
Path Length= 7178 Time= 24.16 S_00007178 Ordinary Pt, Alt= 8680 m (181 points)
Path Length= 8854 Time= 29.60 S_00008854  Reciever at Alt= 7315 m (500 points)
Path Length=15975 Time= 51.68 S_00015975 Ordinary Pt, Alt= 1660 m (300 points)
Path Length=18123 Time= 58.06 S_00018123 **At Ground Reflection **(333 points)
                   Reflection coefficient '1' applied to 12618 wavepoints
Path Length=18123 Time= 58.06 S_00018123 Leaving Ground Reflection(333 points)
Path Length=27393 Time= 86.51 S_00027392  Reciever at Alt= 7315 m (370 points)
Path Length=30151 Time= 95.52 S_00030150 Ordinary Pt, Alt= 9568 m (368 points)
Path Length=38391 Time=123.38 S_00038391 Ordinary Pt, Alt=16413 m (281 points)
Path Length=43904 Time=142.06 S_00043904  End of ray, Alt=20996 m (255 points)


##### Start LoudBoom with inputs: primary.lbin
------- LoudBoom SampleRate for signature Sig53.00 is 53000 Hz ---------------
description *** S_00000219  *** Starting signature ** Time= 0.75 Dist=0
weightl:  PERCEIVED LEVEL SPLPL =    110.673 dB
------- LoudBoom SampleRate for signature Sig53.01 is 53000 Hz ---------------
description *** S_00001276 Ordinary Pt, Alt=  13568 m Time= 4.33 Dist=0.501946
weightl:  PERCEIVED LEVEL SPLPL =    105.538 dB
------- LoudBoom SampleRate for signature Sig53.02 is 52000 Hz ---------------
description *** S_00003333 Ordinary Pt, Alt=  11859 m Time=11.30 Dist=0.981938
weightl:  PERCEIVED LEVEL SPLPL =     99.375 dB
------- LoudBoom SampleRate for signature Sig53.03 is 52000 Hz ---------------
description *** S_00007178  Ordinary Pt, Alt=   8680 m Time=24.16 Dist=1.46394
weightl:  PERCEIVED LEVEL SPLPL =     97.597 dB
------- LoudBoom SampleRate for signature Sig53.04 is 52000 Hz ---------------
description *** S_00008854   ****** At Reciever ****** Time=29.60 Dist=1.59792
weightl:  PERCEIVED LEVEL SPLPL =     93.453 dB
------- LoudBoom SampleRate for signature Sig53.05 is 52000 Hz ---------------
description *** S_00015975  Ordinary Pt, Alt=   1660 m Time=51.68 Dist=1.94407
```

```
weightl:  PERCEIVED LEVEL SPLPL =     92.240 dB
------- LoudBoom SampleRate for signature Sig53.06 is 52000 Hz ---------------
description *** S_00018123    ** At Ground Reflection **Time=58.06 Dist=2.00846
weightl:  PERCEIVED LEVEL SPLPL =     90.823 dB
------------ Special Ground Reflection Calculation with Kr=1.9 --------------
------- LoudBoom SampleRate for signature Sig53.06 is 52000 Hz ---------------
description *** S_00018123    ** At Ground Reflection **Time=58.06 Dist=2.00846
weightl:  PERCEIVED LEVEL SPLPL =     96.780 dB
```

Comparison of SHOCKN and ZEPHYRUS

Introduction

The sample case used to demonstrate operation of the SHOCKN and ZEPHYRUS codes is based on the numerical exercise reported by Cleveland[5]. Using the same shaped (ramp) source waveform, the atmosphere was changed to the Standard Atmosphere with the motivation of comparing the codes under more realistic conditions. Cleveland's study focused on the theoretical aspects of wave propagation and their practical implementation into propagation codes. The current effort is concerned with extending these results to practical design analysis.

The input pressure signature is a "ramp" waveform at a distance of 183meters (600 feet) directly below the source, flying at 14,630m (48,000 feet) altitude with a Mach number of 1.8. The waveform is not representative of a real aircraft configuration, but came from studies of shaping the source waveform for reduced annoyance[10]. The unusual shape with distinct shocks highlights nonlinear (wave steepening) and absorption mechanisms during propagation.

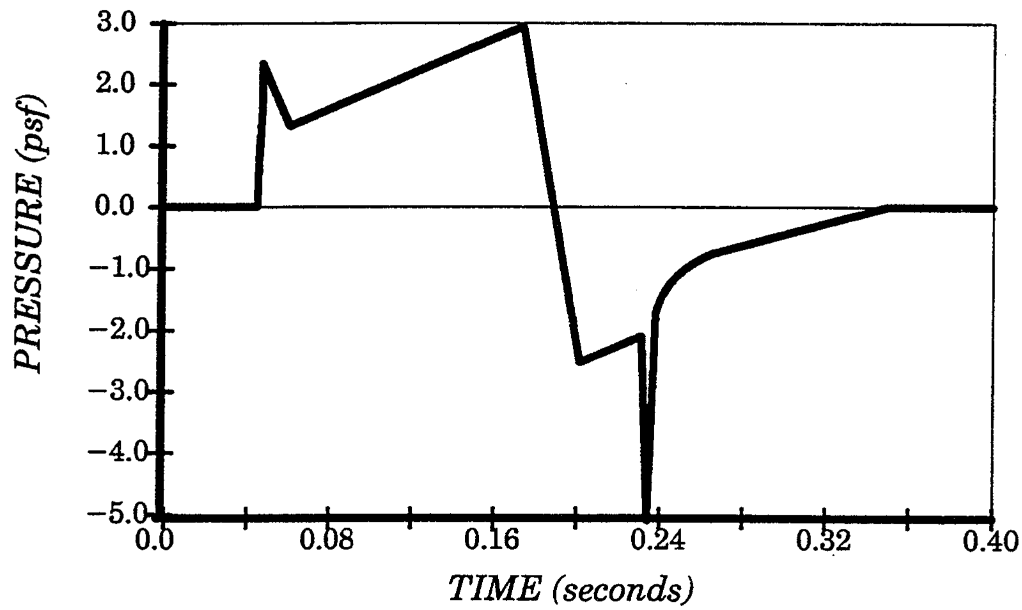


Figure 1 Source Waveform for sample case

Impact of Standard Atmosphere

Cleveland's study used a uniform atmosphere and an isothermal atmosphere to progressively introduce absorptive phenomena. The temperature of these two atmospheres was set at −69.7 F (216.7K), a temperature representative of the stratosphere. This study introduces the standard atmosphere to better quantify absorption in practical analysis. The waveforms presented below are for waves at the ground, with a ground reflection factor of 1.9 multiplying the propagated pressures to simulate the signature as it would be heard by an observer.

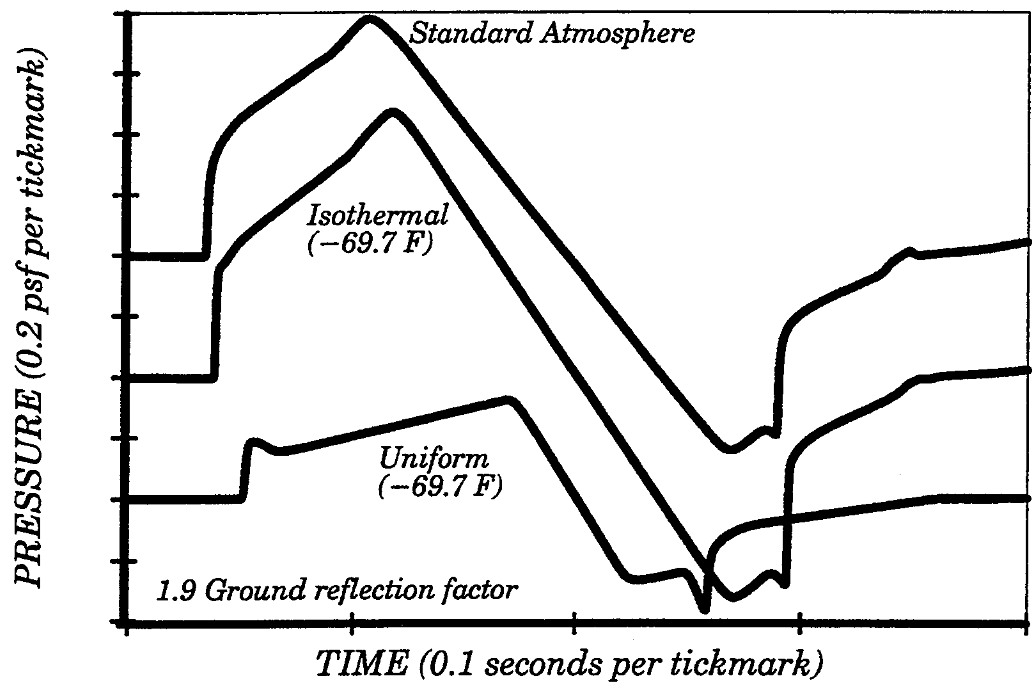


Figure 2 Ground Signatures for sample case for three different atmospheres

The standard atmosphere gives results very close to the isothermal case, suggesting that the initial propagation (where the atmosphere is similar for both cases) dominates the waveform evolution. Overall, the standard atmosphere results in slightly more attenuation (lower pressures) and the same wave steepening (same duration) as the isothermal case.

Comparison Results

Since the standard atmosphere gives results close the isothermal atmosphere results, the same good agreement noted by Cleveland applies here. ZEPHYRUS shows the same wave shape, location of shocks and duration, as seen in Figure 3. Pressures for the ZEPHYRUS propagation are slightly higher and are generally smoother. The minor fluctuations in the SHOCKN case are similar to Cleveland's results and he suggests them to be due to calculational inexactitudes introduced by the large number of Fast Fourier Transform operations.

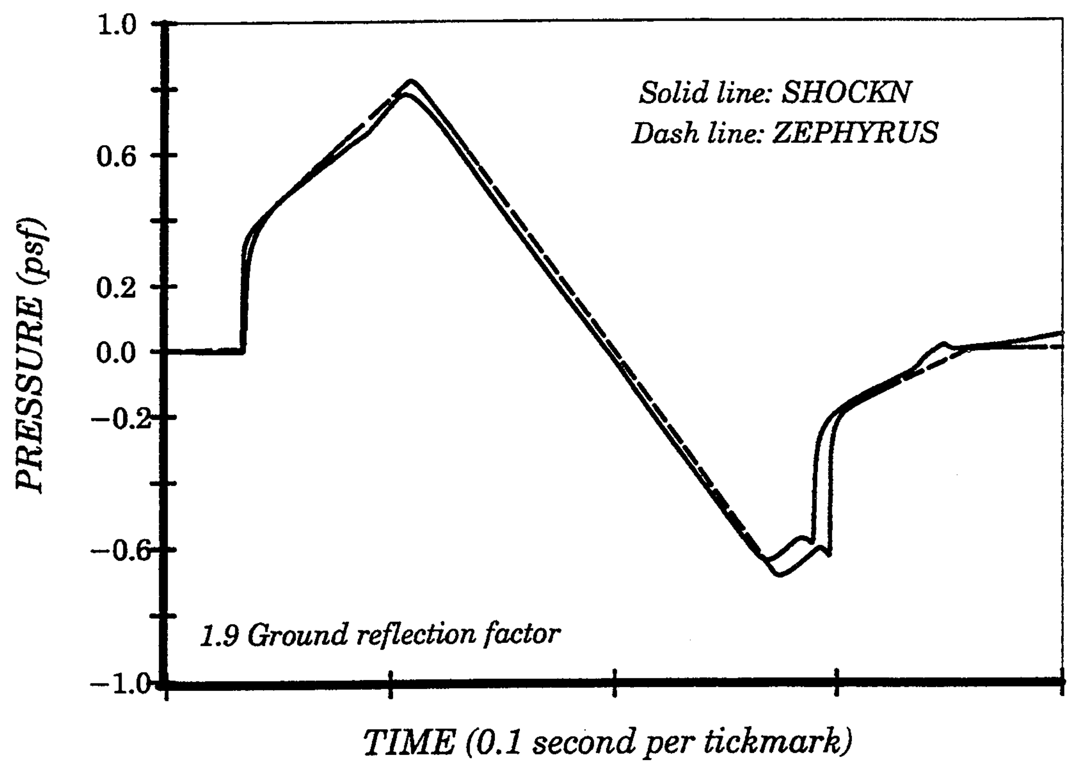


Figure 3 Ground Signatures for sample case propagated with SHOCKN and ZEPHYRUS

As suggested by the shape and duration similarity of the two propagations, the overall sound energy/pressure is essentially the same between SHOCKN and ZEPHYRUS, being controlled by the high noise levels at low frequency (below 40 Hz). See Figure 4 on the following page. However, the implied increase in risetime by the peak pressure reduction over the same duration of the SHOCKN propagation reduces the high frequency content of the noise spectrum, with a corresponding reduction in "ear weighted" noise metrics (five PLdB reduction, for example).

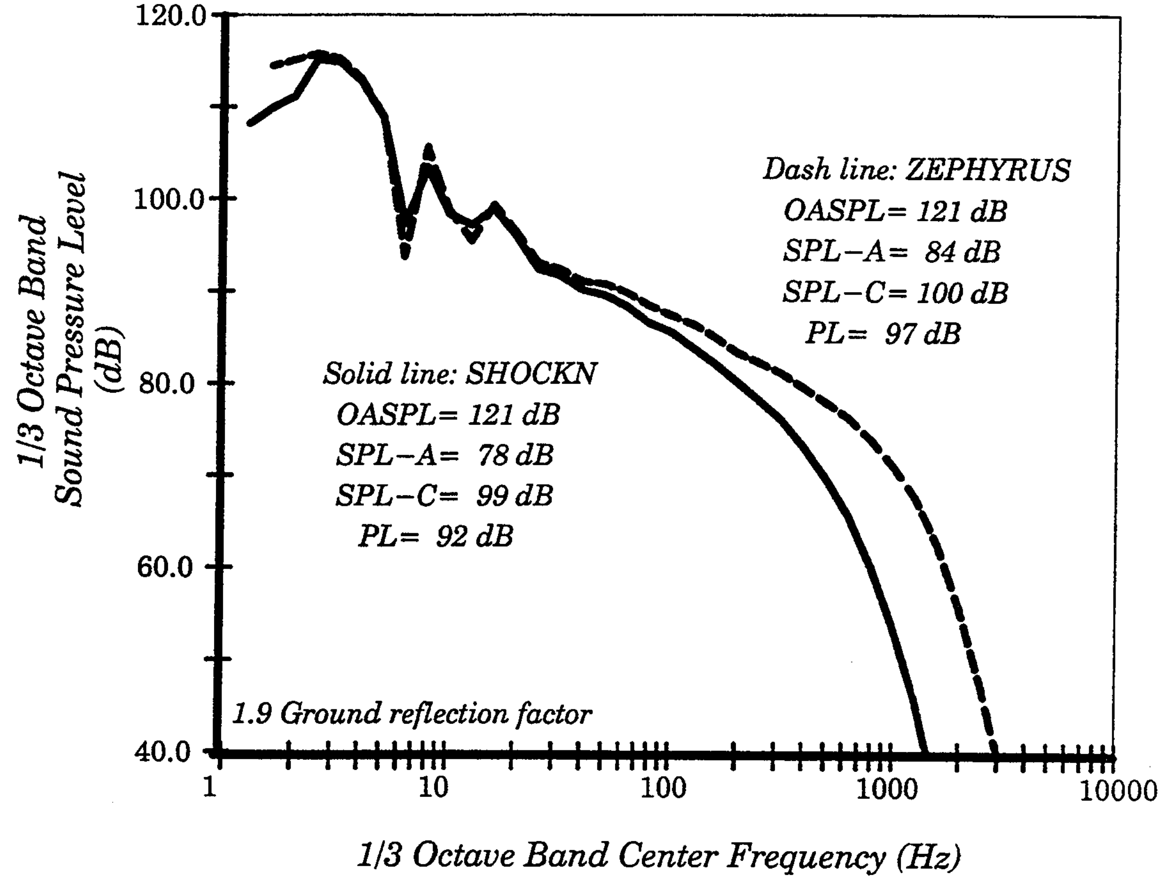


Figure 4 Noise Spectra for sample case propagated with SHOCKN and ZEPHYRUS

For propagation conditions of practical interest, SHOCKN and ZEPHYRUS give the same results. Since they are different implementations of the same physics of the propagation of sonic booms in air, they serve to verify that each implementation has been constructed properly. In addition, ZEPHYRUS offers greater flexibility by allowing winds, ray paths off of the centerline and easy changes to the atmosphere profile. Because of this greater capability, ZEPHYRUS is preferred for solving general propagation problems.

Comparison to Experiment

SR71 Flight Test Summary

Data are becoming available from a 1995 flight test of the SR−71 using a novel technique of probing the pressure field near the aircraft using a F−16XL chase plane flown through the shock waves[11]. Measurements taken around 1000 feet and 5000 feet from the SR−71 were used in an initial verification of the sonic boom propagation codes. The data used were taken on March 16, 1995, with most of the data obtained between 0930 and 1025 PST.

The data supplied by NASA include the weather conditions, flight condition information for both SR−71 and F−16XL and the pressure signature located in space relative to the SR−71. These pressure points were converted to a local pressure−time history based on a simplification to constant lateral and vertical separation and constant probing speed. Appendix A presents the flight data, allowing evaluation of the quality of these assumptions.

Nine of the twenty measurements taken at this range of distances are useful for this exercise. The measurements naturally group into three sets of “near” and “far” pairs, based on the angle from the vertical centerline of the SR−71.

Weather Conditions

Edwards sky condition reports were 22 Kfeet (AGL) scattered clouds at takeoff time and 20Kfeet thin broken clouds the following two hours. Prevailing surface winds were light, with less than five knots at Edwards AFB. Surface temperatures during the day are estimated at 56 to 63 F at Edwards, 62 to 66 F at Mojave, and 68 to 74 F at China Lake, based on hourly measurements. At the ground boom−sensor (PATS) site they are roughly estimated to have been 65 +/− 6 F.

The weather pattern was dominated by a surface high pressure in the Idaho Mountain area with a weak offshore pressure gradient in the Nevada−California area. The pressure dropped approximately 4 mb from the high to southern Nevada and another 4 mb to the California coast. In the morning winds aloft were light at low levles and westerly from 17 to 47 knots between 20 and 50 Kfeet MSL altitude. By mid−afternoon winds increased approximately 20 knots between 20 and 35 Kfeet. IR and moisture satellite imagery showed that a high cloud region trailed across southern California from a core in central Nevada, in advance of a trough aloft. The trough passed Edwards by sundown bringing clear skies from the northwest.

Analysis of upper air synoptic charts and interpolation to flight time indicated that the early morning air profile measurement would be more representative of conditions at flight time than the afternoon observation. Temperature adjustments of 1 degree C or less, and some wind increases reaching about 20 knots were made for the reference air profile based at the Edward location. Larger temperature modifications were made in the surface layer on the basis of the hourly temperature observations.

Pressure heights nominally agree to better than 40 feet. At the surface the semi−diurnal pressure oscillation peak was 66 feet at 6:00 PM. Hence, an approximate adjustment of 46 feet was used for the linearly interpolated synoptic heights derived from noon on March 16 and midnight on March 17 charts. Temperatures at mandatory levels agree to better than 1 deg C at altitudes above 10 Kfeet. Upper level humidities increased from near 25% in the early morning to near 60% in the afternoon. The reference humidity profile values represent a subjectively smoothed interpolation.

The following listing is the air profile configured for use by the sonic boom propagation program, ZEPHYRUS. The entry for zero altitude (required for ZEPHYRUS code) was created from extrapolated temperature and pressure data (24.0 C and 1013.26 mB respectively).

ZEPHYRUS style air profile from SR71 Flight Data

****

Altitude (meters)	Sound Speed (m/s)	Wind Velocity in X-Direction (Eastwardness) (m/s)	Wind Velocity in Y-Direction (Northwardness) (m/s)	Air Density (specific weight) (kg/m3)
0.0	345.580	-1.18	-0.99	1.1879087
2000.0	341.544	-1.18	-0.99	1.1347605
2302.3	340.307	-1.18	-0.99	1.1306385
2403.3	339.893	-1.18	-0.99	1.1292713
2605.9	339.301	-1.09	-1.09	1.1249437
2908.6	339.301	-0.99	-1.18	1.1126849
2915.3	339.301	-0.99	-1.18	1.1124173
3036.4	339.479	-0.99	-1.18	1.1063939
3536.1	339.834	-0.59	-0.84	1.0843346
4035.8	340.011	-0.51	-0.89	1.0638506
4153.8	340.247	-0.51	-0.89	1.0578623
4946.9	339.360	-0.51	-0.89	1.0333713
5035.4	339.242	-0.51	-0.89	1.0307840
5997.8	337.817	0.07	-1.03	1.0036965
6034.6	337.817	0.91	-0.16	1.0023469
7036.4	338.233	2.67	1.54	0.9639376
8035.0	337.401	2.22	2.64	0.9339329
10232.5	334.229	3.60	2.92	0.8773427
14033.6	328.529	6.25	2.92	0.7858023
16032.2	325.950	8.06	2.16	0.7384183
18887.8	321.167	11.32	0.20	0.6786824
20033.4	319.725	14.00	0.00	0.6536466
24272.3	313.505	14.87	1.30	0.5698102
28023.9	307.486	16.35	2.01	0.5035302
30813.8	302.279	18.49	1.29	0.4596891
34714.2	295.217	24.20	0.00	0.4016229
36002.3	293.099	23.53	0.00	0.3829193
36999.0	291.655	21.93	0.00	0.3683661
39321.3	295.285	18.53	0.00	0.3211502

Selected Flight Conditions

The "mid–field" data from Flight 24 were selected for this study, which includes twenty measurements. Within this set, fourteen signatures were examined for use in the code verification exercise. Measurements 9 and 13 were rejected because the lateral angle (PHI) was much greater than the other measurement conditions. Measurements 12, 18 and 20 were rejected because the flight direction of the probing aircraft was very non–parallel to the SR–71 during measurement. Measurement 12, in particular, did not even traverse the length of the sonic boom waveform. The acceptable measurements, with parameters of interest for the analytic projection are listed in the following table.

	Time		Probing Conditions			SR71 Flight			
Measurement	Signature Start SAM	Signature End SAM	dz0 feet	dy0 feet	Phi deg	Mach	Alt feet	GW klb	speed fps
1	63001	63006	757.1	−17.1	−1.3	1.24	31140	118.0	1281.2
2	63035	63039	866.8	−90.3	−5.9	1.24	31082	116.7	1285.9
3	63392	63395	1372.1	107.2	+4.5	1.26	30961	109.0	1205.4
4	63438	63441	1991.8	26.8	+0.8	1.26	31007	107.8	1197.8
5	63492	63495	1871.6	48.0	+1.5	1.25	31081	106.4	1192.1
6	63949	63954	845.3	−10.0	−0.7	1.25	31163	103.2	1297.1
7	63994	63997	762.6	−67.3	−5.0	1.25	31162	102.5	1294.5
8	64078	64081	567.8	−54.9	−5.5	1.26	31097	101.7	1306.8
10	64310	64317	5323.2	−198.6	−2.1	1.25	30991	97.8	1191.7
11	64320	64327	5215.5	395.3	+4.3	1.24	31012	97.3	1184.8
14	65729	65732	1752.4	34.2	+1.1	1.26	31147	86.0	1310.3
15	65759	65761	956.9	−135.7	−8.1	1.27	31128	85.8	1313.4
16	65811	65815	714.3	−6.8	−0.5	1.25	31142	85.3	1300.7
17	65841	65845	1073.0	−53.9	−2.9	1.26	31181	84.6	1306.5
19	66223	66226	5127.1	−878.3	−9.7	1.26	31126	78.8	1195.2

Figure 5 Flight Conditions for SR–71 Flight Test

The signature start and end times in the above table, measured in Seconds After Midnight (SAM), are not the start and end times for data acquisition as listed in other test documentation but rather represent the duration of the actual boom signature, taken to the nearest whole second outside the actual signature. These boundaries were established by inspection while preparing the data as described in the following section.

With Mach number essentially constant at 1.25 and source altitude at 31,100 ft, examination of measurement distance and angle suggests comparison of "near" (around 1000 feet) and "far" (around 5000 feet) signatures at angles of −8.9, −1.6, and 4.4 degrees from vertical downward. This is shown in the following graph. The "near" signature will be projected to the "far" distance for each set.

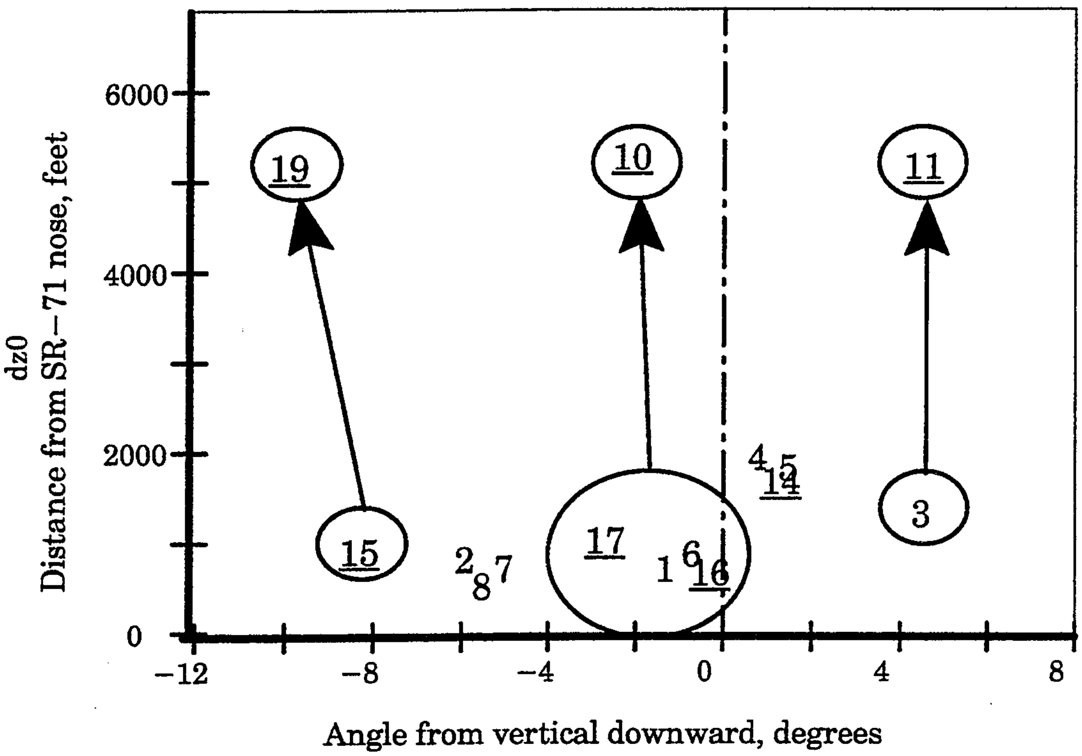


Figure 6 Selection of "Near" and "Far" Measurements for ZEPHYRUS Propagation

Derivation of Measured Waveforms for Extrapolation

The key measurement supplied from the SR71 flight test was pressure versus longitudinal distance relative to the SR−71. However, to use the measurement in the propagation code, it needs to be converted to pressure versus time at a fixed point in space. If the fixed point is chosen as the start of the signature (local longitudinal distance, dx0=0) at position (local lateral distance, dy0), (local vertical distance, dz0) relative to the the SR−71 nose (the origin of the coordinate system tied to the SR−71) it will be appreciated that if dy0, dz0 and the SR−71 velocity are independent of time, a longitudinal point at dx will arrive at the fixed point after the time interval:

(incremental time of arrival, dt) = (longitudinal distance, dx) /[−(SR−71 speed)]

where the negative sign is required because of direction of flight of the SR−71 in the earth−based frame of reference. Because the real signature exists in three−dimensional space and assumptions listed above were not strictly fulfilled, the ability of a calculated value of dt based on a measured value of dx0 to correctly describe the time sequence of the pressure signature is suspect. The degree of suspicion for individual signatures may be assessed from examination of the distance by which dy0 and dz0 deviate from their average value as well as how steady the SR−71 speed is. This information is presented in Appendix A. The resolution was to add the assumption that the relative speed of the SR−71 and the measurement probe in the longitudinal direction is constant. The line comparing average dx0/(measurement time) to actual dx0 is also shown in Appendix A.

For the nine signatures used for propagation, Appendix B shows the derived signature time histories. Of particular interest is the variation in signature duration, or length (since the speed is known). The far signatures are either extremely short (#10) or long (#11 and #19) and also have noticeable "fuzz" (short duration pressure fluctuations) in the data. The far measurements were also taken with the probe aircraft trajectory the most non–parallel to the SR–71 flight path. Extreme pressure spikes, which tend to be in adjacent pairs of values distinctly above and below the local average value, were manually deleted in the three far waveforms in order to reduce the number of points that ZEPHYRUS would consider significant on output to an amount within the current capability of the code. Points were only deleted away from shocks to preserve the character of the waveforms.

#	Signature Duration sec	Signature Length		Relative Distance	Fuzz in data
		feet	Percent of SR–71 length		
1	0.1101	141.1	130	Near	Little
3	0.0983	118.5	110	Near	Little
6	0.0988	127.5	119	Near	Little
10	0.0659	78.5	73	Far	Yes
11	0.2060	244.1	227	Far	Yes
15	0.0643	84.5	79	Near	Little
16	0.0916	119.2	111	Near	Little
17	0.1201	156.9	146	Near	Little
19	0.1509	180.3	168	Far	Yes

Figure 7 Measured Signature Durations

Analytic Propagation

"Near" measurements 1, 3, 6, 15, 16, and 17 were extrapolated from their measurement location to their corresponding "far" signature locations. The "far" measurements were also processed through the extrapolation code without changing the signature location in order to generate waveform files in the same format as the extrapolated near measurements. Since the extrapolated signatures were compared to measurements made "in the air", the ground reflection factor was set to 1.0 (no reflection). The following table lists several parameters important to setting up inputs to the ZEPHYRUS code and the distances between the "source", "signature" and "receiver". The source is the SR−71 generating a pressure signal, the signature is the pressure signal actually measured by the F−16XL and the receiver is a conceptual device detecting the pressure signal after it has propagated to a new location. The propagation distance in the table describes where the new location is.

#	Propagation Parameters				Propagation Distances				
	Mach	Heading degrees	Wave Duration sec	Average PHI angle degrees	(SR−71) Source Altitude feet	Vertical Distance (dz0) feet	Signature Altitude feet	Receiver Altitude feet	Propagation Distance feet
15	1.265	62	0.0643	−8.9	31128	957	30171	26000	4171
19	1.262	242	0.1509	−8.9	31127	5127	26000	26000	0
1	1.237	61	0.1101	−1.6	31141	757	30384	25667	4717
6	1.252	61	0.0988	−1.6	31165	845	30320	25667	4653
16	1.254	62	0.0916	−1.6	31142	714	30428	25667	4761
17	1.261	62	0.1201	−1.6	31181	1073	30108	25667	4441
10	1.249	242	0.0659	−1.6	30993	5323	25667	25667	0
3	1.262	242	0.0983	4.4	30961	1372	29589	25796	3793
11	1.244	243	0.2060	4.4	31011	5215	25796	25796	0

Figure 8 Propagation Parameters for ZEPHYRUS

Propagation parameters have to be "tuned" to each ZEPHYRUS propagation. Since these data have many points in each signature and are propagated only a short distance, the propagation parameters are different than those used in the example case:

```
 rel hum (%)  power of 2   padding ratio  attenuation threshold
-----------  ----------  -------------  ---------------------@
   45.0         14          0.25                 9

 nonlinear     absorption     dispersion
 ---------     ----------     ---------@
  1(yes)         1(yes)         1(yes)

resampratio    stepratio
-----------    ---------@
   25            10

ground impedance    ground flow resistivity
----------------    -----------------------@
    6.0e06                270.0

reflectcoeff
-----------@
1(hard ground)

attenerrorthresh    attensampm
----------------    ---------@
    0.000001           12
```

Although the range of distance from "near" to "far" is not great, the expected trends of increased duration, shock coalescence and peak pressure reduction are still seen. Appendix C presents plots comparing "near" measured signatures to the extrapolated signatures.

Comparison of Measured and Analytic Waveforms

First of all, it should be remembered that the range of extrapolation is not great for this initial set of data. The "far" signature, approximately fifty body lengths away from the source, shows some effects of non–linear steepening, with pressures reduced by a factor of two to three and duration slightly increased, as shown by the signatures in Appendix C. Most of the "fuzz" in the measurement has been smoothed out but significant shocks from bow, canopy, and inlets are still evident in the propagated waves.

The following plots compare extrapolated waveforms to measured waveforms as would be measured by the probe aircraft, that is, with no pressure increase due to ground reflection (ground reflection factor equal to one). Considering pressure versus time, two of the comparisons (#15–#19 and #3–#11) show the extrapolated signature to be of much shorter duration than the signature measured at the far position.

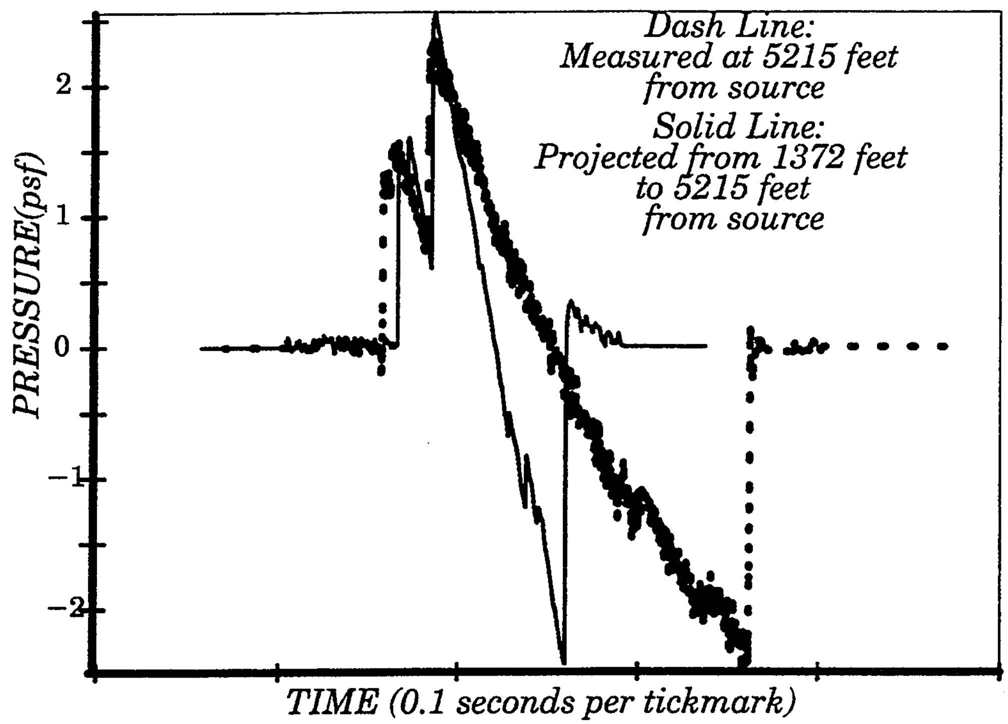


Figure 9 Time History for Measurements #3 and #11

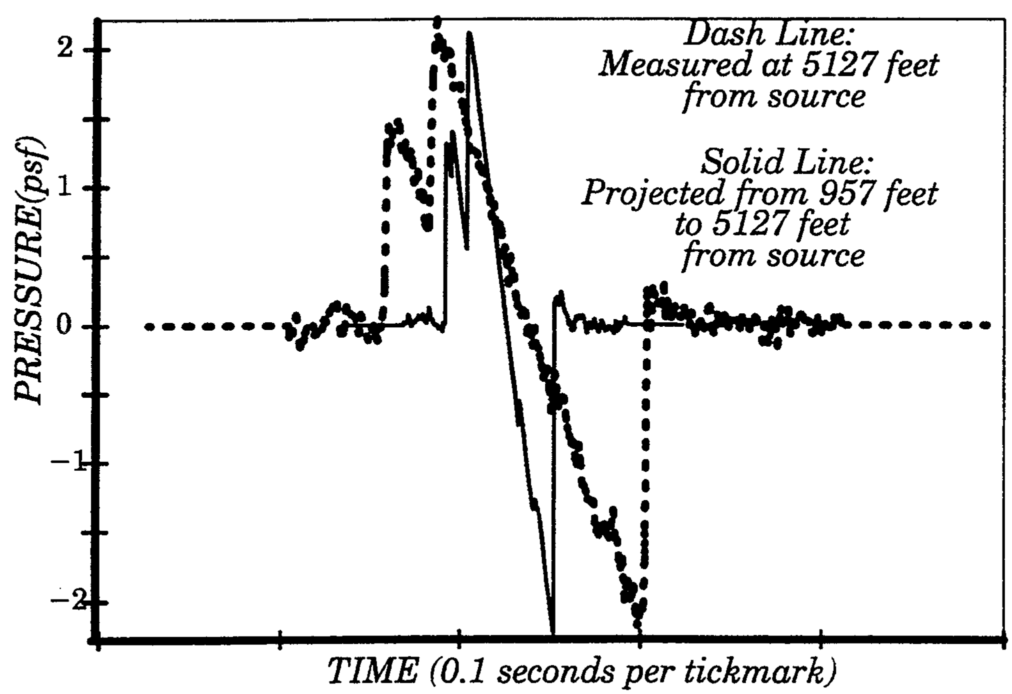


Figure 10 Time History for Measurements #15 and #19

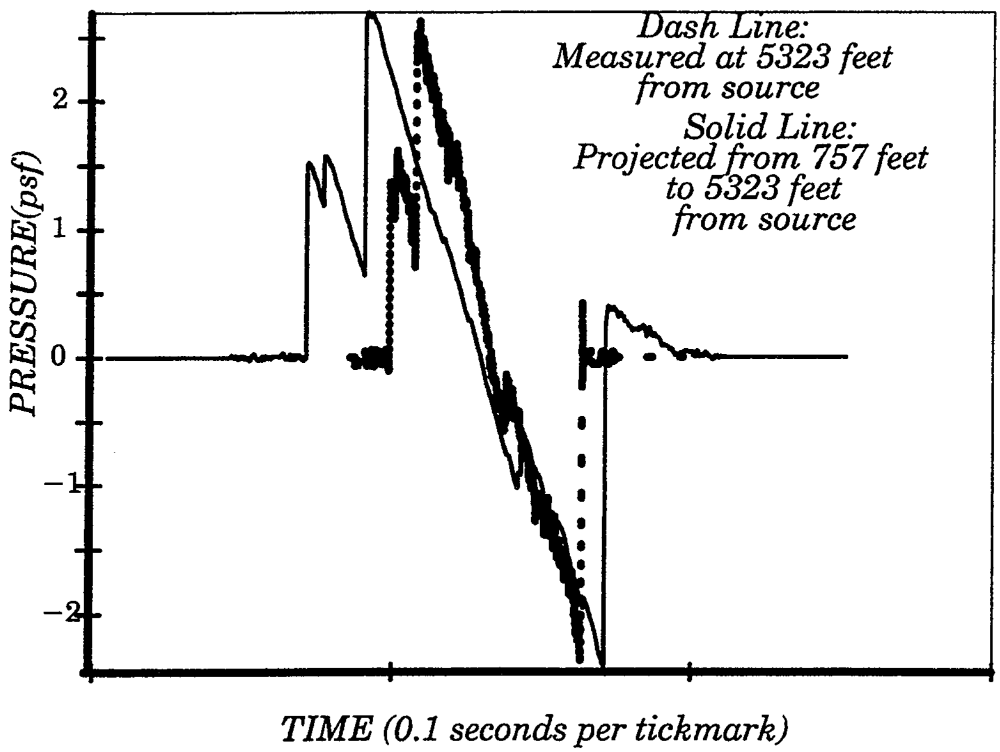


Figure 11 Time History for Measurements #1 and #10

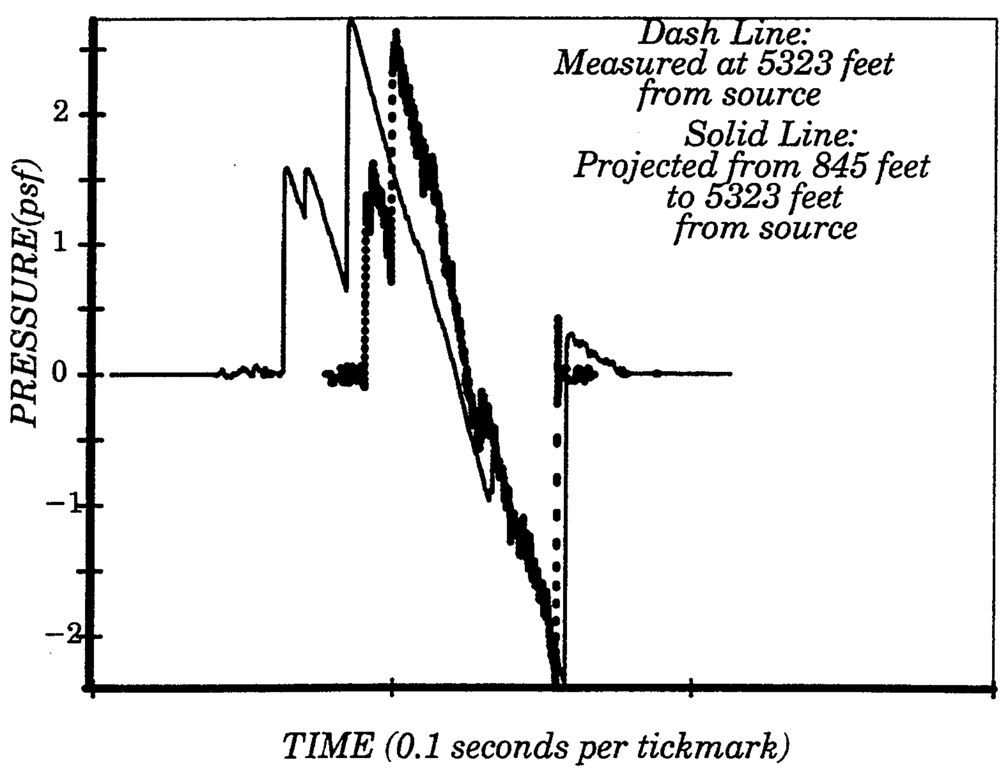


Figure 12 Time History for Measurements #6 and #10

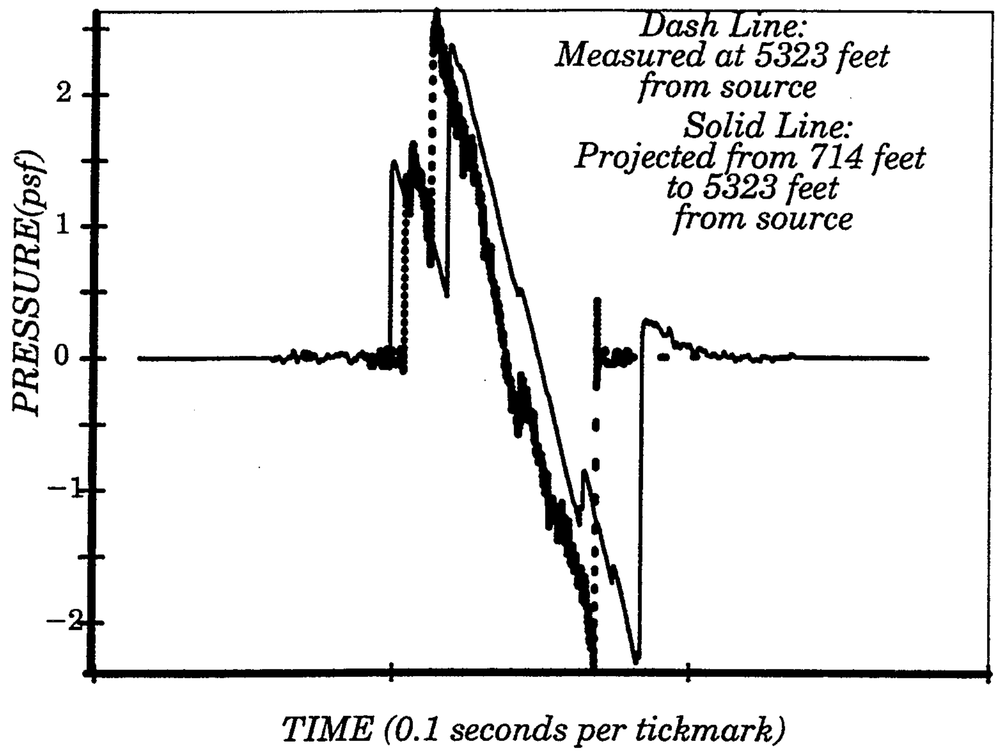


Figure 13 Time History for Measurements #16 and #10

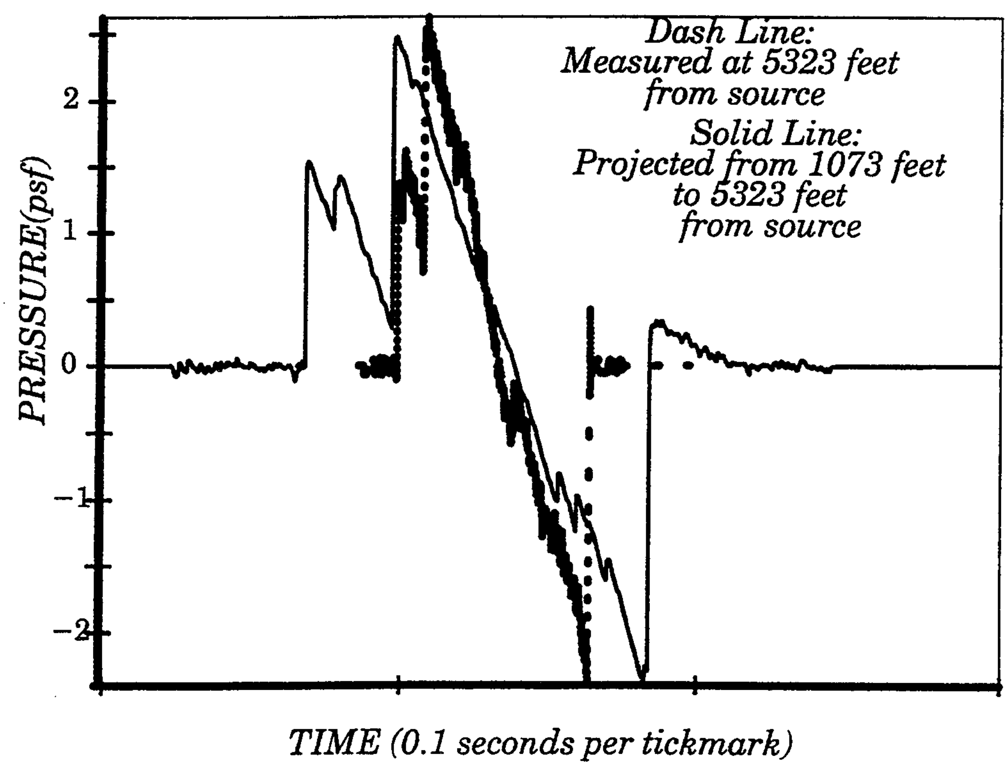


Figure 14 Time History for Measurements #17 and #10

In each of the comparisons, the measured far signature is at odds with expectation. The signature generated at the aircraft is essentially the length of the aircraft, and will only get longer with distance away from the source. Simple theoretical considerations[12] indicate the signature duration should grow at (ratio of distance)$^{1/4}$, which is somewhat faster than the duration growth rate seen in the detailed propagations of Appendix C. Nevertheless, this indicates that it is primarily the measured "far" signatures that are not consistent. Measurement 10 is too short and measurement 11 is too long. Measurement 19 is actually close to the expected duration, but is paired with the shortest duration "near" signature.

During informal discussion of these results with Ed Haering[11] of Dryden Flight Research Center, he suggested a refined data reduction method that appears to resolve these duration anomalies. Rather than setting the lateral (dy_0) and vertical (dz_0) distances to the average value, the radial distance from the SR−71,

$$dr_0 = \sqrt{(dy_0^2 + dz_0^2)} \qquad \text{(at each measurement point)}$$

is calculated as the perpendicular component of the ray from the point of signal generation at the SR−71 to the point of measurement, d_{ray}. The longitudinal component of d_{ray} is then found from the Mach angle, μ ,

$$\mu = \text{arcsine } (1.0 / (\text{Mach}_{SR-71})$$

$$dx_{ray} = d_{ray} / \tan(\mu)$$

dx_{ray} is then added to the geometrical longitudinal distance, x_0, resulting in a total distance back from the nose of the SR−71,

$$d_{back} = dx_0 + dx_{ray} = dx_0 + (d_{ray} / \tan \mu)$$

The distance d_{back} is then converted to time at a fixed point in space using the same equation as the simplified procedure;

$$\text{incremental time of arrival} = d_{back} / [-(\text{SR}-71 \text{ speed})]$$

where again the negative sign is needed to reconcile the coordinate system local to the SR−71 to the ground based coordinate system. Note that the additional term, dx_{ray}, has a constant value under the simplified procedure and would only shift the time axis but has a variable value in the new procedure and decreases the relative time of points measured closer to the SR−71.

Pressures of the shocks within the waveform match very well between the measured and extrapolated waveforms, both the peak overpressures and intermediate peaks from nose, canopy and other details of the aircraft geometry. Thus, by employing the proposed new conversion for incremental time to resolve duration differences, the prediction should match the measured signatures.

Noise Metrics

The frequency spectra and integrated noise metrics for each signature time history were calculated using procedures outlined in Reference 13. Additionally, Reference 14 describes the details of calculating the integrated metric, Perceived Level, which has been found to give the best estimate of annoyance reaction to sonic boom signatures. Because Perceived Level is calculated differently than the conventional dB(A), dB(C) metrics, the procedure is outlined in Appendix D.

Reference 13 includes an instructive discussion of which aspects of a general N−wave signature affect the sound spectrum. The salient aspects to the results of this study are the similarity in low frequency (below 300 Hz) sound pressure levels due to the similarity of peak pressures in the various signatures and the dissimilarity of high frequency noise due to duration variation changing the time from beginning of signature to peak pressure (an implied risetime). The duration/risetime also shifts the specific frequencies that the low frequency maxima occur at, which changes the overall energy of the spectra because the maxima fall along a six dB/octave slope from the peak SPL. The change is three to four decibels in sound pressure level for the signatures in these comparisons.

Measurement Number	Signature Parameters			
	Peak Pressure psf	Wave Duration sec	Overall Sound Pressure Level dB	Perceived Level PLdB
15 extrapolated	2.111	0.0603	120	115
19 measured	2.208	0.1509	123	112
1 extrapolated	2.692	0.1006	121	116
6 extrapolated	2.752	0.0953	120	115
16 extrapolated	2.367	0.0848	119	115
17 extrapolated	2.475	0.1168	121	115
10 measured	2.627	0.0659	118	119
3 extrapolated	2.559	0.0935	117	114
11 measured	2.339	0.2060	121	108

Figure 15 Extrapolated Signature Characteristics

Comments on specific comparisons of spectra are illustrated by plots following these two paragraphs. The pairs, measurements #15−#19 and #3−#11, feature an increase in OASPL (extrapolated to measured) but a decrease in PLdB. Additional acoustic energy indicated by the increase in OASPL is at frequencies below 10 Hz (as discussed above) which contributes very little to the annoyance response indicated by PLdB. This energy appears to have partially come from frequencies above 1000 Hz, thus encouraging reduction of PLdB. Measurements #3−#11, in particular, show well defined peaks and valleys in their spectra, illustrating how duration shifts the frequency of the acoustic energy distribution.

The four extrapolated signatures compared to measurement #10 are substantially the same, with a spread in noise levels of only two decibels. Extrapolated durations are all close to 0.1 second. They are compared to a far signature of 0.7 seconds duration, so the ratio of durations (extrapolated to measured) is much closer to unity than the previously discussed pairs. The high frequency spectra are also close, as would be expected, but low frequency shifting of spectral peaks and valleys is still evident, resulting in the three to four decibel differences between the extrapolated and measured noise metrics.

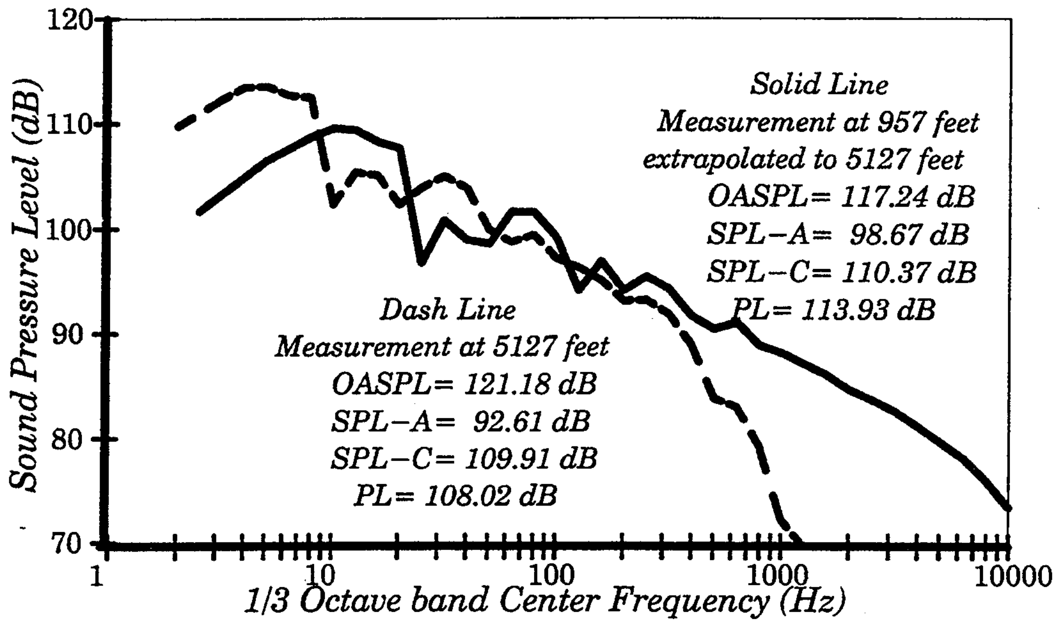


Figure 16 Spectra for Measurements #3 and #11

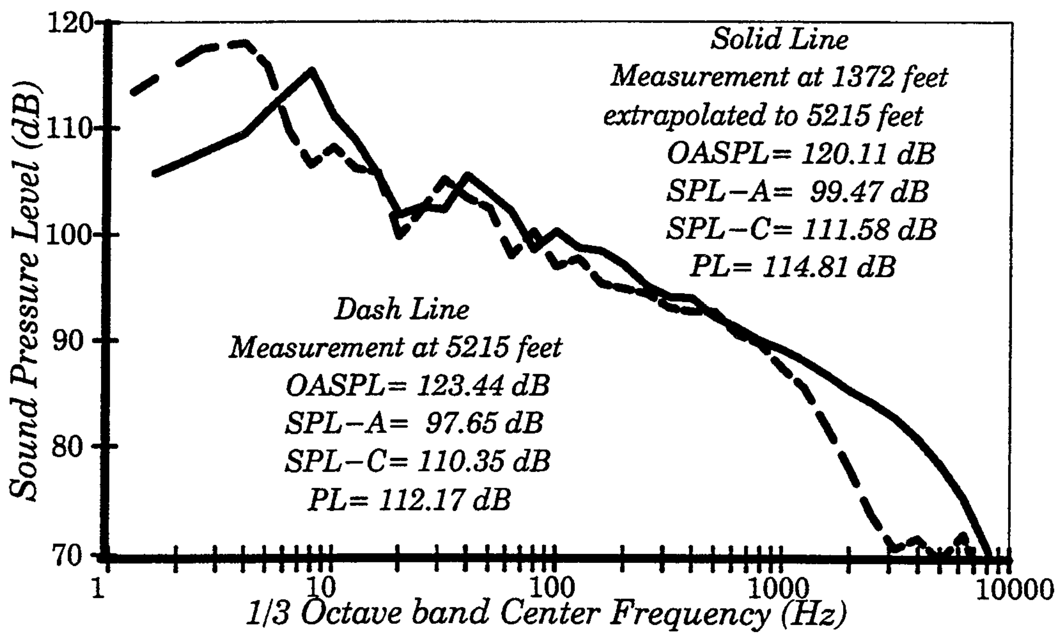


Figure 17 Spectra for Measurements #15 and #19

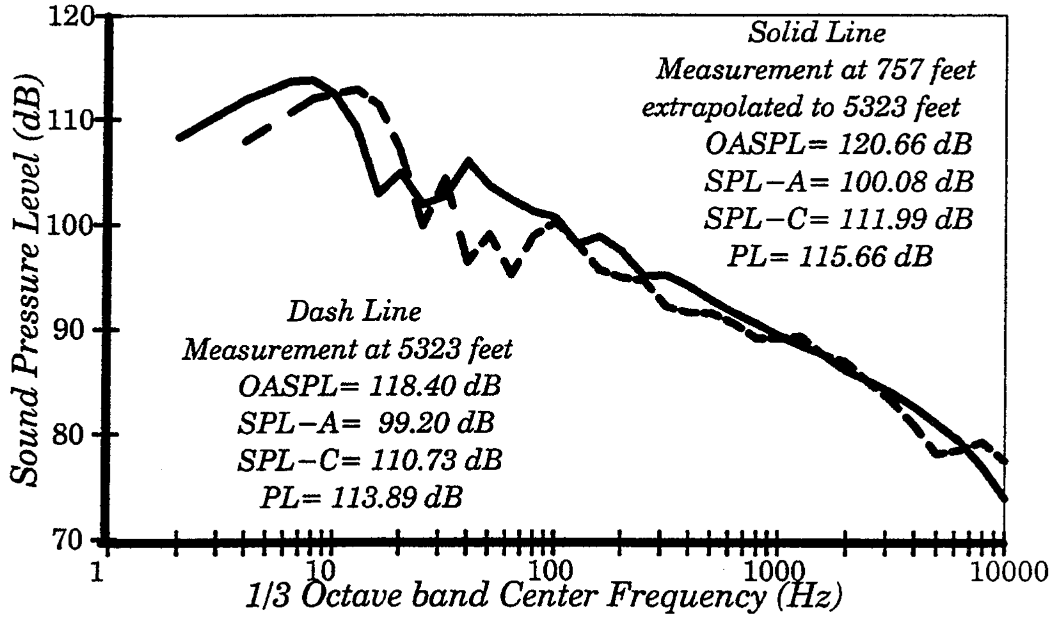


Figure 18 Spectra for Measurements #1 and #10

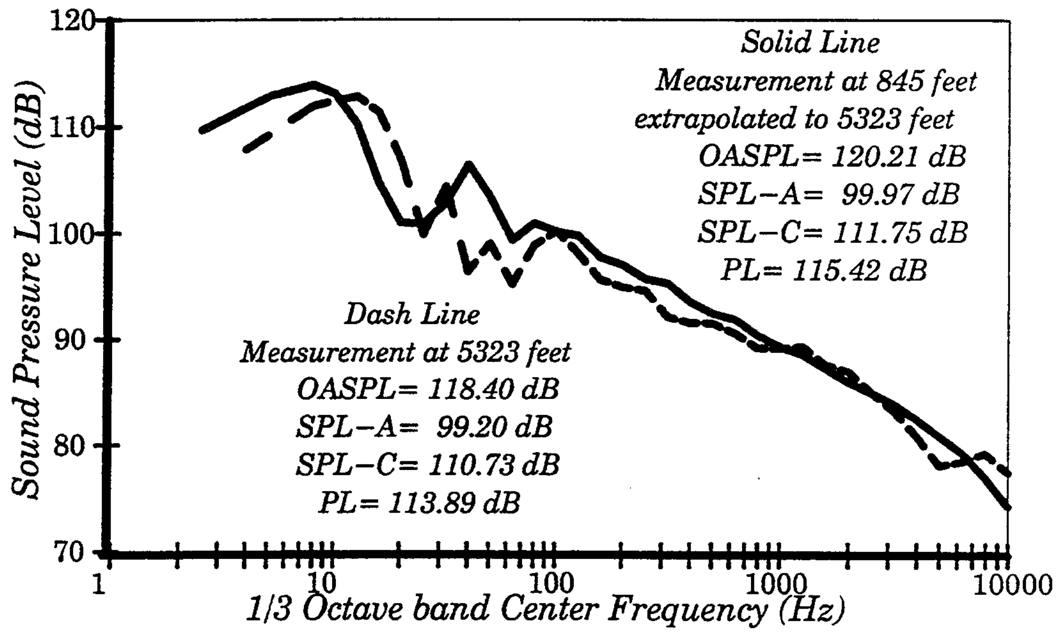


Figure 19 Spectra for Measurements #1 and #6

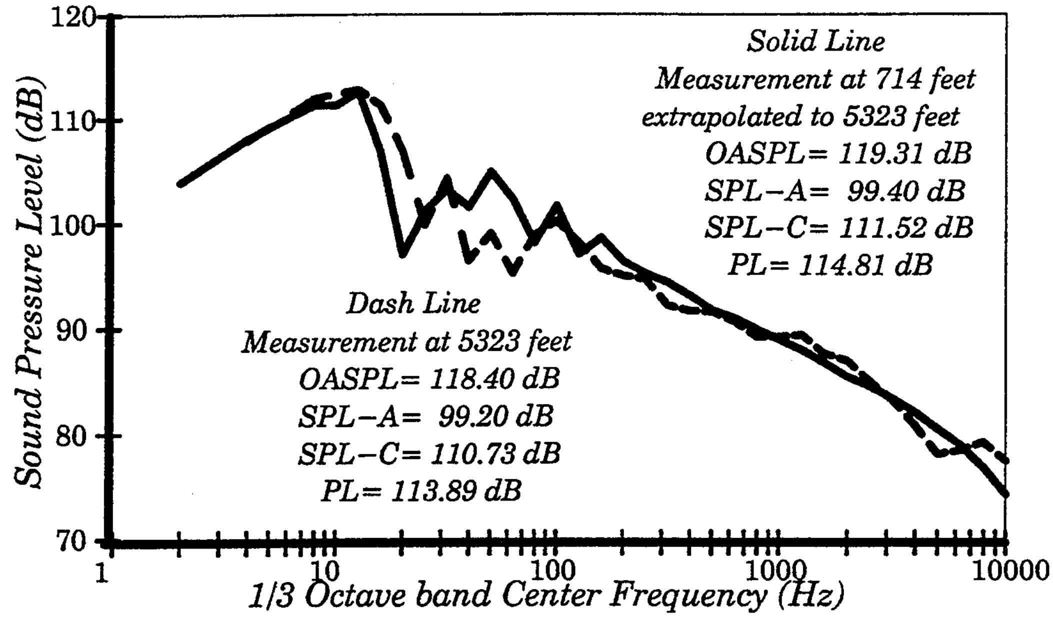


Figure 20 Spectra for Measurements #1 and #16

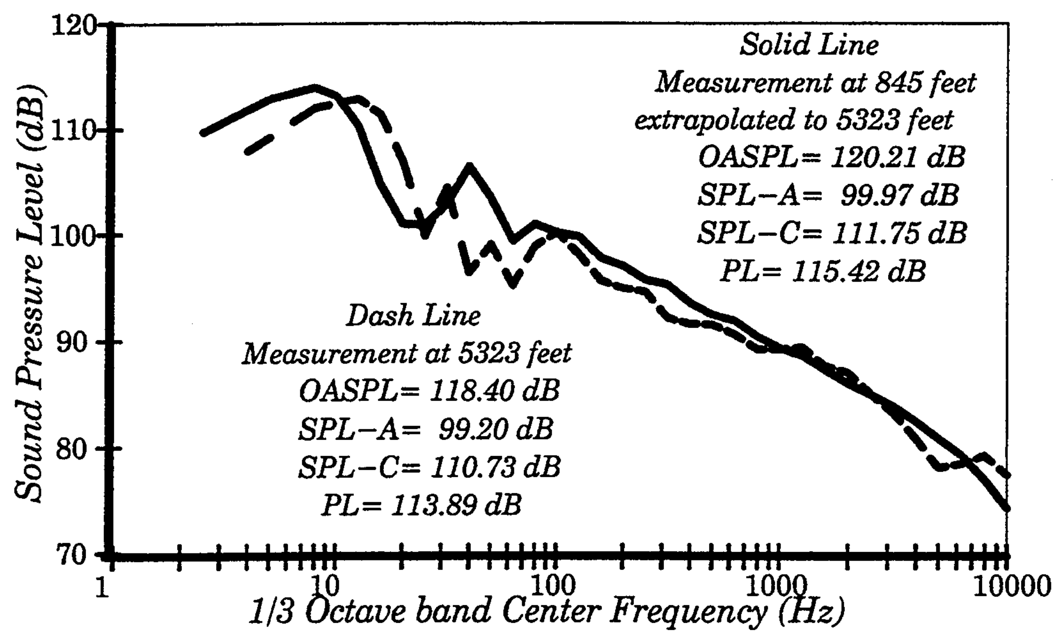


Figure 21 Spectra for Measurements #1 and #17

Conclusions

Propagation Codes

The sonic boom propagation codes reviewed in this study, SHOCKN and ZEPHYRUS, implement current theory on air absorption using different computational concepts. Review of the codes with a realistic atmosphere model confirm the agreement of propagation results reported by others for simplified propagation conditions. ZEPHYRUS offers greater flexibility in propagation conditions and is thus preferred for practical aircraft analysis.

Comparison to Measurement

The ZEPHYRUS code was used to propagate sonic boom waveforms measured approximately 1000 feet away from an SR−71 aircraft flying at Mach 1.25 to 5000 feet away. These extrapolated signatures were compared to measurements at 5000 feet. Pressure values of the significant shocks (bow, canopy, inlet and tail) in the waveforms are consistent between extrapolation and measurement. Of particular interest is that four (independent) measurements taken under the aircraft centerline converge to the same extrapolated result despite differences in measurement conditions. Extrapolated and measured signature durations disagree because the measured duration of the 5000 foot signatures either much longer or shorter than would be expected. The measured durations are 0.07 seconds, 0.21 seconds and 0.15 seconds where a value of 0.1 might be expected.

These duration anomalies may have been introduced by the simplified method of converting the measured pressure at a position relative to the SR−71 to a time history at a fixed point in space. A more refined procedure has been suggested that accounts for changes in SR−71 speed and position of the probe aircraft during pressure measurement. Implementation of this procedure by others indicates a much better resolution of near and far measurements.

Appendix A
SR−71 Measured Pressure Signatures and Flight Conditions

Measurements of primary interest for sonic boom propagation study are the aircraft (source) location and the signature pressures and location away from the aircraft. Current propagation codes generally require non−accelerated flight, and ZEPHYRUS in particular, requires steady level flight. The measured aircraft position and speed for the 1995 SR−71 flight test (flight #24) are compared to the average values in this appendix. The measurements taken around 5000 feet from the source are less steady and less parallel the source than the measurements taken less than 1000 feet from the source, introducing more uncertainty to the propagation validation.

	Time		Probing Conditions			SR71 Flight			
Measure ment	Signature Start SAM	Signature End SAM	dz0 ft	dy0 ft	Phi deg	Mach	Alt ft	GW klb	speed fps
1	63001	63006	757.1	−17.1	−1.3	1.24	31140	118.0	1281.2
2	63035	63039	866.8	−90.3	−5.9	1.24	31082	116.7	1285.9
3	63392	63395	1372.1	107.2	+4.5	1.26	30961	109.0	1205.4
4	63438	63441	1991.8	26.8	+0.8	1.26	31007	107.8	1197.8
5	63492	63495	1871.6	48.0	+1.5	1.25	31081	106.4	1192.1
6	63949	63954	845.3	−10.0	−0.7	1.25	31163	103.2	1297.1
7	63994	63997	762.6	−67.3	−5.0	1.25	31162	102.5	1294.5
8	64078	64081	567.8	−54.9	−5.5	1.26	31097	101.7	1306.8
10	64310	64317	5323.2	−198.6	−2.1	1.25	30991	97.8	1191.7
11	64320	64327	5215.5	395.3	+4.3	1.24	31012	97.3	1184.8
14	65729	65732	1752.4	34.2	+1.1	1.26	31147	86.0	1310.3
15	65759	65761	956.9	−135.7	−8.1	1.27	31128	85.8	1313.4
16	65811	65815	714.3	−6.8	−0.5	1.25	31142	85.3	1300.7
17	65841	65845	1073.0	−53.9	−2.9	1.26	31181	84.6	1306.5
19	66223	66226	5127.1	−878.3	−9.7	1.26	31126	78.8	1195.2

The following plots show the measured data for each of the above measurements. Line segments show the range defining “the signature”, set to the nearest whole second beyond the (non−zero) pressure signature. The lines mark the average value (dy0, dz0, vtotsr) or speed (dx0 vs time) over that duration of (measurement) time. The values beyond the line segment are not included in calculating the averages. The SR−71 source speed, vtotsr, is very steady over the signature duration. The relative lateral (dy0) and vertical distance (dz0) tend to change steadily over time, especially as distance between the SR−71 and the probe aircraft is increased. The longitudinal position (dx0) has to change over time so the whole signature may be measured. An average speed, dx0/dt, is plotted to show the unsteadiness in speed during signature sampling.

Figure A.1 Measurement Number 1 of SR–71 Flight 24

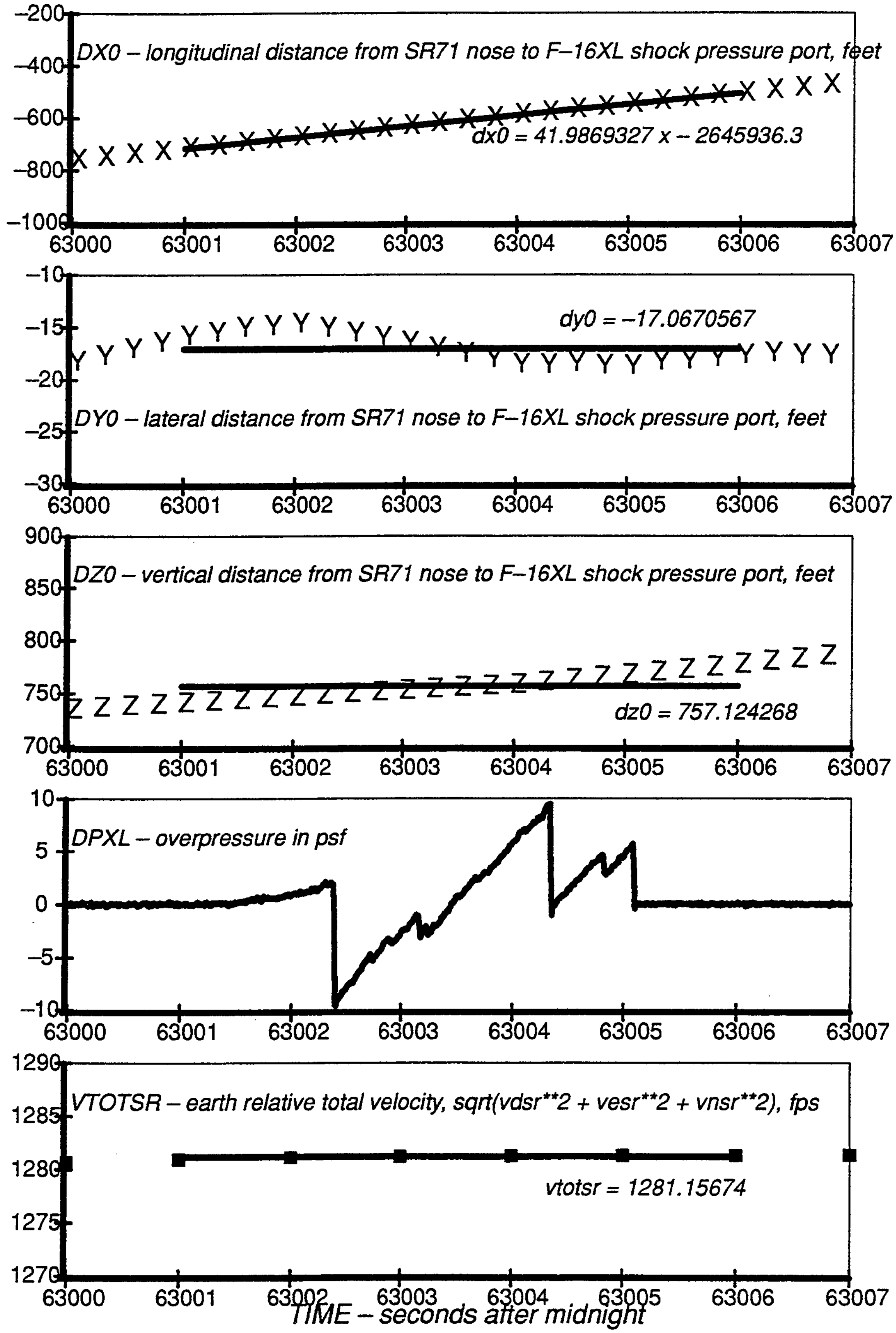


Figure A.2 Measurement Number 2 of SR−71 Flight 24

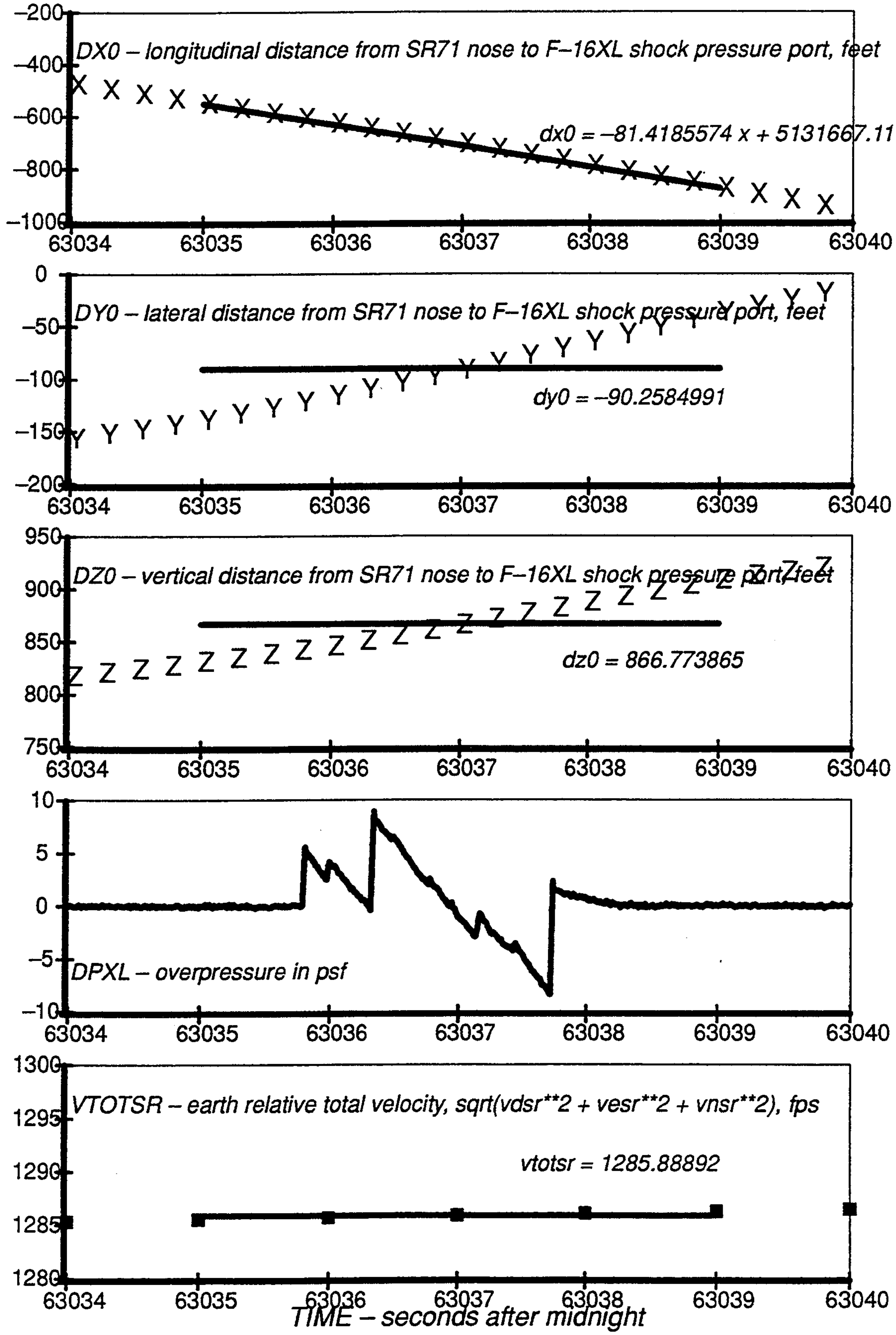


Figure A.3 Measurement Number 3 of SR–71 Flight 24

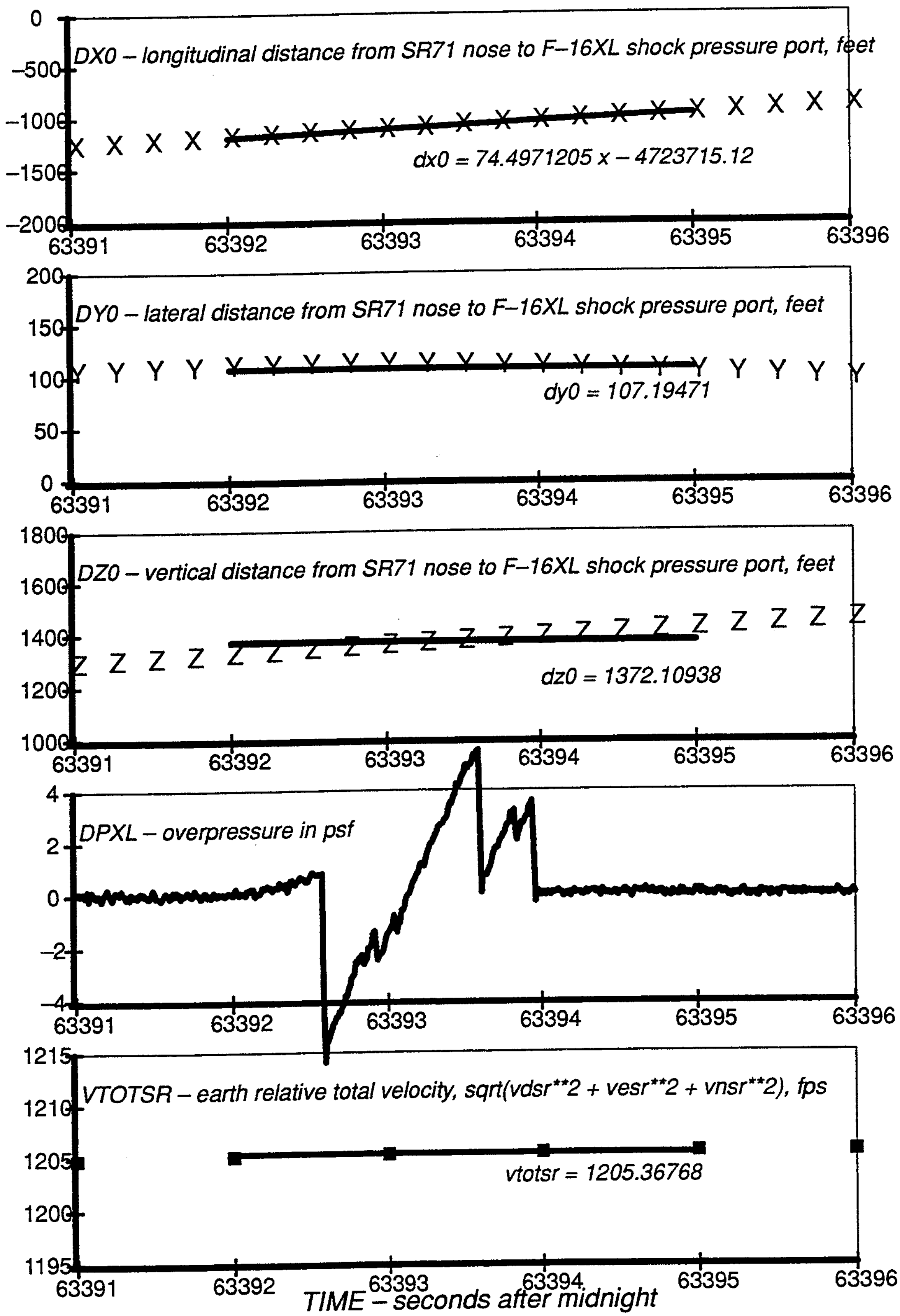


Figure A.4 Measurement Number 4 of SR−71 Flight 24

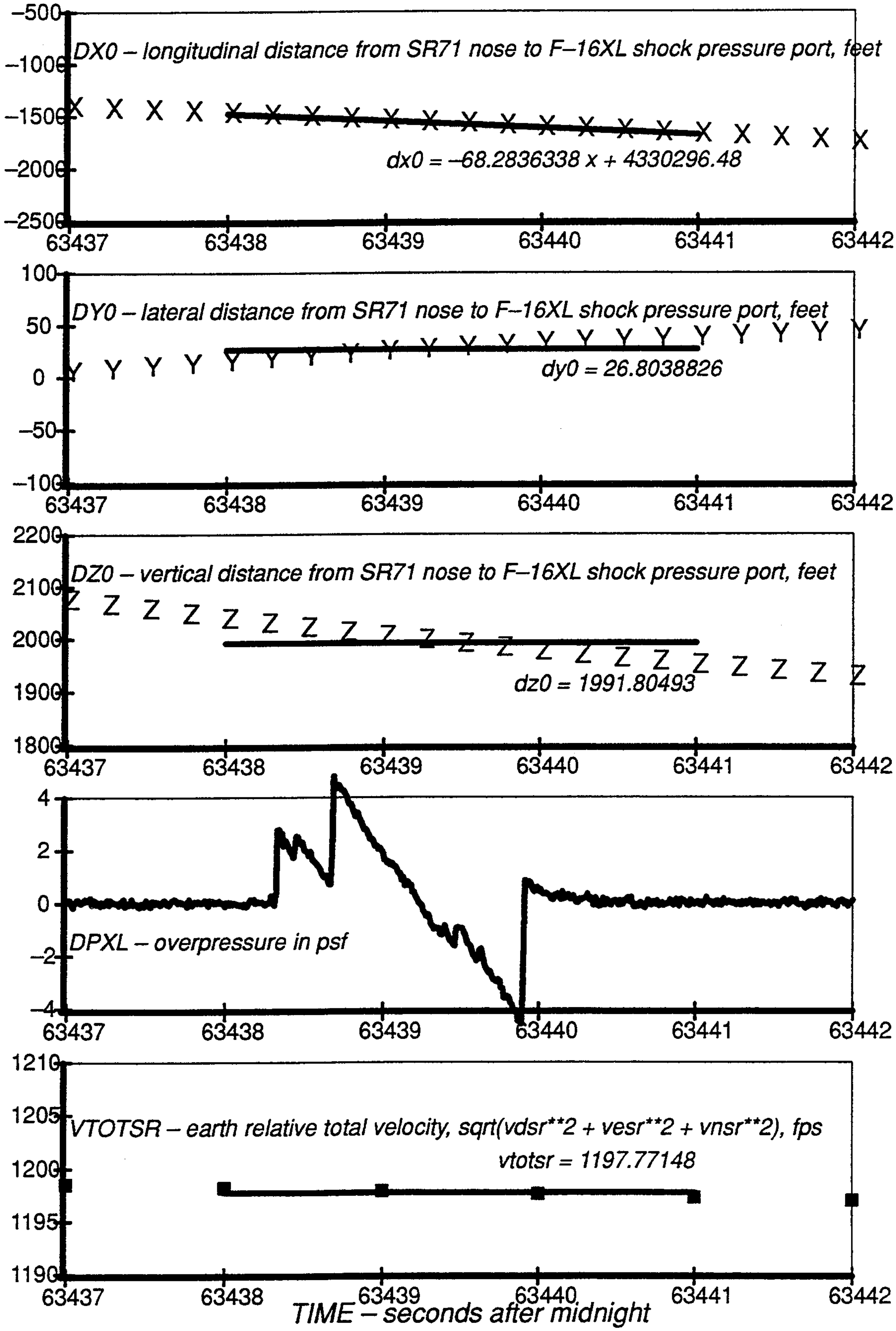


Figure A.5 Measurement Number 5 of SR–71 Flight 24

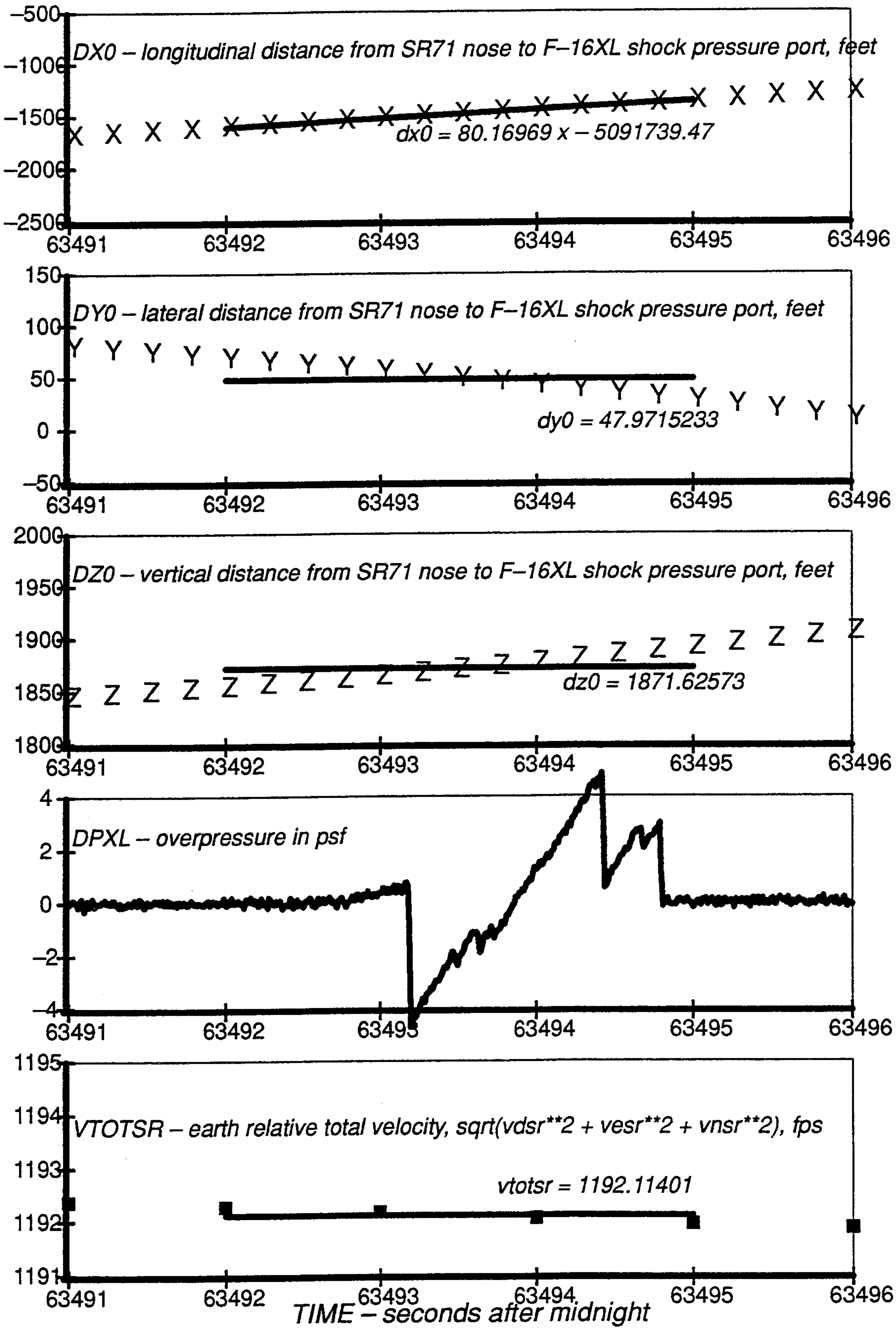


Figure A.6 Measurement Number 6 of SR−71 Flight 24

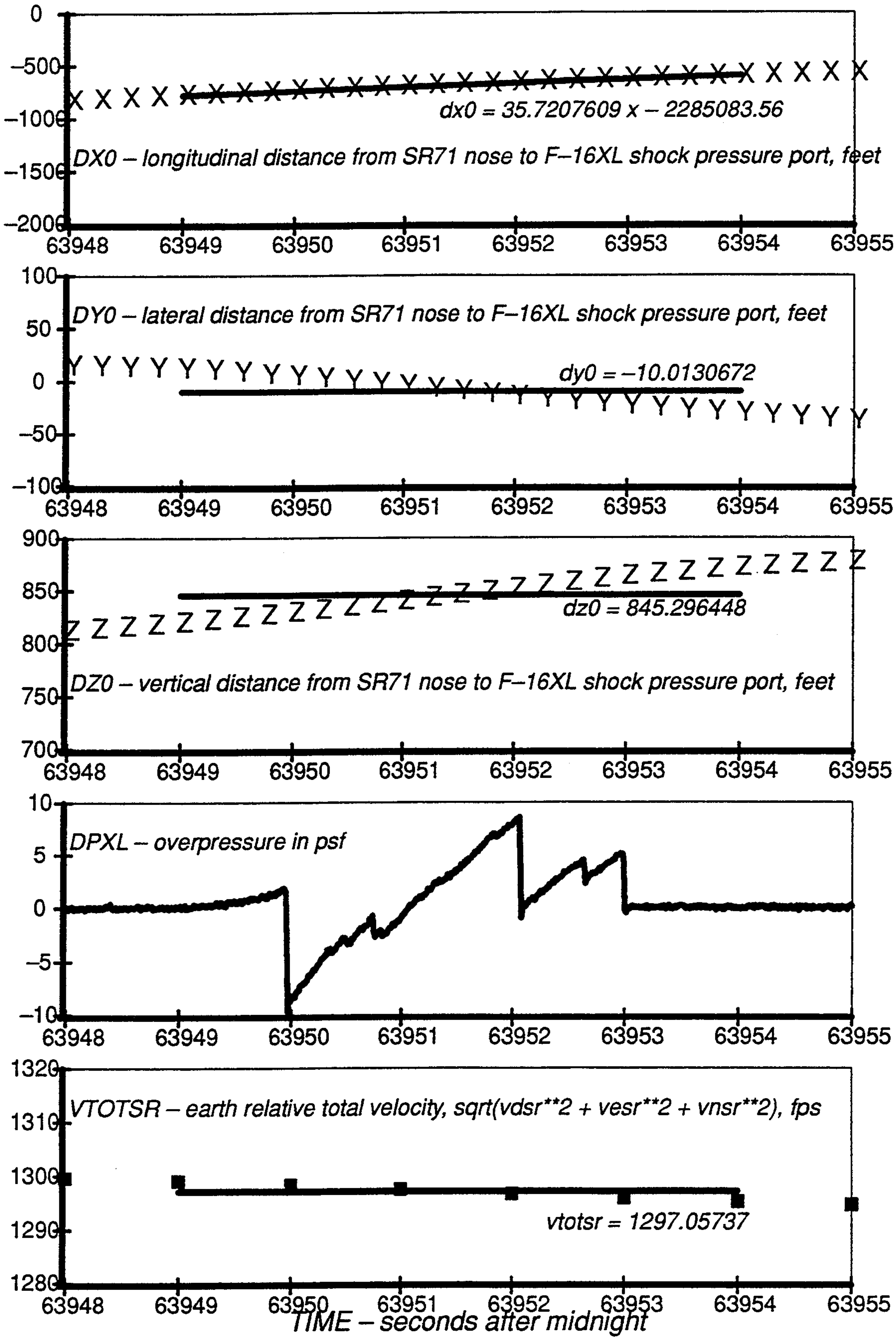


Figure A.7 Measurement Number 7 of SR−71 Flight 24

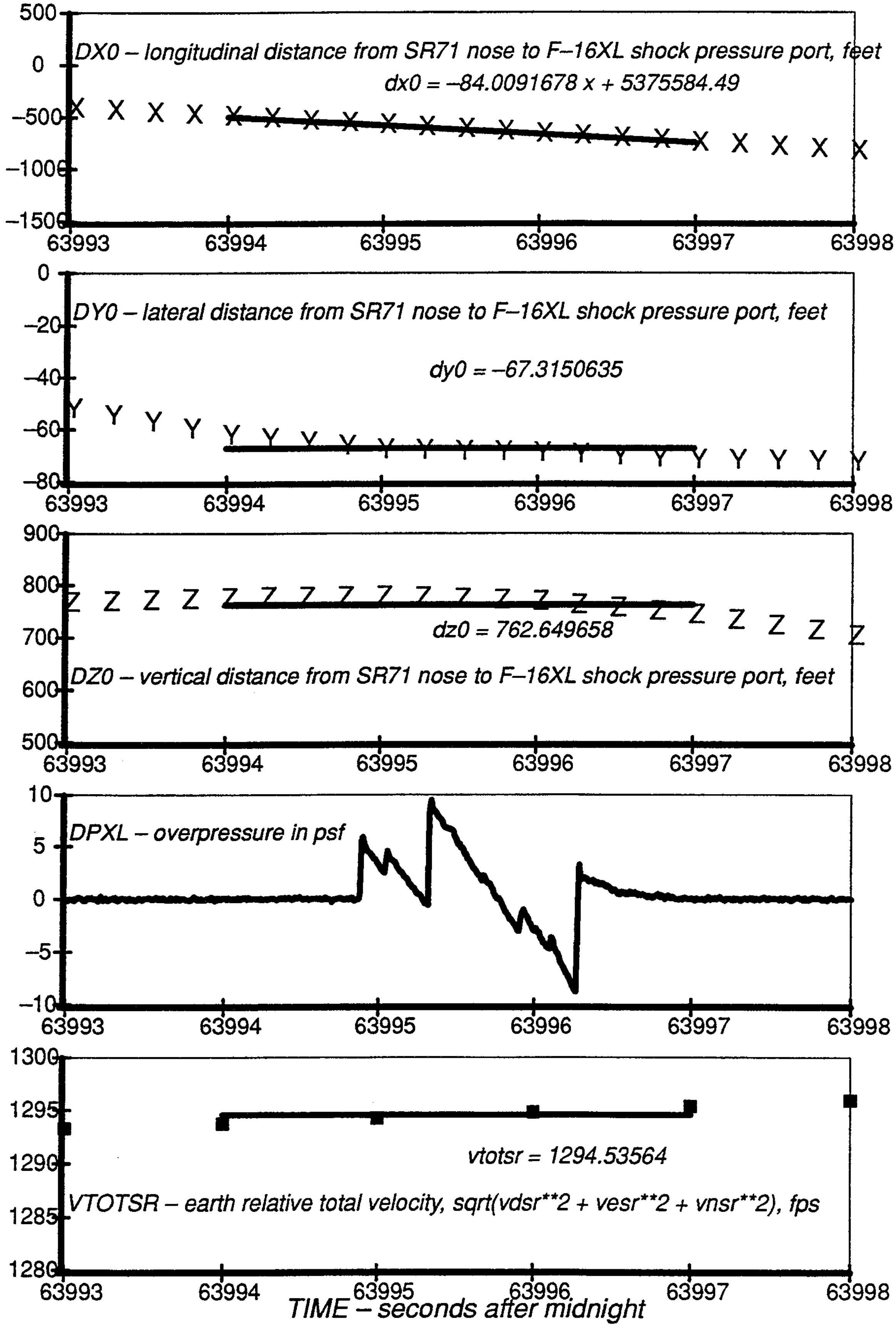


Figure A.8 Measurement Number 8 of SR−71 Flight 24

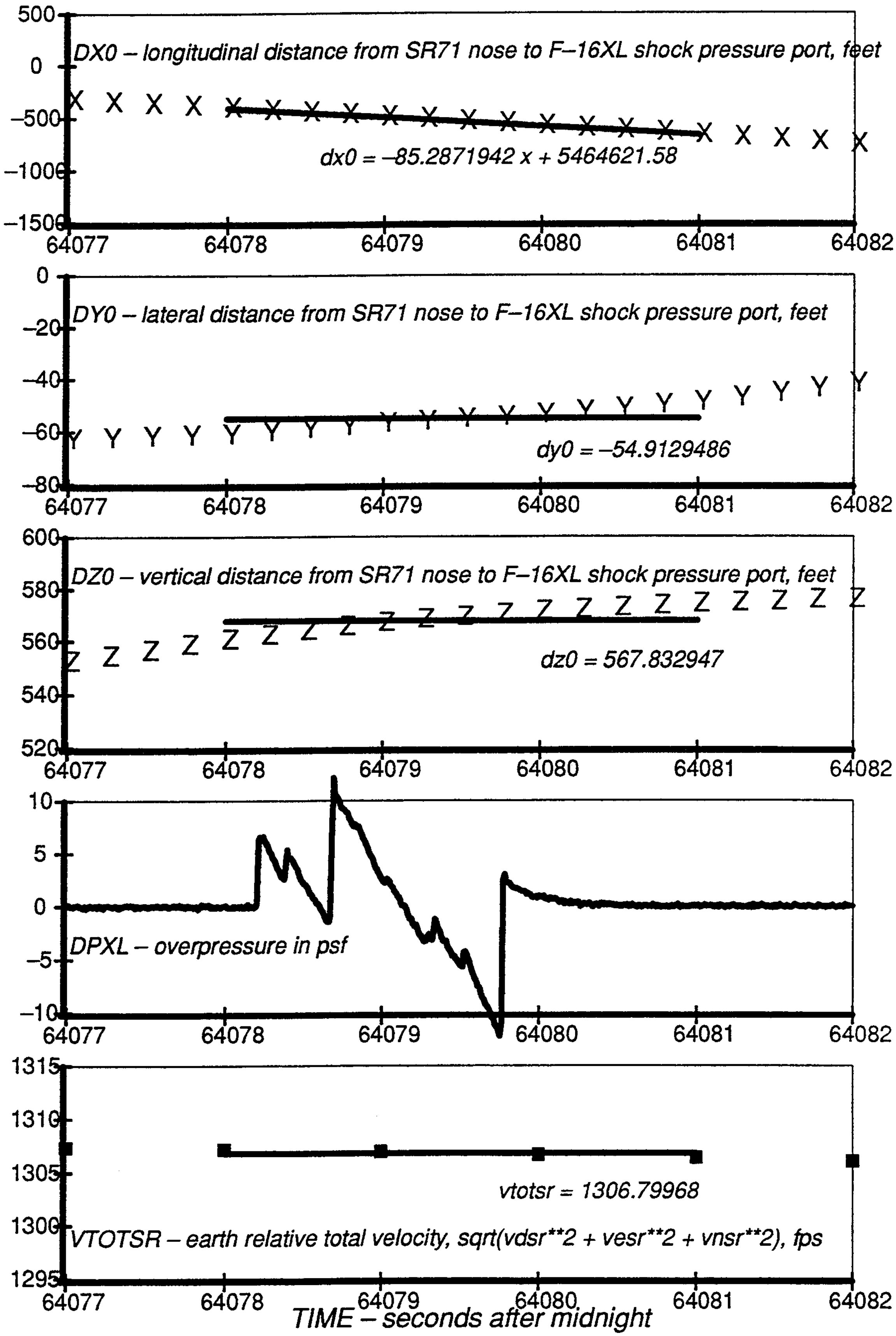


Figure A.9 Measurement Number 10 of SR−71 Flight 24

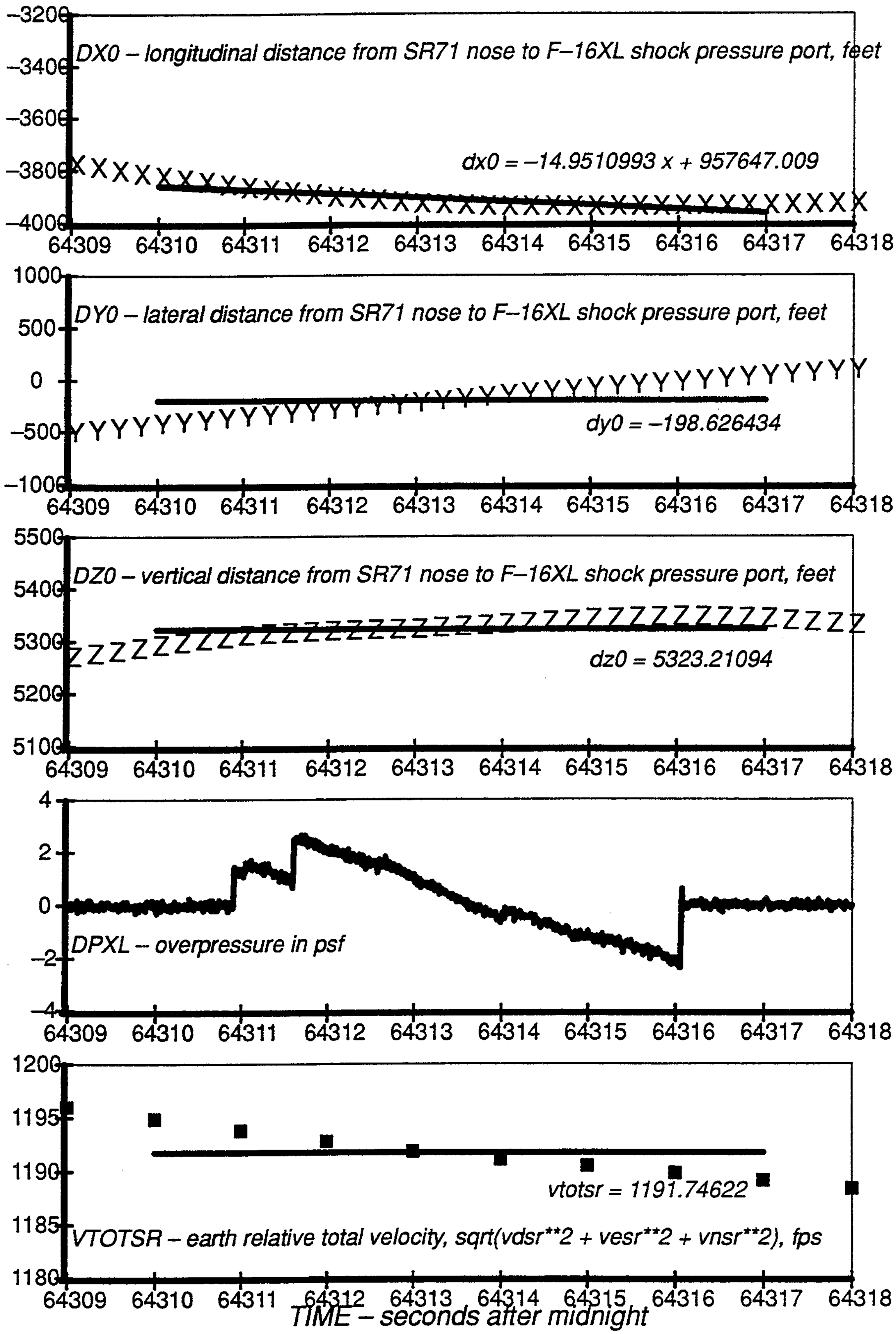


Figure A.10 Measurement Number 11 of SR–71 Flight 24

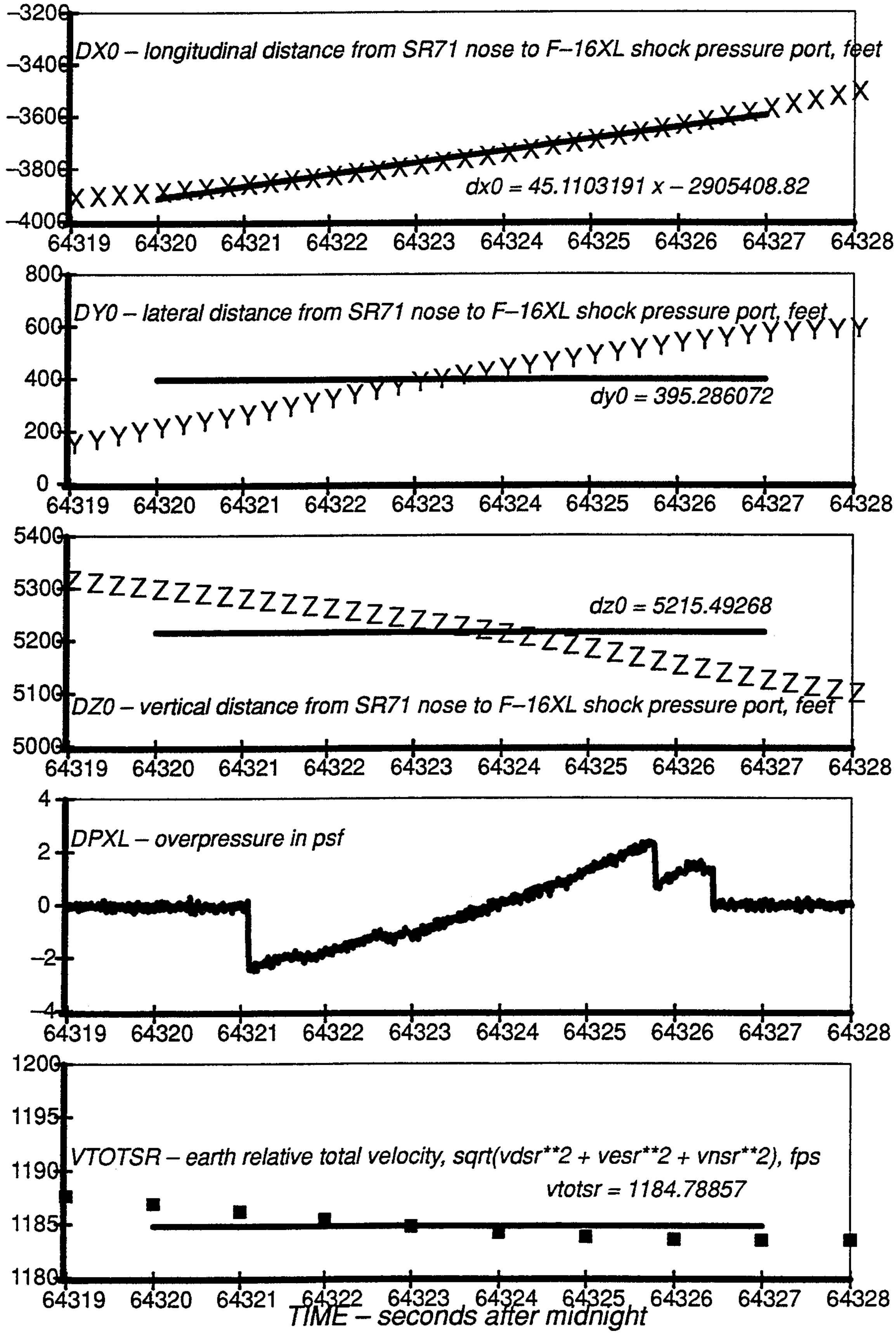


Figure A.11 Measurement Number 14 of SR–71 Flight 24

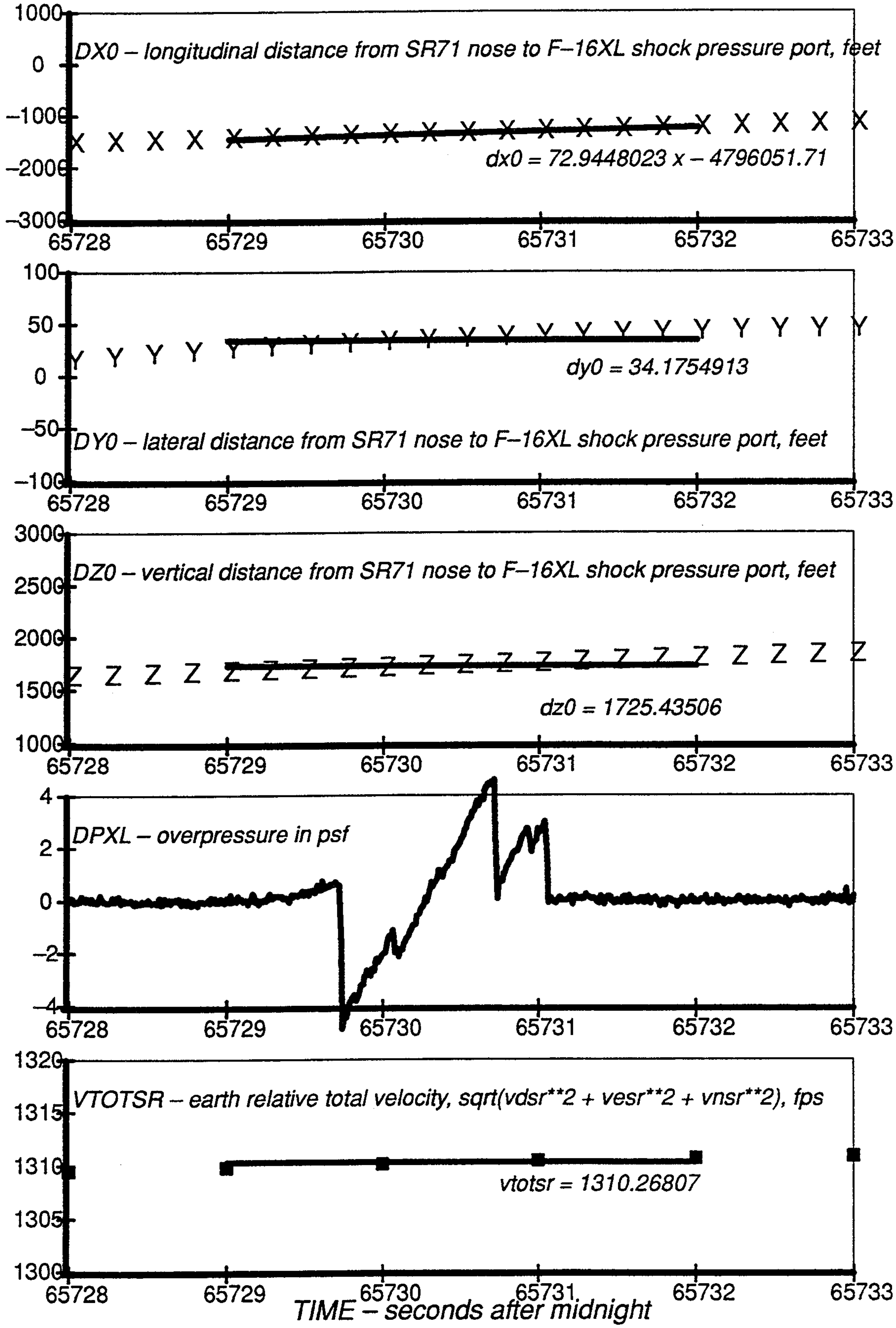


Figure A.12 Measurement Number 15 of SR–71 Flight 24

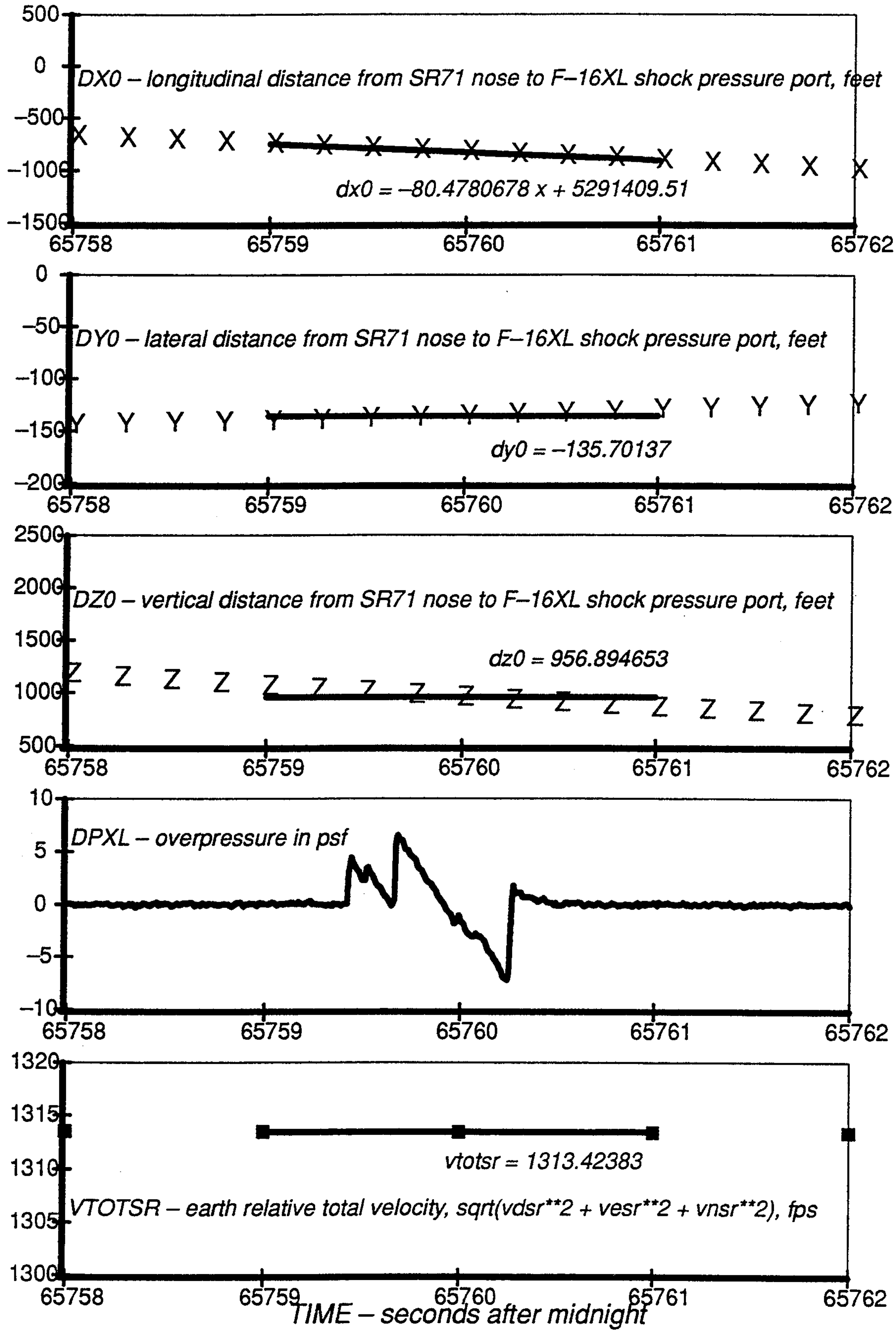


Figure A.13 Measurement Number 16 of SR–71 Flight 24

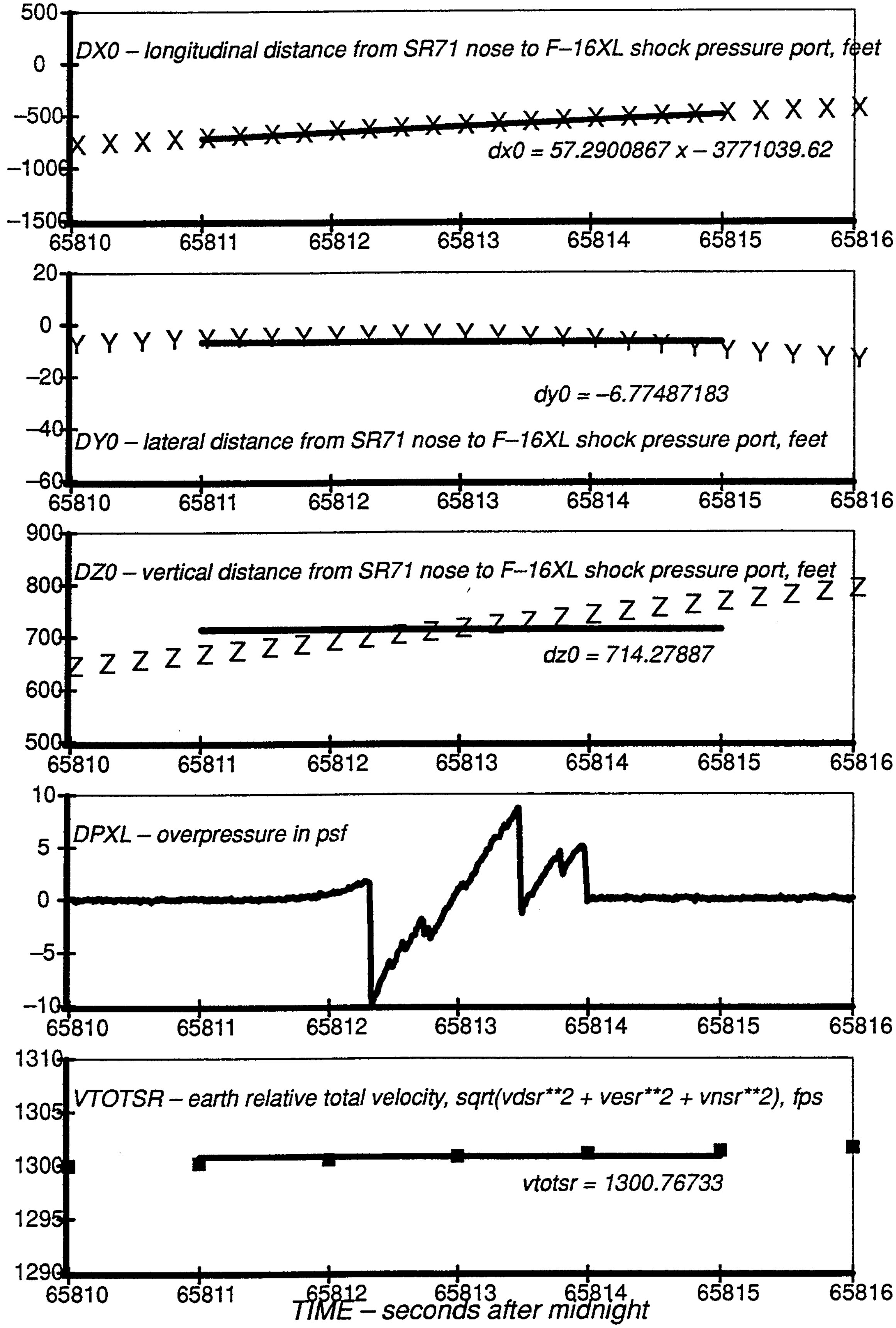


Figure A.14 Measurement Number 17 of SR−71 Flight 24

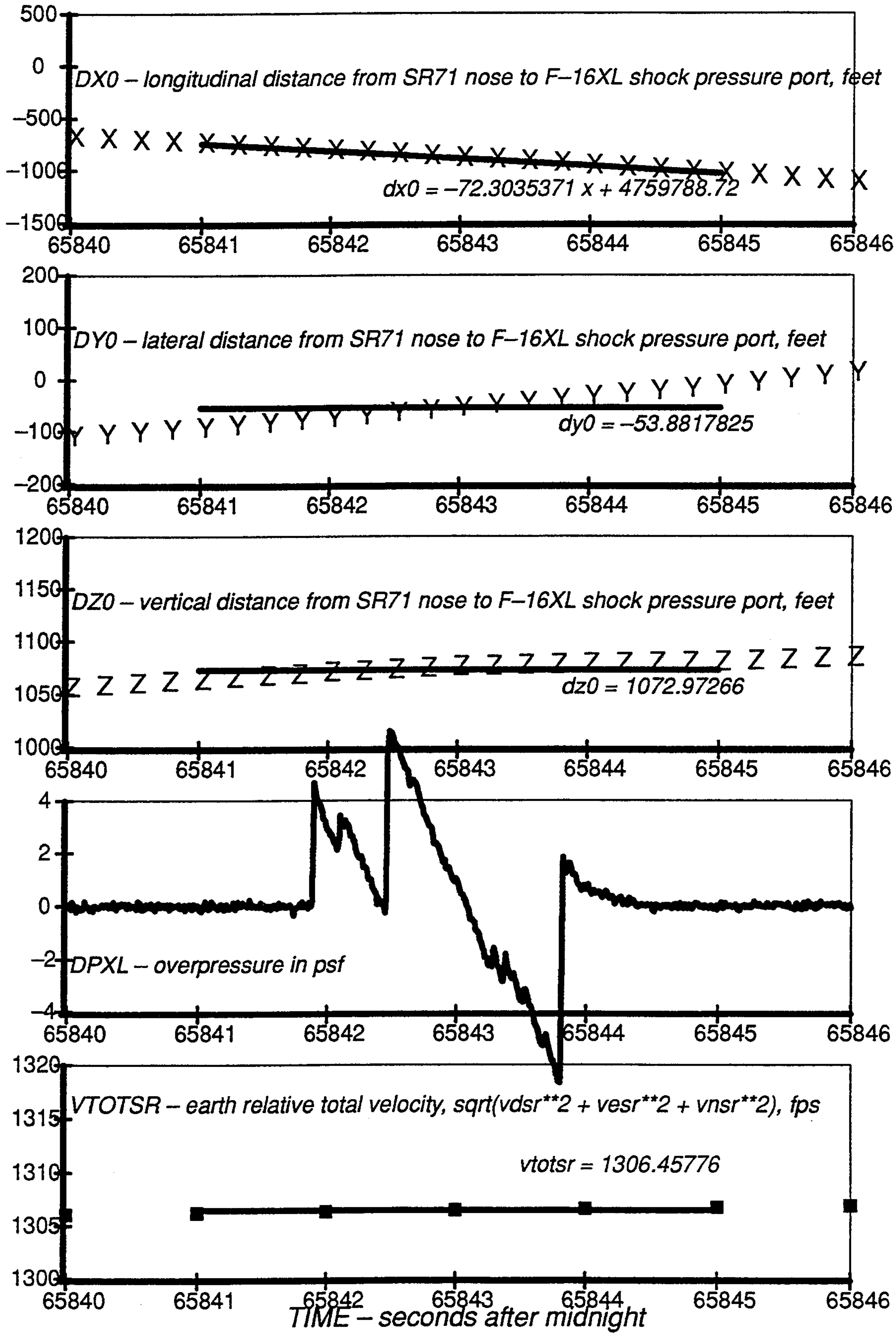
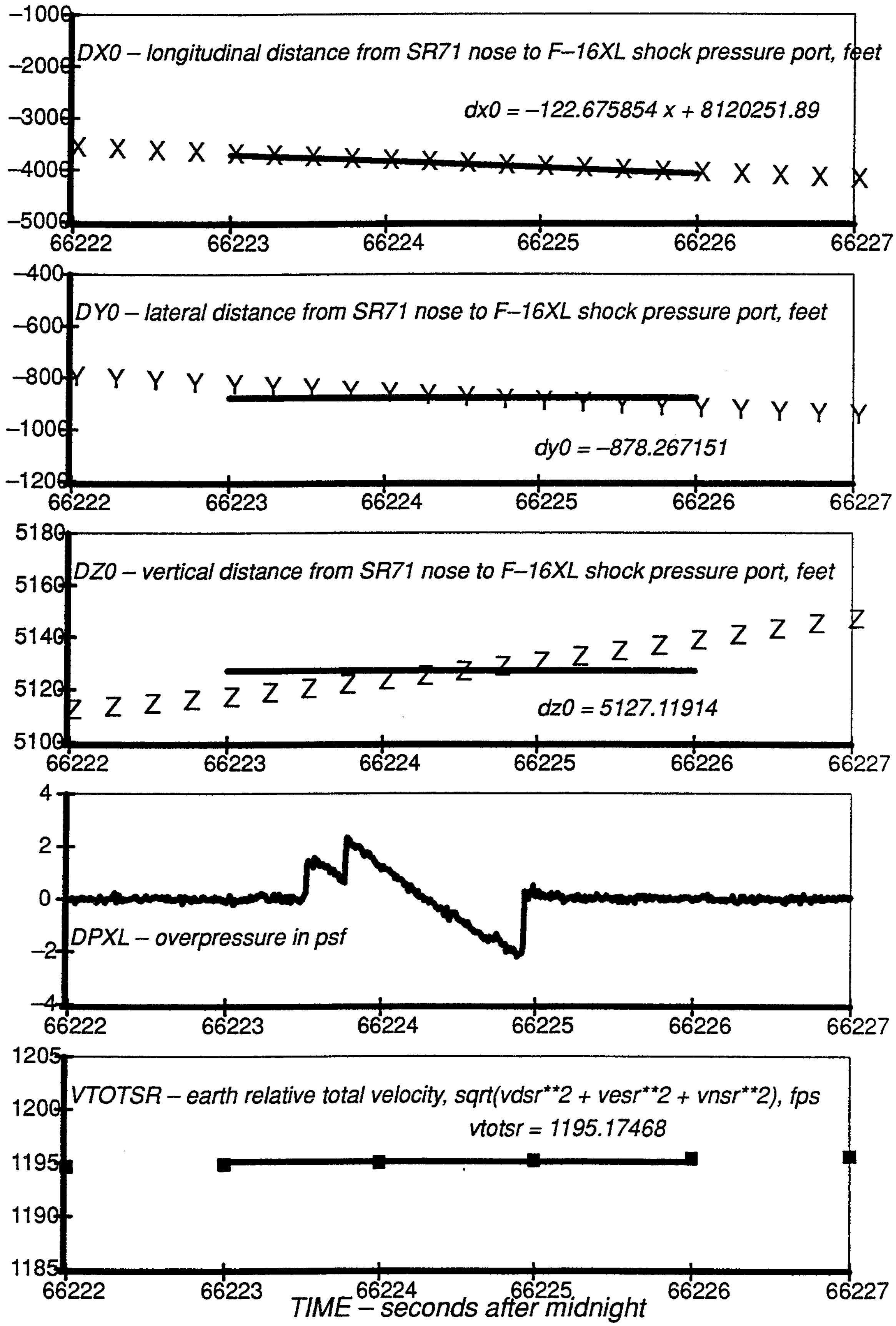


Figure A.15 Measurement Number 19 of SR−71 Flight 24



Appendix B
Signature Time Histories for Extrapolation

To prepare measurements of SR–71 sonic boom pressure and location (relative to the SR–71) for analytic propagation, they need to be converted to pressure versus time at a fixed point in space. If the fixed point is chosen as the start of the signature (local longitudinal distance, dx0=0) at position (local lateral distance, dy0), (local vertical distance, dz0) relative to the the SR–71 nose (the origin of the coordinate system tied to the SR–71) it will be appreciated that if dy0, dz0 and the SR–71 velocity are independent of time, a longitudinal point at dx will arrive at the fixed point after the time interval:

(incremental time of arrival, dt) = (longitudinal distance, dx) / [–(SR–71 speed)]

where the negative sign is required because of direction of flight of the SR–71 in the earth–based frame of reference.

With the assumptions of dy0, dz0 and SR–71 velocity constant and dx0 a linear function of measurement time, the above equation was solved for the nine signatures used for propagation. The plots in this appendix show these pressure signatures.

#	Mach	Wave Duration sec	Average PHI angle degrees	(SR–71) Source Altitude feet	Vertical Distance (dz0) feet	Signature Altitude feet
1	1.237	0.2	–1.6	31141	757	30384
3	1.262	0.2	4.4	30961	1372	29589
6	1.252	0.2	–1.6	31165	845	30320
10	1.249	0.1	–1.6	30993	5323	25667
11	1.244	0.3	4.4	31011	5215	25796
15	1.265	0.1	–8.9	31128	957	30171
16	1.254	0.1	–1.6	31142	714	30428
17	1.261	0.2	–1.6	31181	1073	30108
19	1.262	0.3	–8.9	31127	5127	26000

Figure B.1 Time History for Measurement Number 1 of SR–71 Flight 24

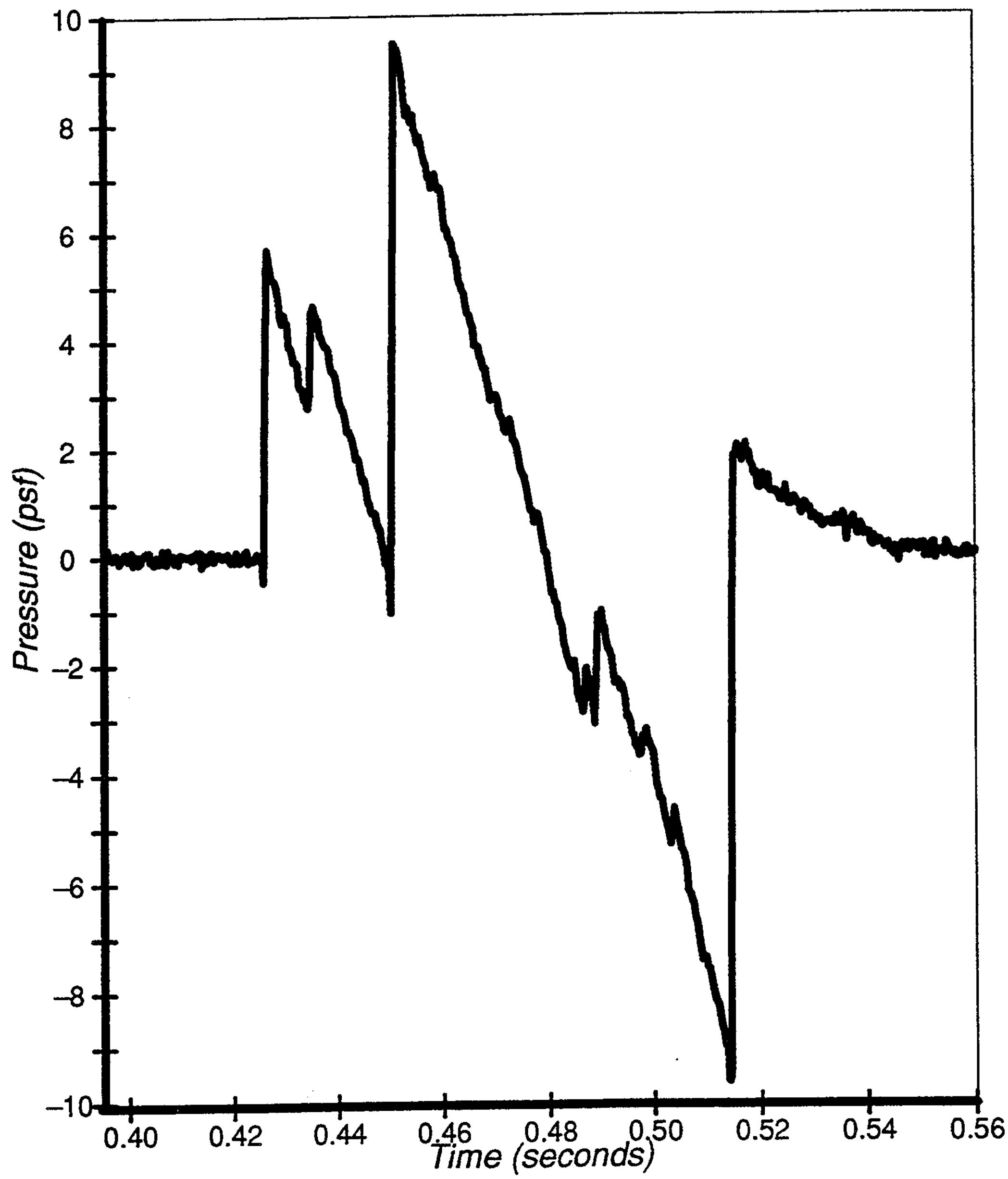


Figure B.2 Time History for Measurement Number 3 of SR−71 Flight 24

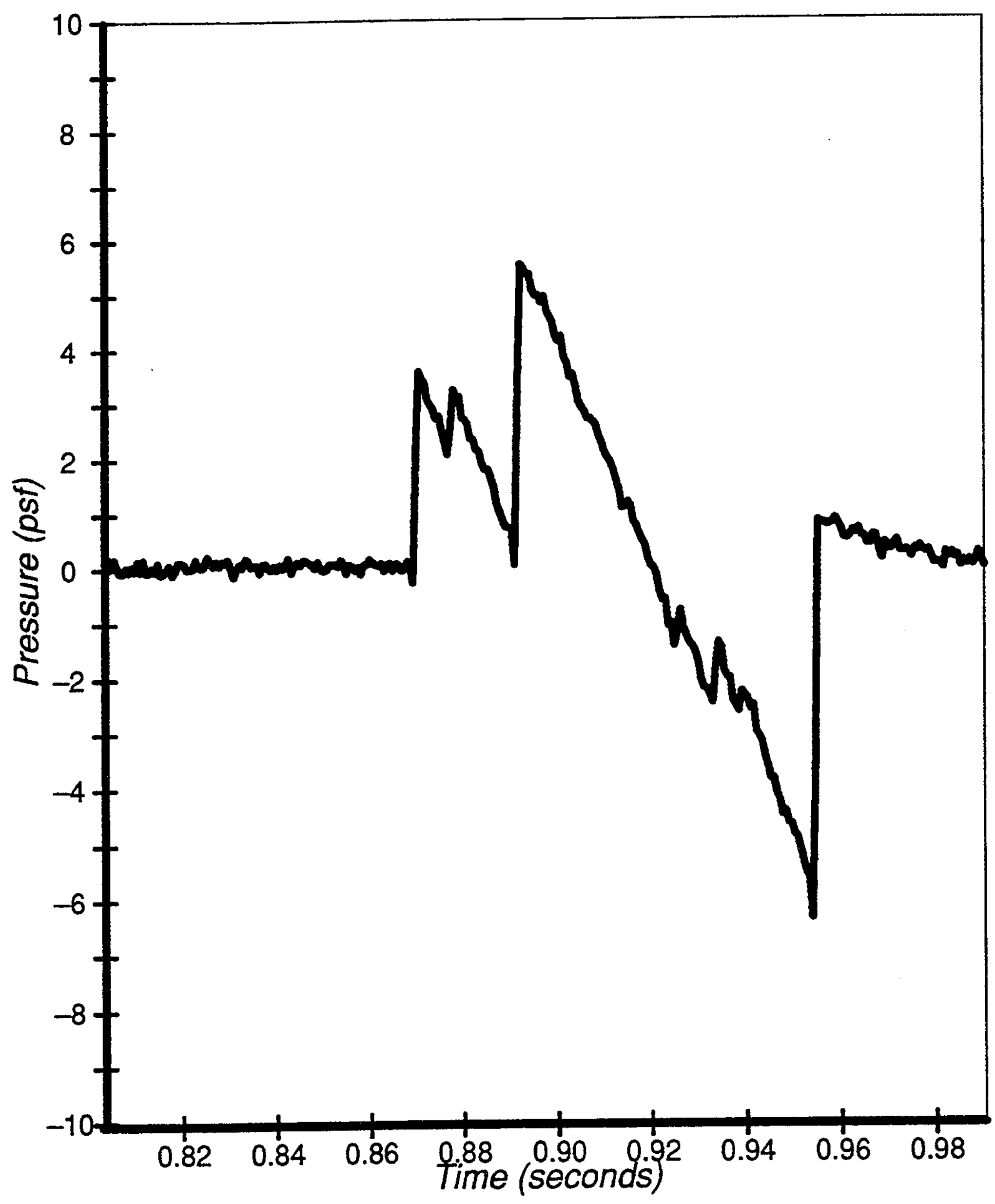


Figure B.3 Time History for Measurement Number 6 of SR−71 Flight 24

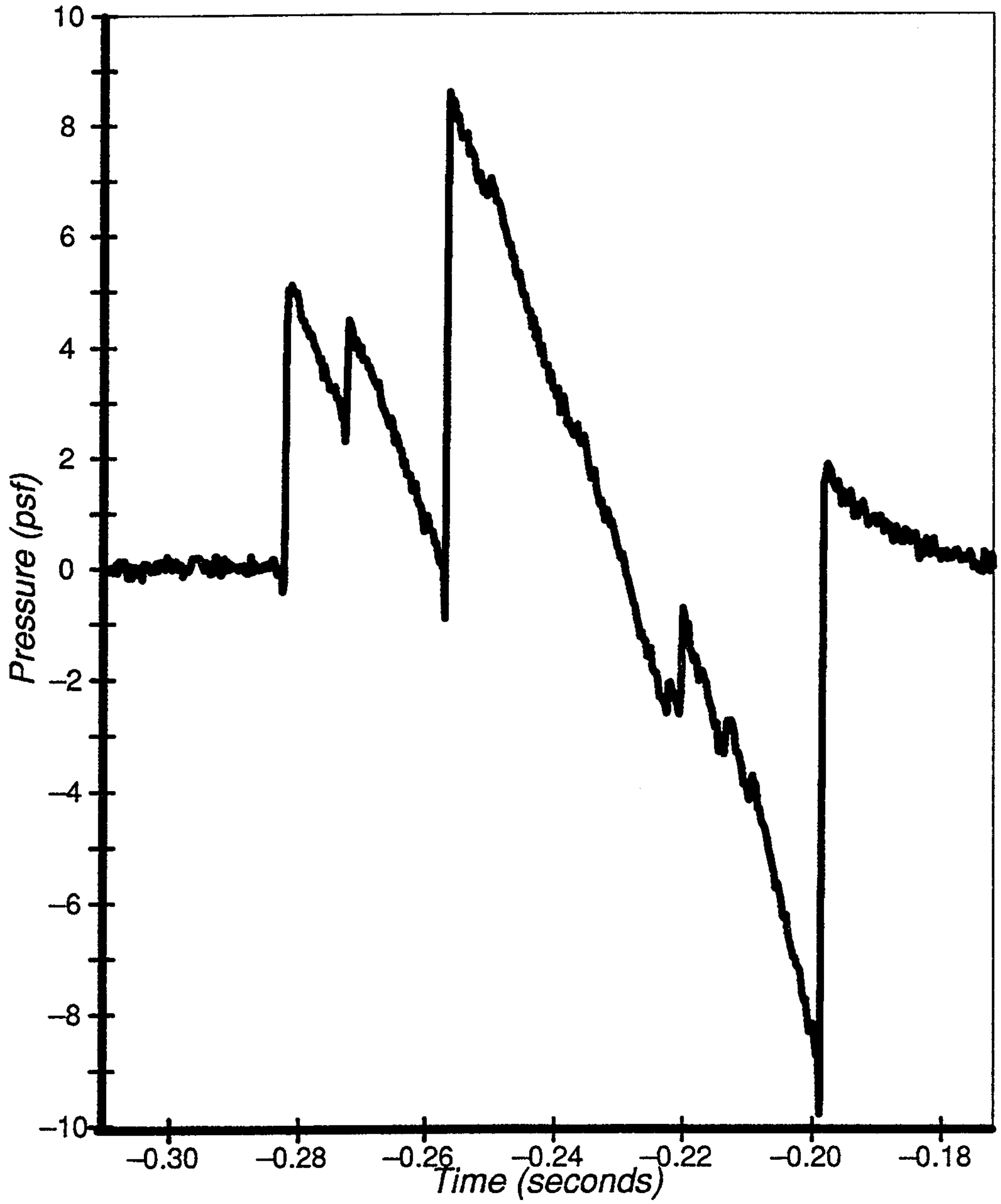


Figure B.4 Time History for Measurement #10 of SR−71 Flight 24

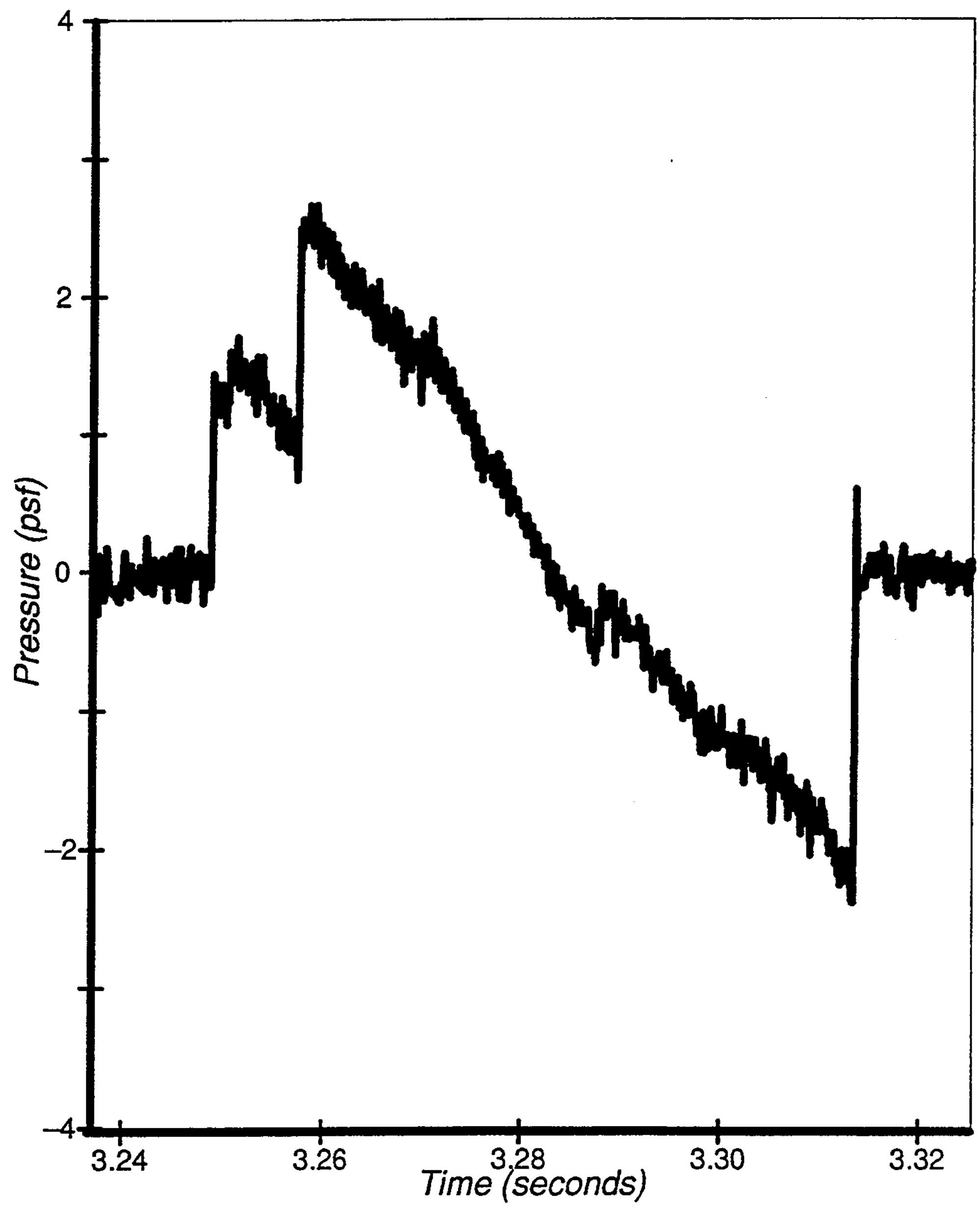


Figure B.5 Time History for Measurement #11 of SR−71 Flight 24

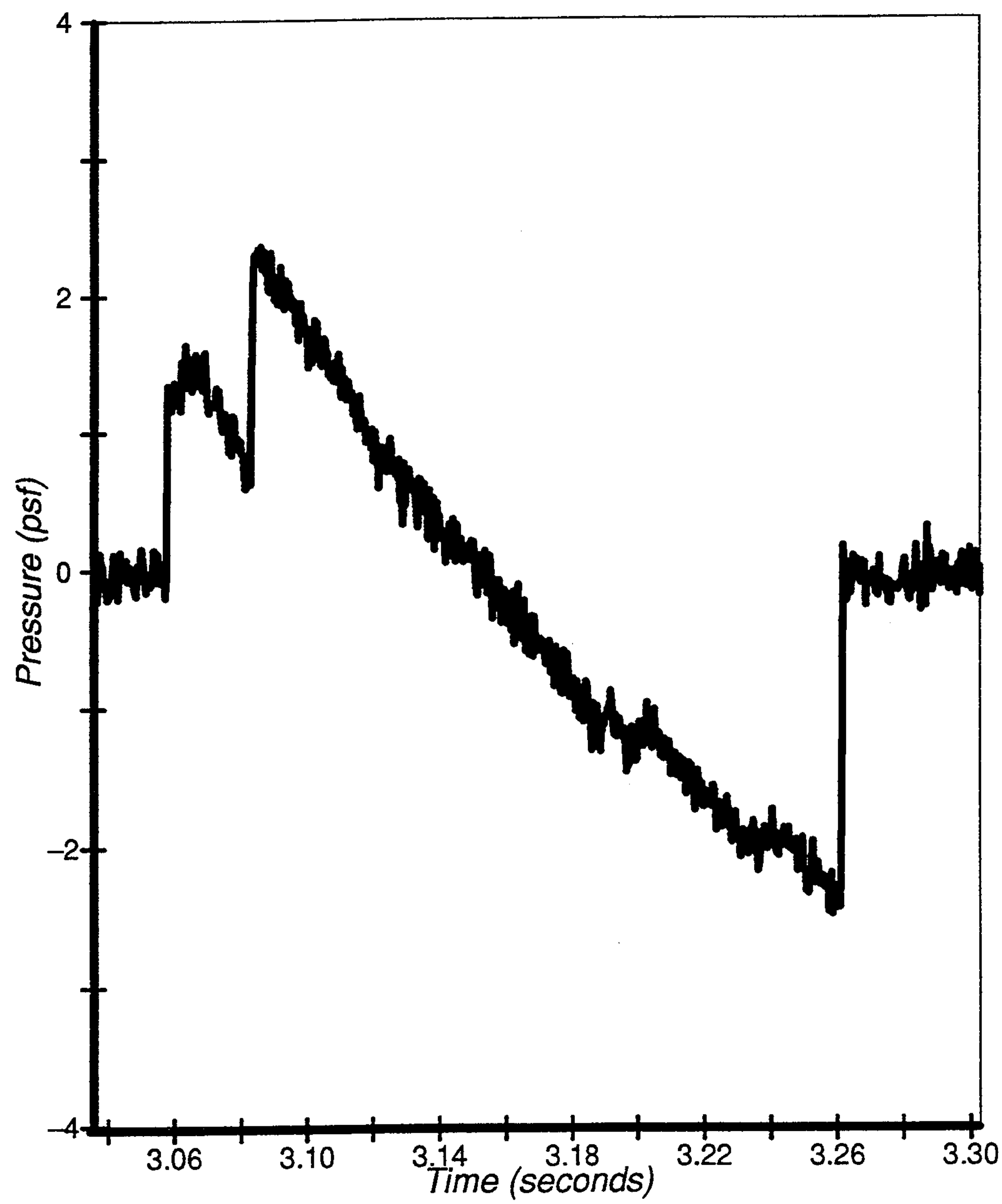


Figure B.6 Time History for Measurement #15 of SR−71 Flight 24

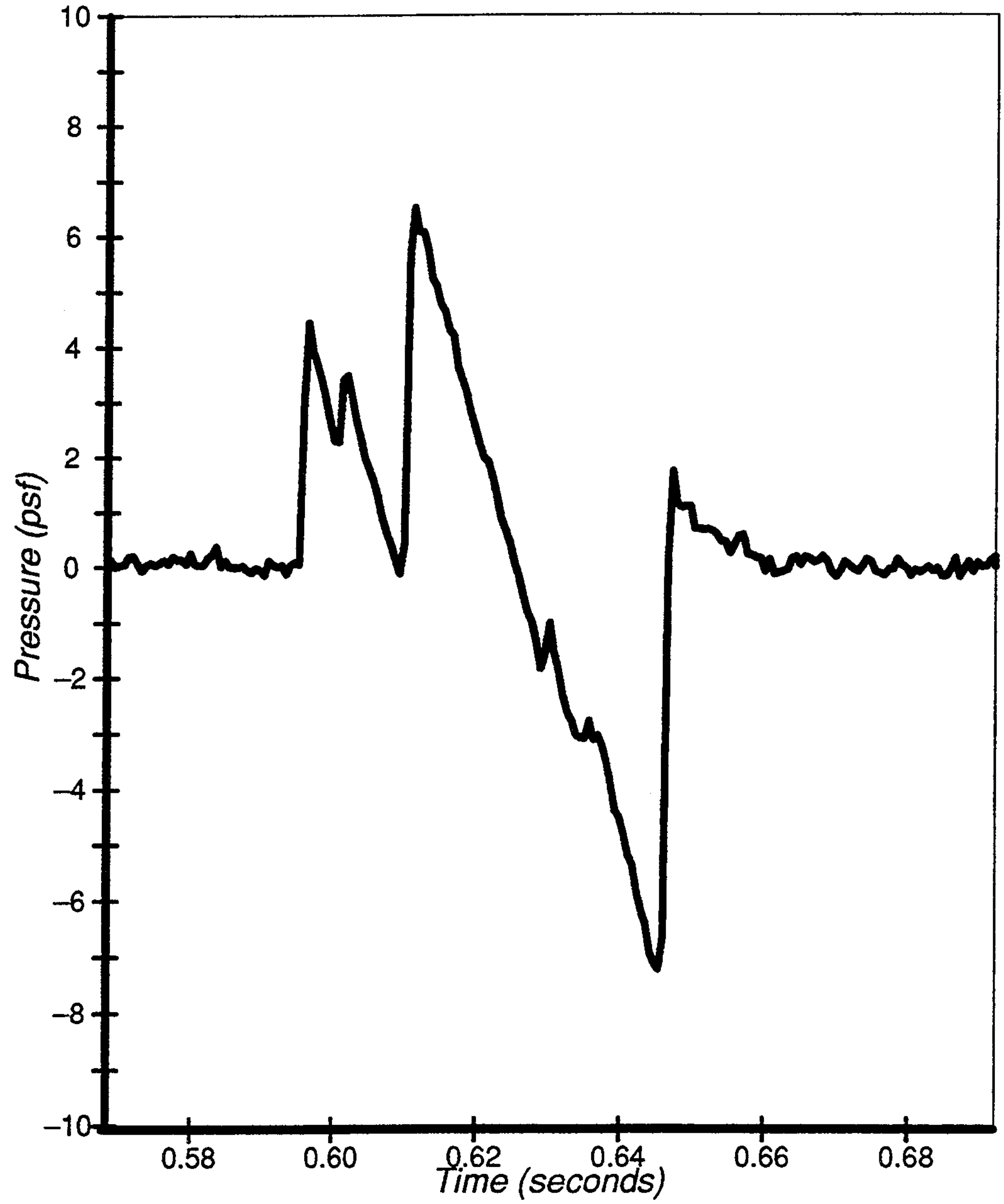


Figure B.7 Time History for Measurement #16 of SR−71 Flight 24

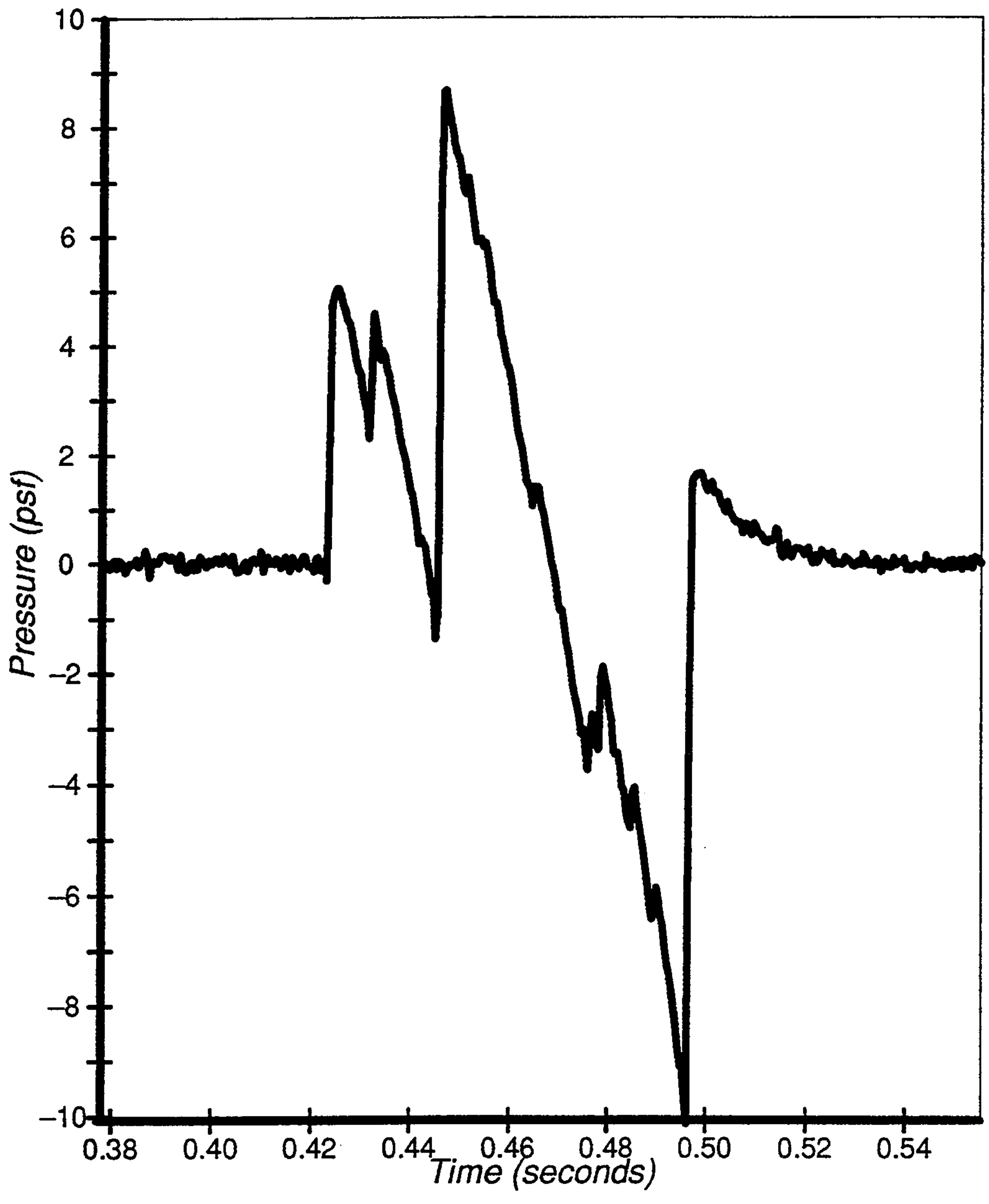


Figure B.8 Time History for Measurement #17 of SR−71 Flight 24

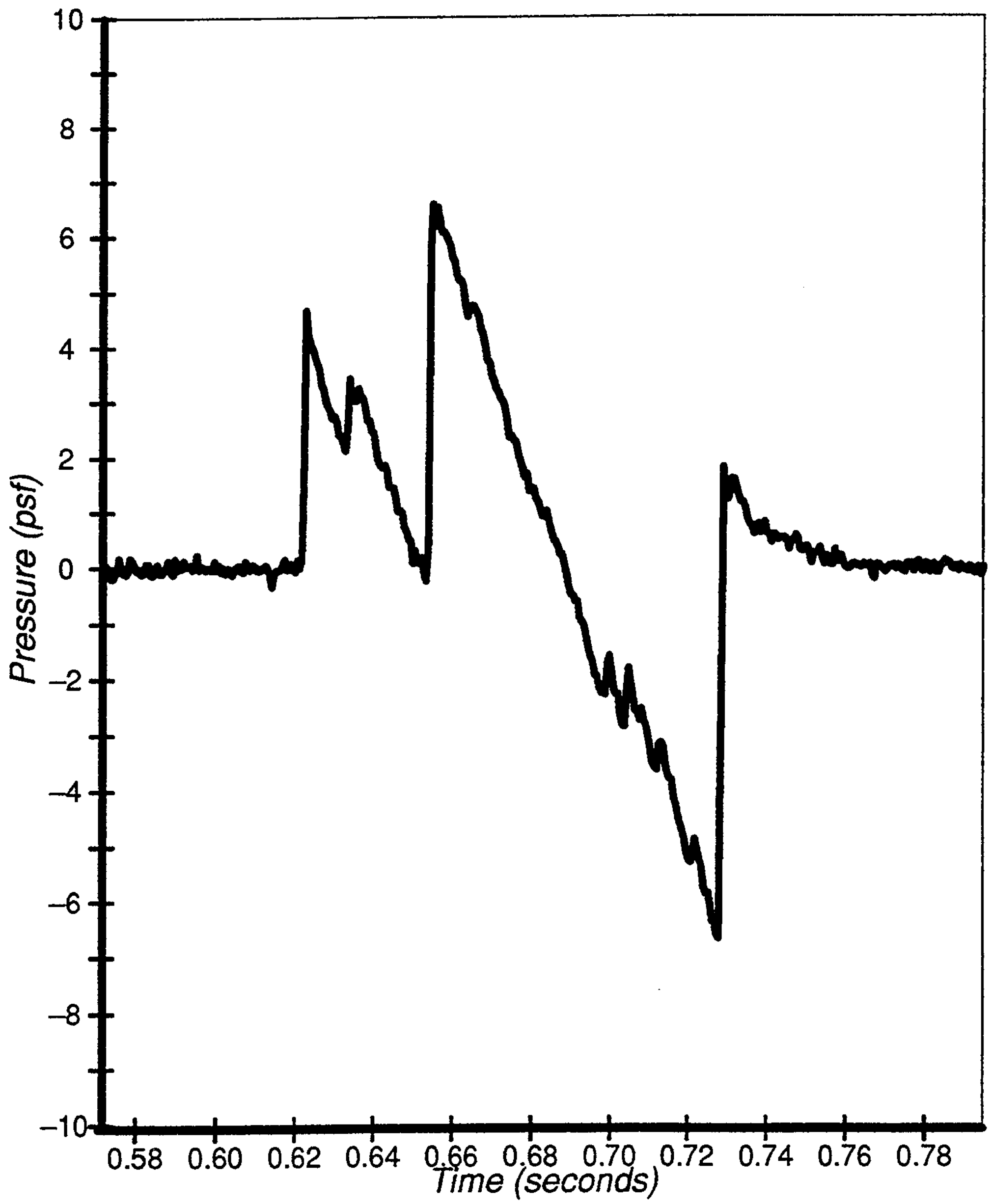
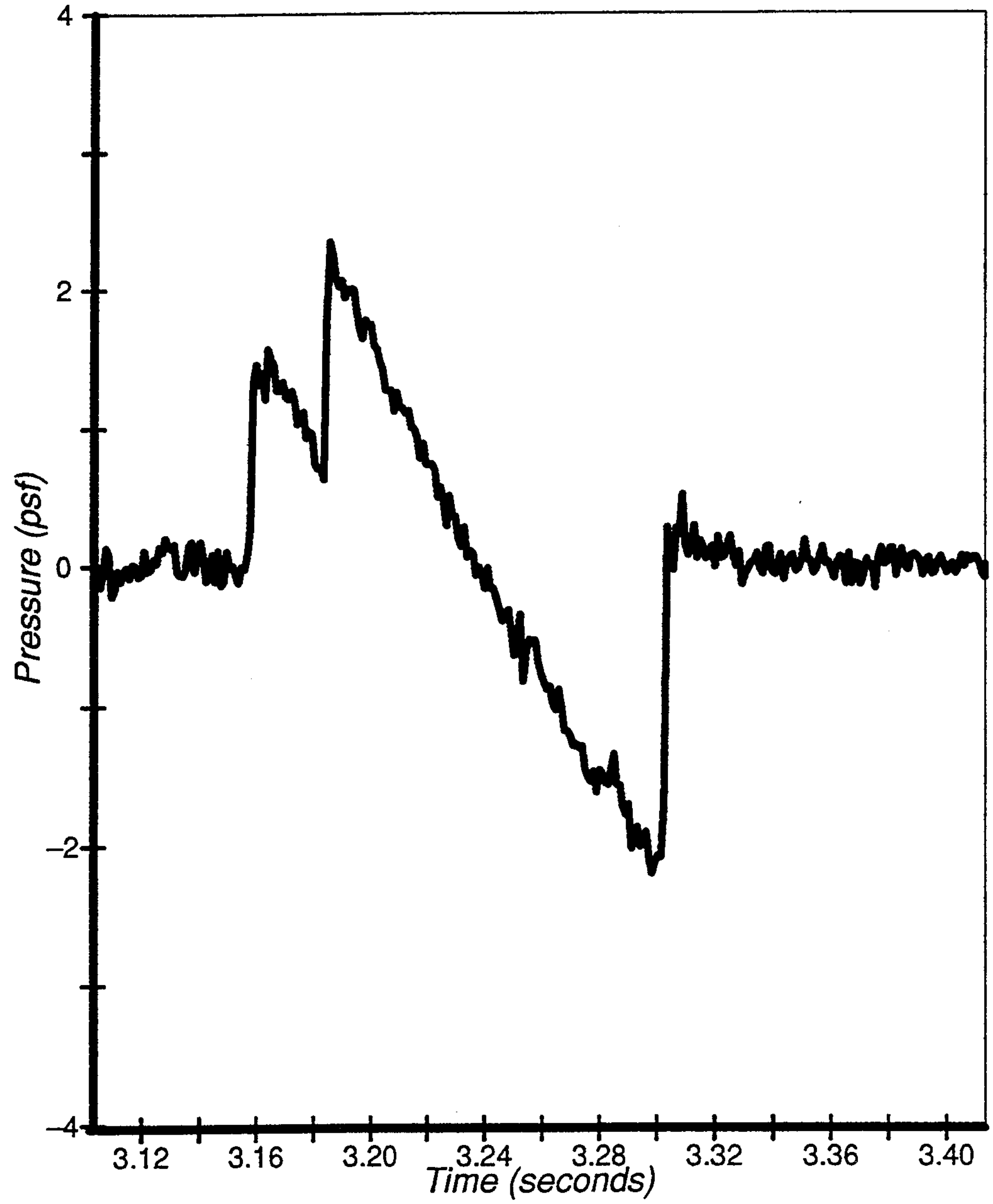


Figure B.9 Time History for Measurement #19 of SR−71 Flight 24



Appendix C
Waveform Evolution

For the six examples of "near" waveforms propagated to "far" distances, the original waveform is compared to the resulting far waveform after propagation. Pressures have been reduced by a factor of two to three, duration has increased slightly and most of the "fuzz" in the measurement has been smoothed out by non–linear steepening effects. The significant shocks from bow, canopy, and inlets are still evident in the propagated waves, however.

Figure C.1 Extrapolation of Measurement Number 1 of SR−71 Flight 24

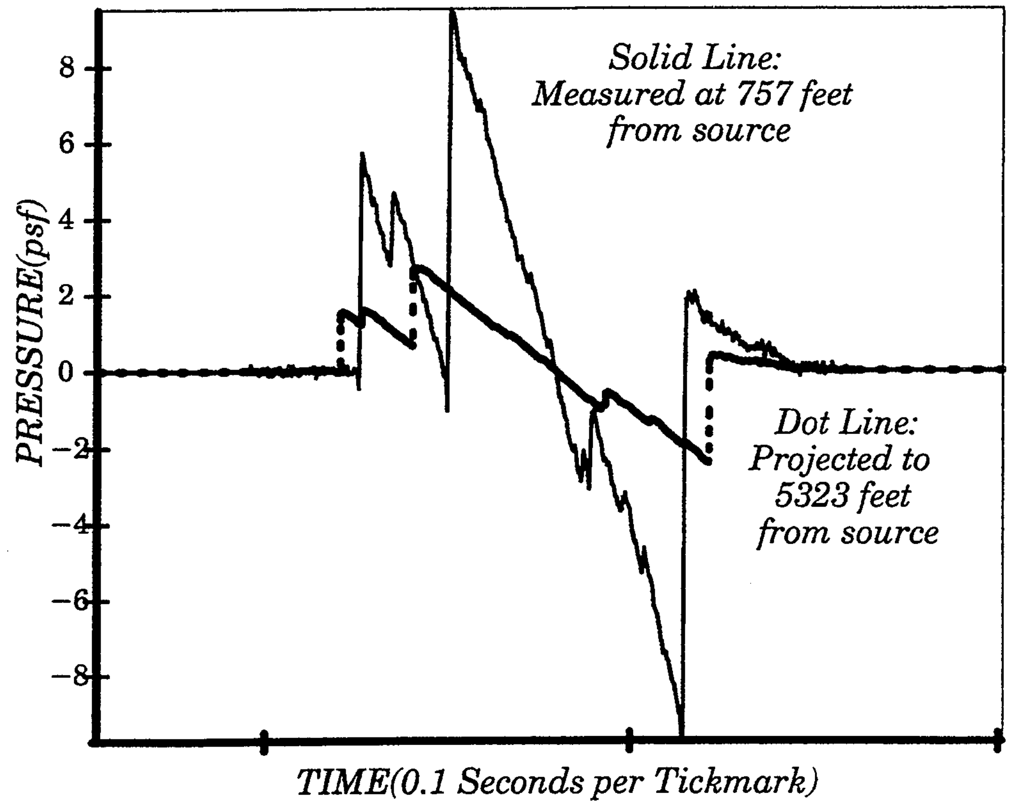


Figure C.2 Extrapolation of Measurement Number 3 of SR−71 Flight 24

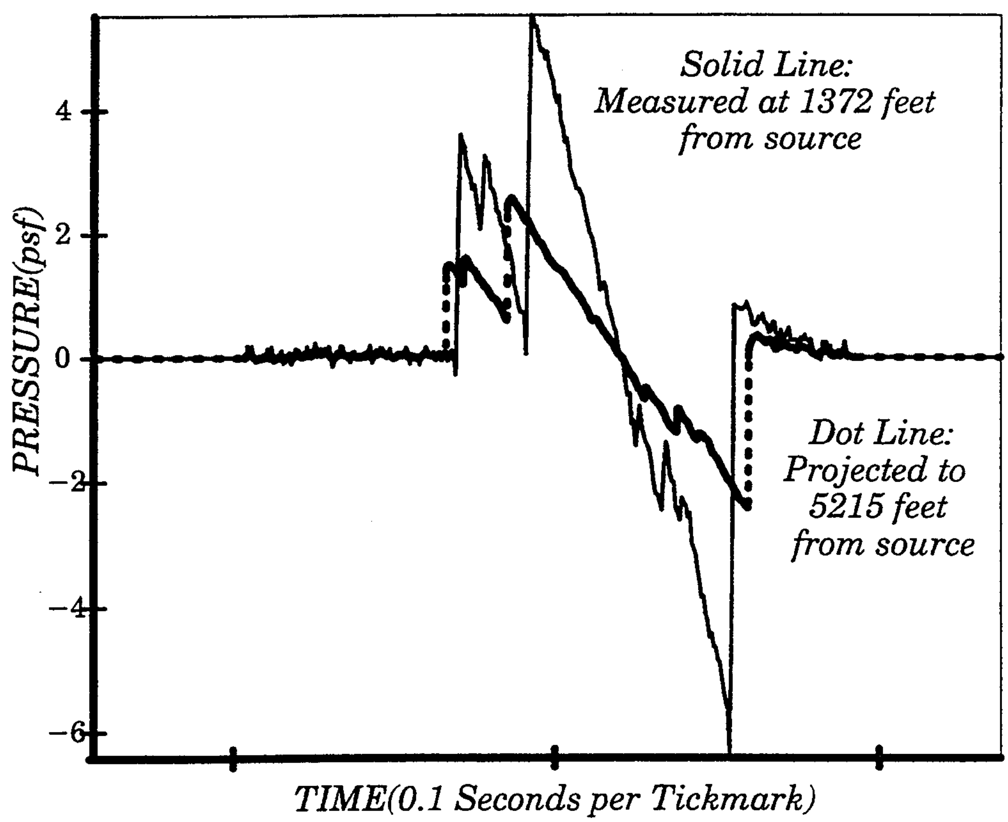


Figure C.3 Extrapolation of Measurement Number 6 of SR–71 Flight 24

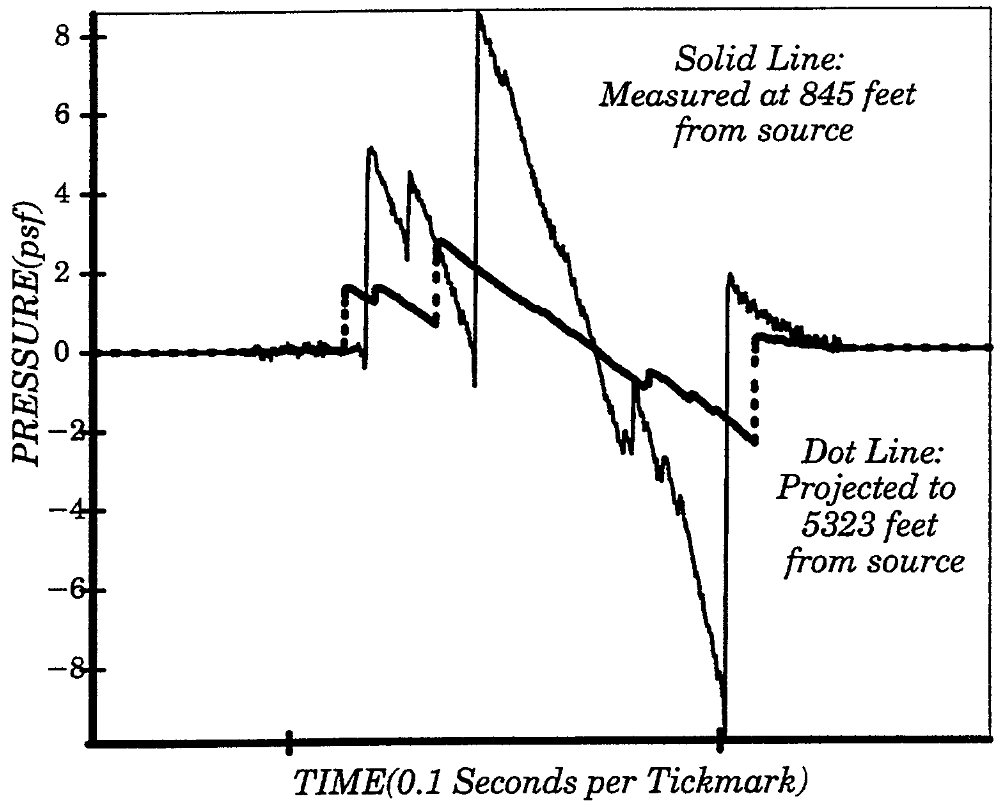


Figure C.4 Extrapolation of Measurement Number 15 of SR–71 Flight24

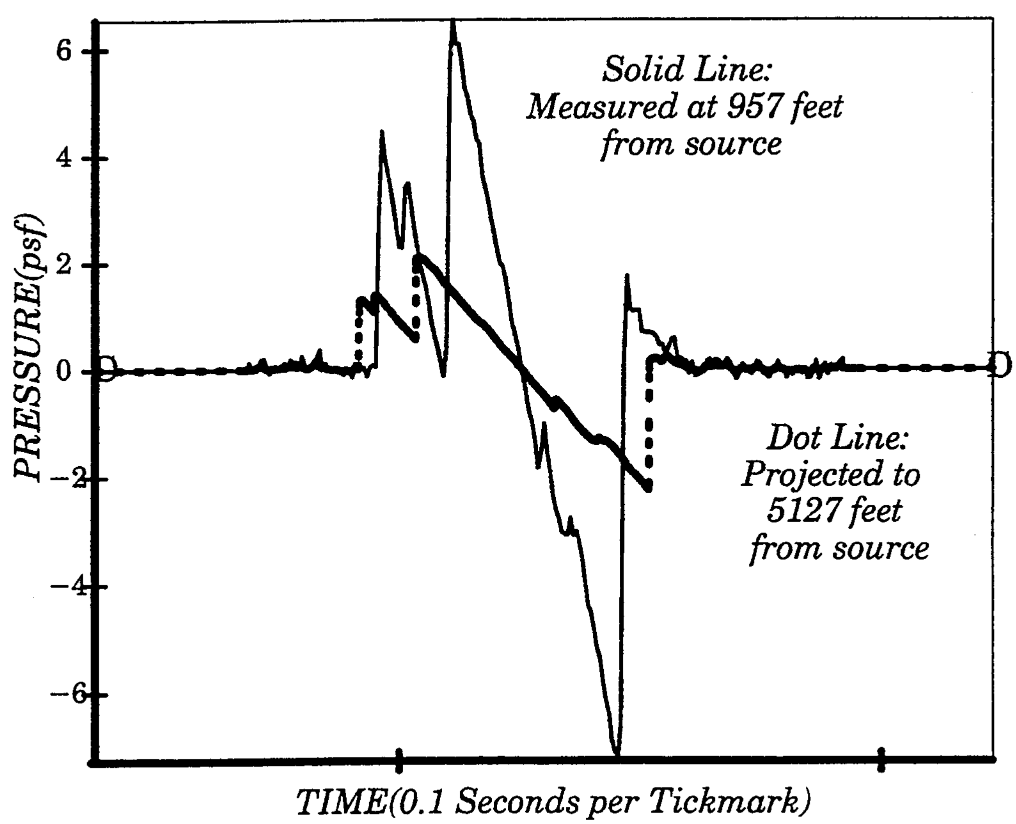


Figure C.5 Extrapolation of Measurement Number 16 of SR−71 Flight24

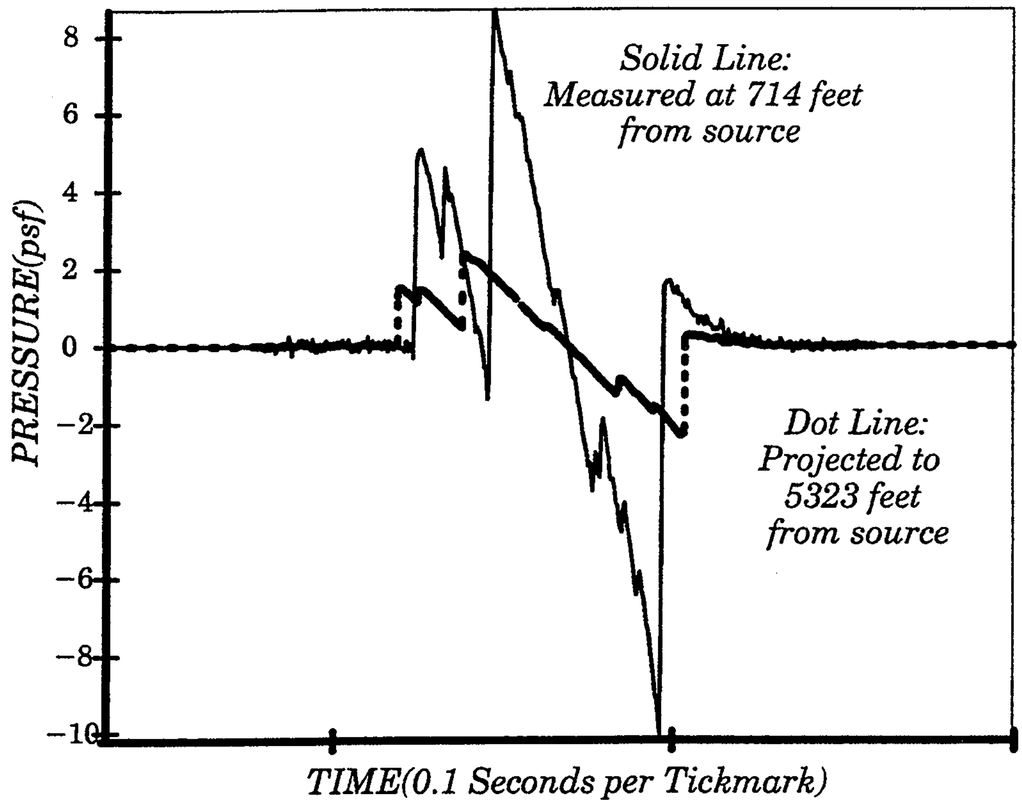
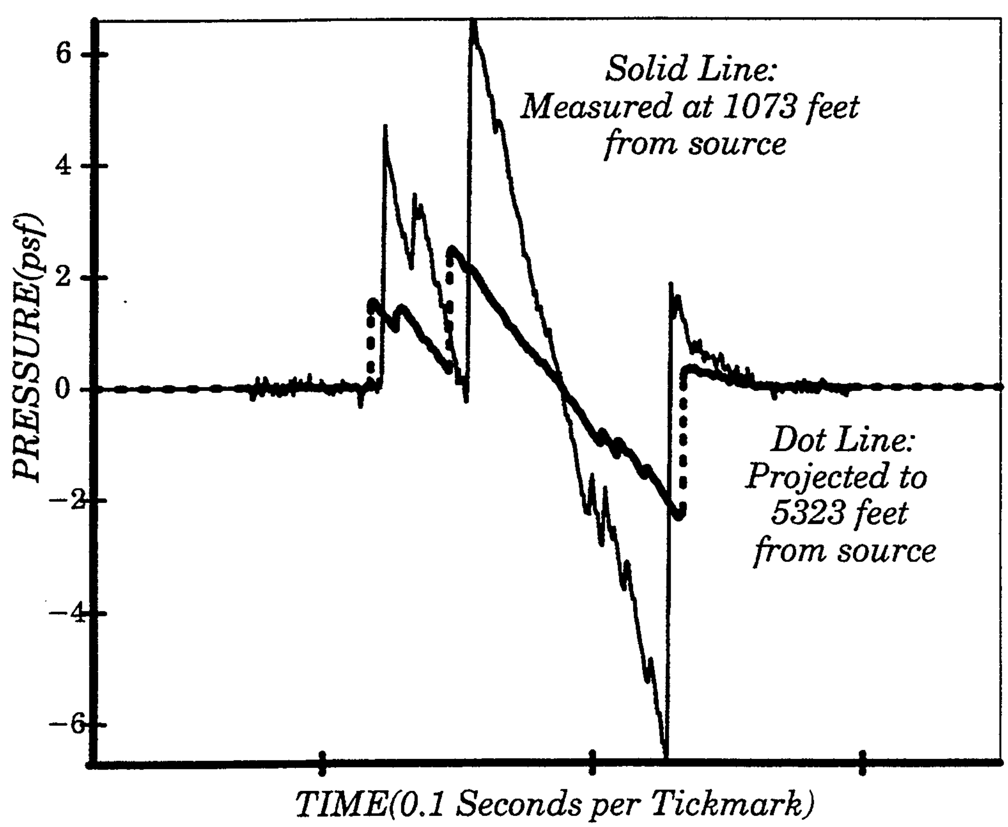
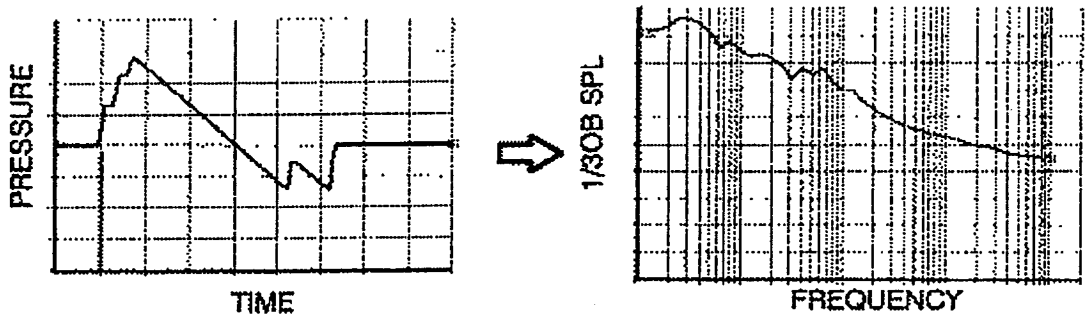


Figure C.6 Extrapolation of Measurement Number 17 of SR−71 Flight24

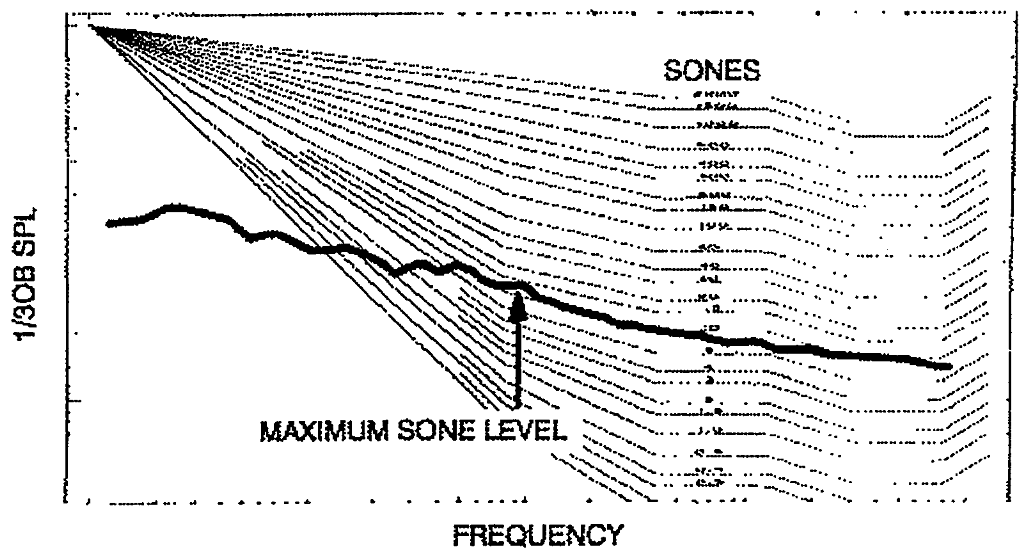


Appendix D
Calculation of Percieved Level

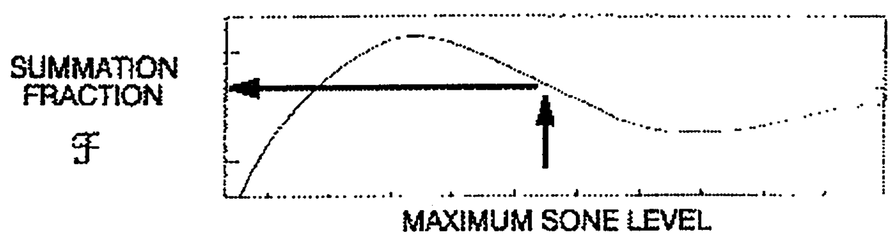
CALCULATE 1/3OB SPECTRUM FROM GIVEN PRESSURE SIGNATURE



CONVERT BAND PRESSURE LEVELS TO SONES (PERCEIVED MAGNITUDE)



FLAG MAXIMUM SONE LEVEL AND READ SUMMATION FRACTION FUNCTION AT THIS VAL
TO ACCOUNT FOR MASKING OF SPECTRUM BY LOUDEST BAND



CALCULATE TOTAL LOUDNESS IN SONES AND CONVERT TO PL IN DECIBELS

$$S_{TOTAL} = S_{MAX} + \mathfrak{F}\left(\sum S_i - S_{MAX} \right) \quad \Rightarrow \quad PL = 32 + 9 \log_2(S_{TOTAL})$$

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13. ABSTRACT *(Maximum 200 words)*

The sonic boom propagation codes reviewed in this study, SHOCKN and ZEPHYRUS, implement current theory on air absorption using different computational concepts. Review of the codes with a realistic atmosphere model confirm the agreement of propagation results reported by others for idealized propagation conditions. ZEPHYRUS offers greater flexibility in propagation conditions and is thus preferred for practical aircraft analysis.

The ZEPHYRUS code was used to propagate sonic boom waveforms measured approximately 1000 feet away from an SR-71 aircraft flying at Mach 1.25 to 5000 feet away. These extrapolated signatures were compared to measurements at 5000 feet. Pressure values of the significant shocks (bow, canopy, inlet and tail) in the waveforms are consistent between extrapolation and measurement. Of particular interest is that four (independent) measurements taken under the aircraft centerline converge to the same extrapolated result despite differences in measurement conditions. Agreement between extrapolated and measured signature duration is prevented by measured duration of the 5000 foot signatures either much longer or shorter than would be expected. The duration anomalies may be due to signature probing not sufficiently parallel to the aircraft flight direction.

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