Notes on Program: liftoff.cpp, version 6.0 Revision A

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Variables

$DI(b,\theta)$	=	directivity (dB) at the angle θ for band centered on frequency b
d_e	=	effective nozzle diameter in meters
d_{ei}	=	exit diameter of individual nozzle in meters
F	=	thrust of each engine or motor in Newtons
f	=	center frequency (Hertz) of the one-third octave band b
Δf_b	=	one-third octave bandwidth in Hertz
L_W	=	overall sound power level in dB
n	=	number of nozzles
r	=	length of the radius line from the assumed position of the frequency source to the point on the vehicle in meters (see Figure 17).
S	=	Strouhal number
$SPL_{b,p}$	=	Sound pressure level (dB) at position p, in the band centered at frequency b.
$SPL_{OA,p}$	=	Overall sound pressure (dB) at point p
U_e	=	fully expanded exit exhaust velocity in (m/sec)
$W(f)$	=	sound power (Watts) in a one-third octave band with center frequency f
W_{OA}	=	overall acoustic power in Watts
W_c	=	Wilby correction factor for surface reflections
x	=	source axial position
x_1	=	height of nozzle exit above ground
η	=	acoustic efficiency
θ	=	angle between the flow centerline and r (see Figure 17).
β	=	angle between radius line and the line normal to the vehicle (see Figure 17).

The L_W reference is 10^{-12} W.

The SPL reference is 20 micro Pa.

Figures from Reference 1

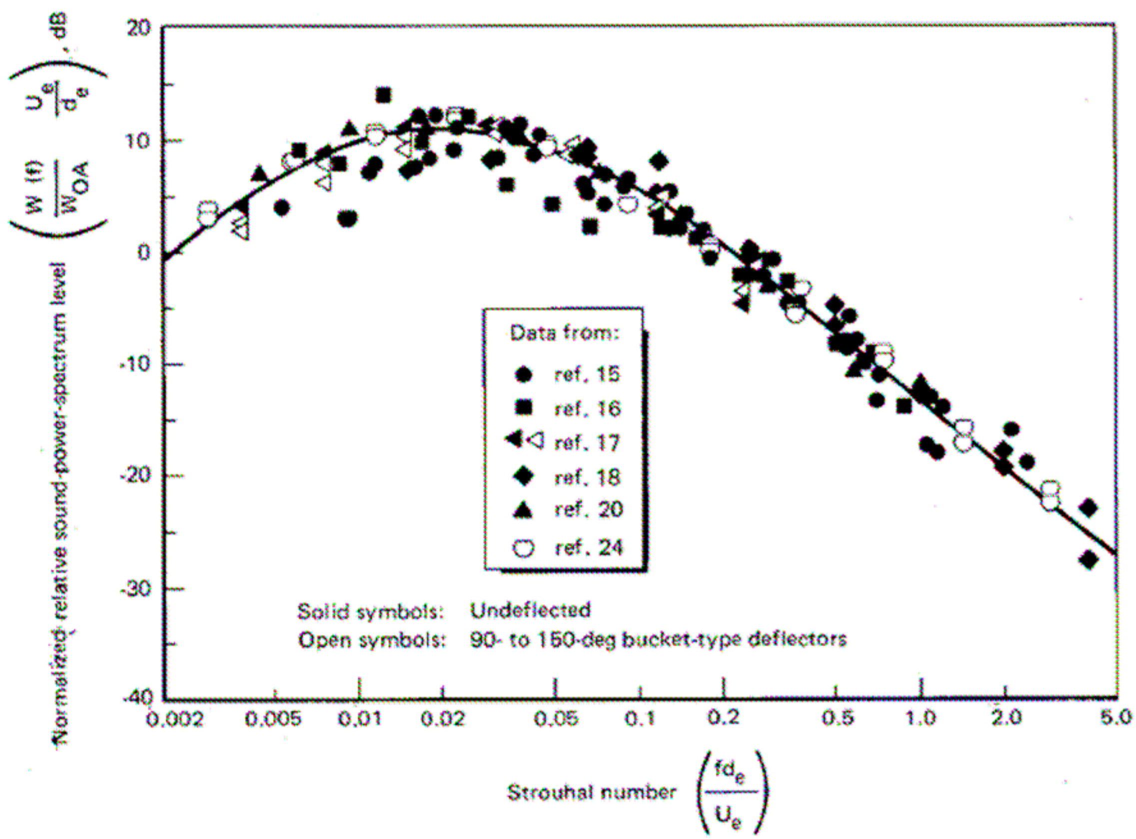


Figure 5. — Normalized relative power spectrum as a function of Strouhal number for standard solid- and liquid-fueled chemical rockets with single nozzles, including a thrust range of 1.56 to 31 100 kN (350 to 7 000 000 lb).

The curve in Figure 5 can also be used for multiple nozzles since d_e is the effective diameter
Note that the Y-axis unit is more properly

$$10 \log\left(\frac{W(f)}{W_{OA}} \frac{U_e}{d_e \, \Delta f_b}\right), \text{dB}$$

Also, there is an alternative Eldred-Wilby method for the following two geometry configurations:

- deflected, single 45 deg plate
- deflected, 90 deg flat plate, conical diffuser, or wedge

The Eldred-Wilby method is given in Appendix B.

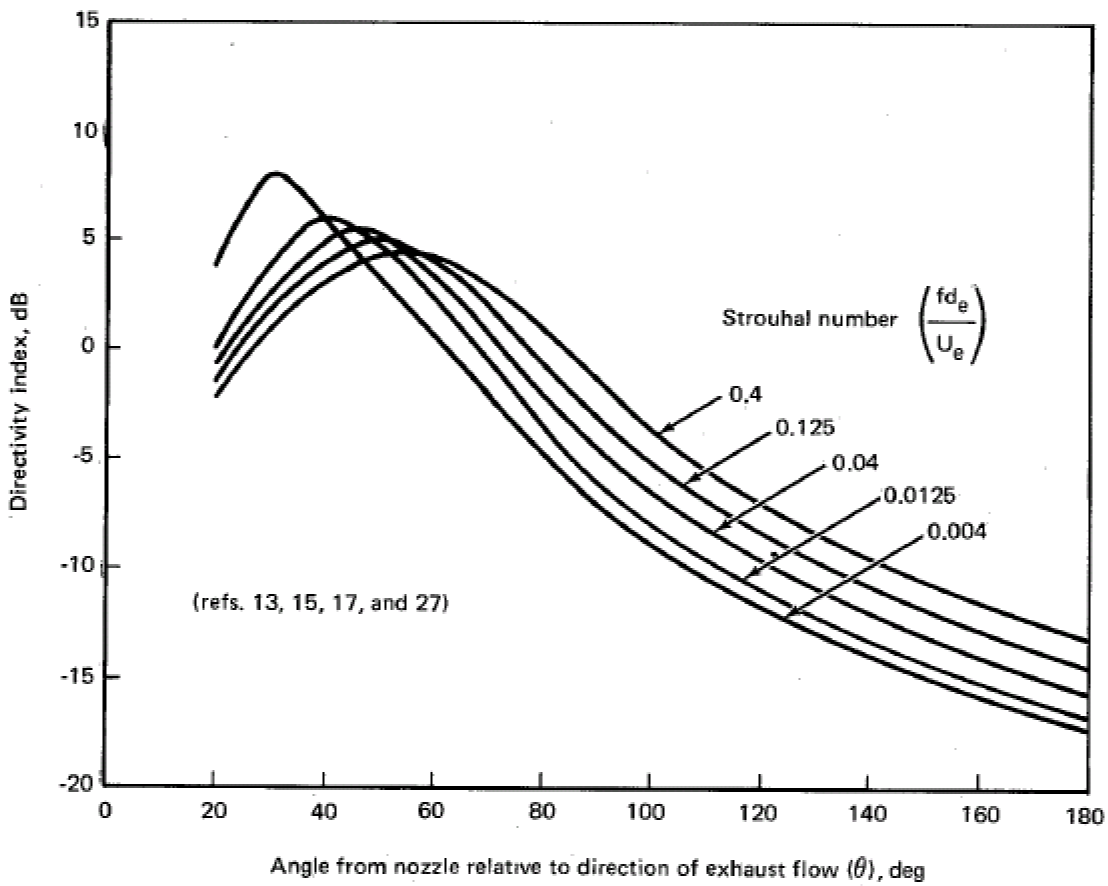


Figure 10. – Directivity of far-field noise for standard chemical rockets for several values of Strouhal number.

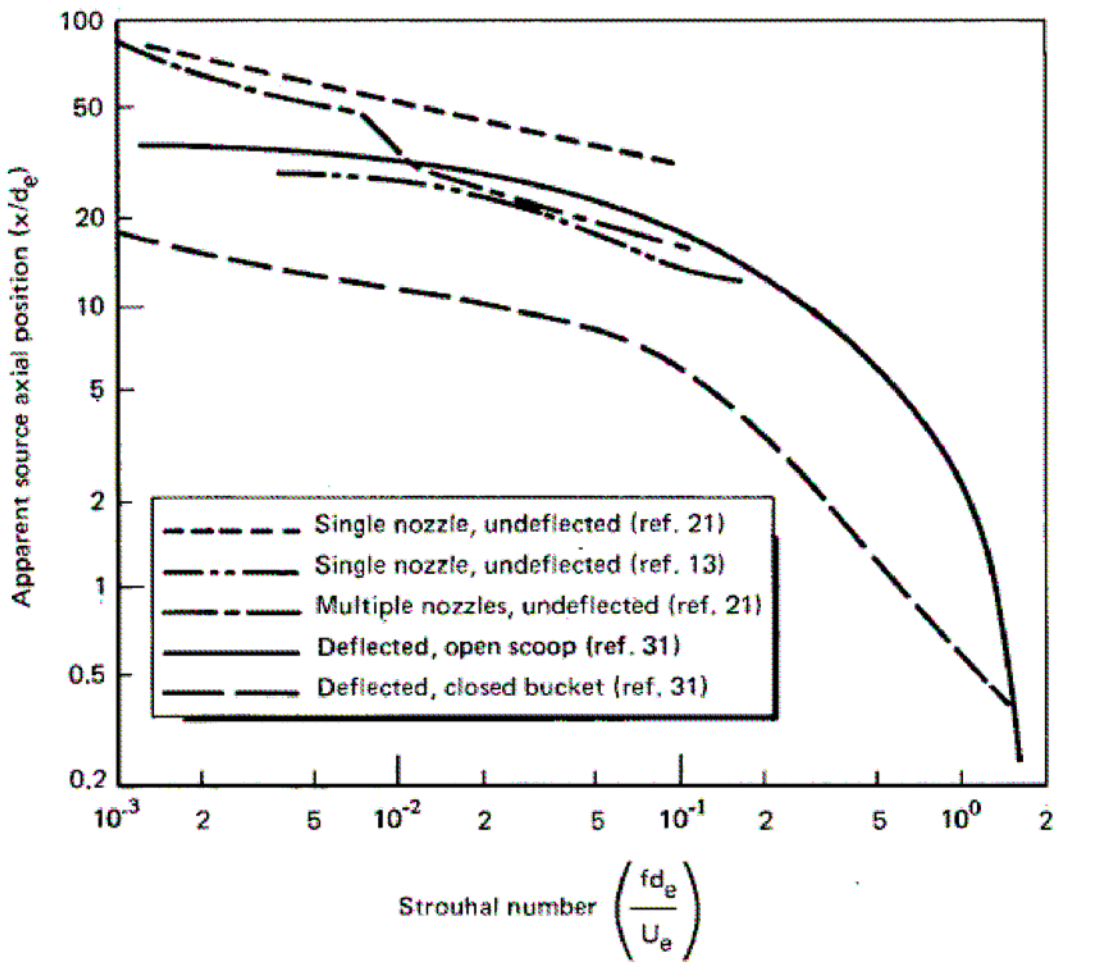
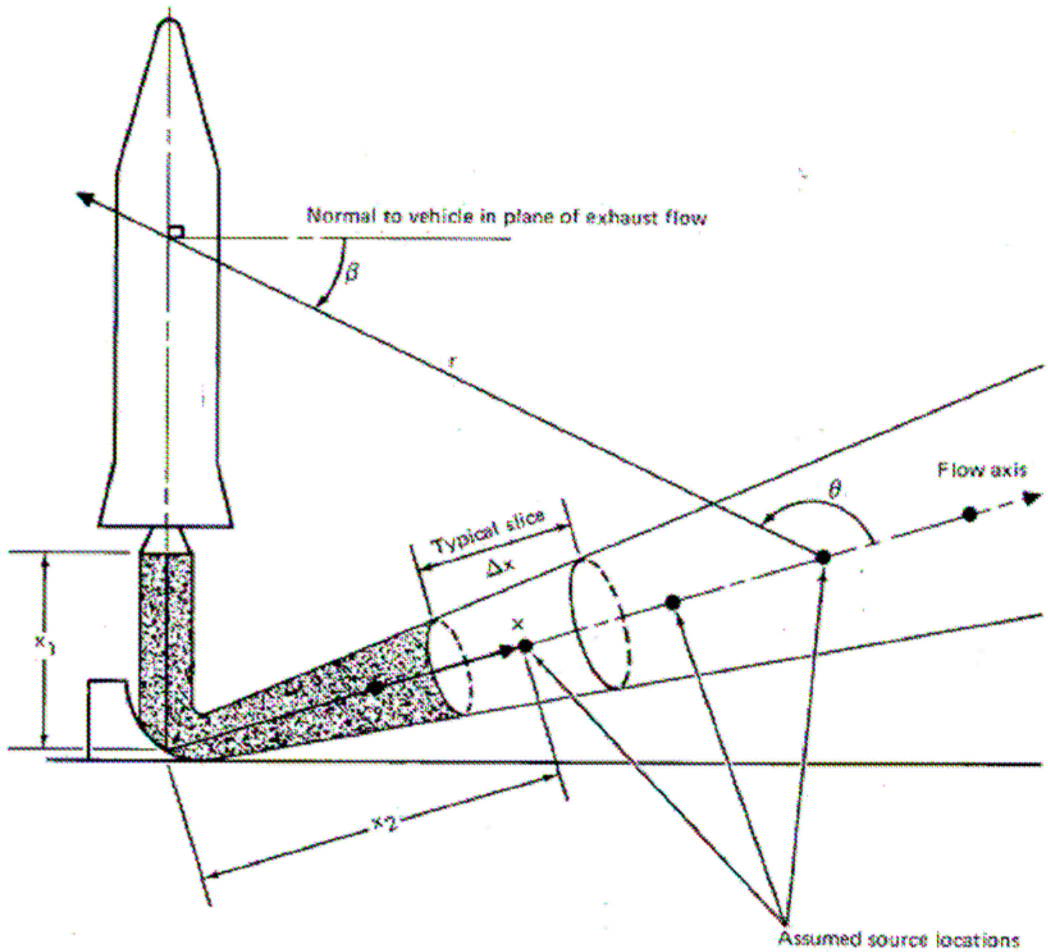


Figure 14. – Axial location of apparent sources as a function of Strouhal number for chemical rockets.



$x = x_1 + x_2$

(b) Side view

Figure 17. – Sketch of source locations and geometry for figures 18 and 19.

References

1. Rocket Vehicle Liftoff Acoustics and Skin Vibration Acoustic Loads Generated by the Propulsion System, NASA SP-8072, Monograph N71-33195, 1971.

APPENDIX A

Example

Program liftoff.cpp, ver 6.0, uses the “The First Source Allocation Method.” The values in Table 1 are used to demonstrate the operation of this program.

Table A-1. Example Parameters

Parameter	Value
Thrust at Liftoff per Engine	391,500 lbf (1.742e+06 N)
Specific Impulse, Sea Level	300 lbf-sec/lbm
Exhaust Velocity	10,000 ft/sec (3048 meter/sec)
Acoustic Efficiency	0.01
Angle from Deflected Flow to Ground	5 deg
Number of Nozzles	2
Nozzle Exit Diameter	58.7 inch (1.491 meters)
Nozzle Exit Area	2706 in^2
Distance from Ground to Nozzle Exit Plane	240 inch (6.1 meters)
Geometry	90 deg flat plate
Station of Interest, Diameter	154 inch (3.9 meters)
Station of Interest, length above nozzle exit plane	1246 inch (31.6 meters)

Step 1

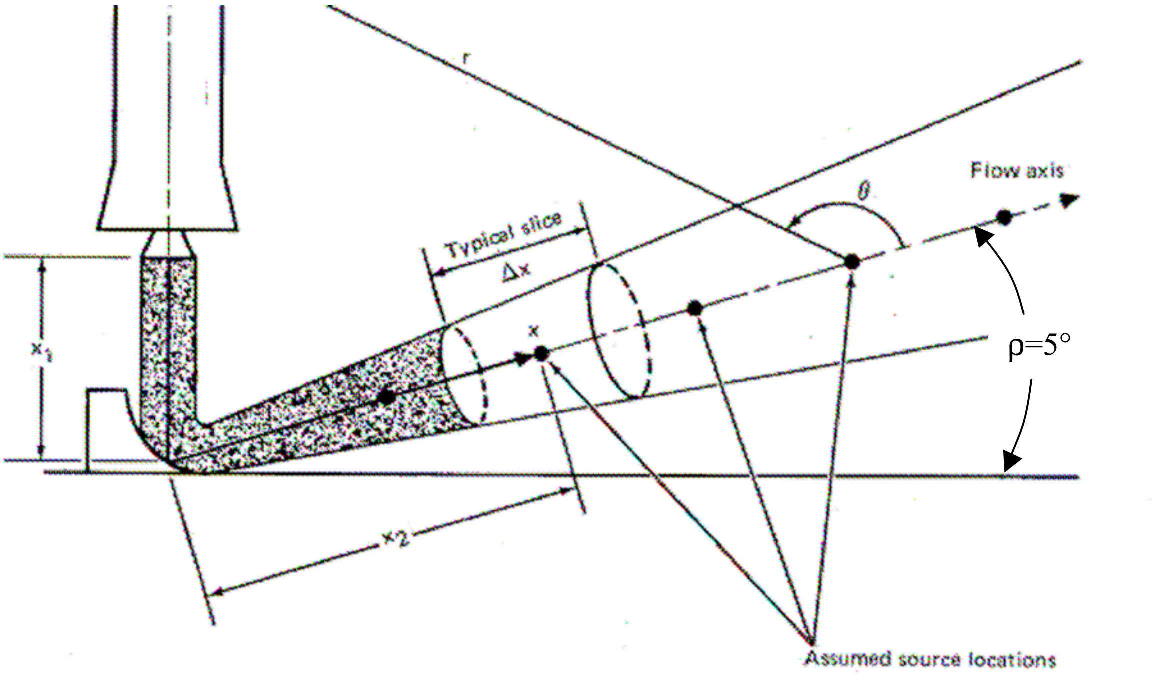


Figure A-1.

Determine the flow axis relative to the vehicle and stand.

Define an angle ρ and set it equal to 5°.

Step 2

Estimate the overall acoustic power from

$$W_{OA} = \frac{1}{2} \eta \, n \, F \, U_e \tag{A-1}$$

$$W_{OA} = \frac{1}{2}(0.01)(2)(1.742e+06 \text{ N})(3048 \text{ meter/sec}) = 5.31E+07 \text{ W} \tag{A-2}$$

Step 3

Calculate the overall sound power.

$$L_W = 10 \log W_{OA} + 120 \quad \text{dB} \tag{A-3}$$

$$L_W = 10 \log (5.31E+07) + 120 = 197 \text{ dB} \tag{A-4}$$

Subtract 3 dB for: deflected, 90 deg flat plate, conical diffuser, or wedge.

$$L_W = 194 \text{ dB} \quad (\text{reference } 10^{-12} \text{ W}) \tag{A-5}$$

Step 4

Calculate the effective nozzle diameter.

$$d_e = \sqrt{n}\, d_{ei} \tag{A-6}$$

$$d_e = \sqrt{2}\ (1.491 \text{ meters}) = 2.11 \text{ meters} \tag{A-7}$$

Step 5

Calculate the Strouhal number for each one-third octave band. The band centered at 20 Hz is used an example.

$$S = \left(\frac{f\, d_e}{U_e} \right) \tag{A-8}$$

$$S = \left(\frac{(20 \text{ Hz})(2.11 \text{ meters})}{3048 \text{ meter/sec}} \right) = 0.0138 \tag{A-9}$$

The normalized power spectrum is given in Figure 5. The level for $S = 0.0138$ is

$$10 \log \left(\frac{W(f)}{W_{OA}} \frac{U_e}{d_e\, \Delta f_b} \right) = 11.1 \text{ dB} \tag{A-10}$$

The bandwidth for the one-third octave band centered at 20 Hz (b=1) is

$$\Delta f_1 = 0.232\ f \tag{A-11}$$

$$\Delta f_1 = 0.232\ (20\ \text{Hz}) = 4.63\ \text{Hz} \tag{A-12}$$

The power level for a given one-third octave band is

$$L_{W,b} = 10\ \log\left(\frac{W(f)}{W_{OA}}\frac{U_e}{d_e\ \Delta f_b}\right) + L_W - 10\log\left(\frac{U_e}{d_e}\right) + 10\log(\Delta f_b) \tag{A-13}$$

$$L_{W,b} = 10\ \log\left(\frac{W(f)}{W_{OA}}\frac{U_e}{d_e\ \Delta f_b}\right) + L_W - 10\log\left(\frac{U_e}{d_e\,\Delta f_b}\right) \tag{A-14}$$

The sound power level for the example problem at 20 Hz (b=1) is

$$L_{W,1} = 11.1\ \text{dB} + 194\ \text{dB} - 10\log\left(\frac{3048\ \text{meter/sec}}{(2.11\ \text{meters})(4.63\ \text{Hz})}\right) \tag{A-15}$$

$$L_{W,1} = (11.1\ + 194 - 24.94)\ \text{dB} = 179.8\ \text{dB} \tag{A-16}$$

Step 6

Allocate the sources along the exhaust flow centerline for each frequency band using either Figure 14 or the method in Appendix A depending on the geometry.

The geometry for the example is a 90 deg flat plate. The Eldred-Wilby method in Appendix A is thus appropriate.

The calculation steps are omitted for brevity. The resulting axial position for 20 Hz is 62.8 meters.

Step 7

Determine theta and the radius for the given frequency and its corresponding axial position. The following diagram represents the 20 Hz case.

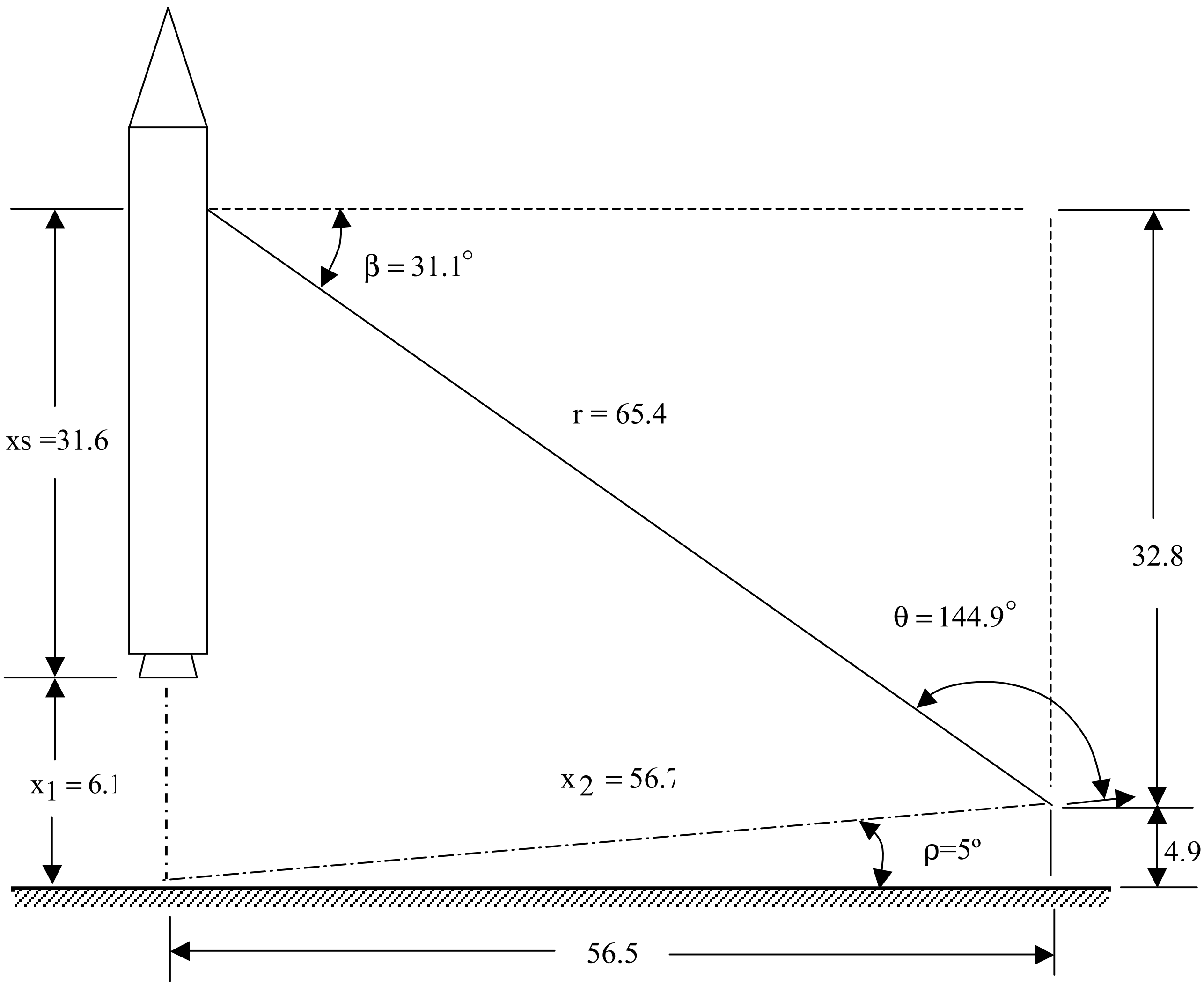


Figure A-2.

The diagram is "not to scale." The length dimensions are in meters.

Recall that x is the axial position of the source.

$$x = x_1 + x_2 \tag{A-17}$$

$$x = 6.1 + 56.7 = 62.8 \tag{A-18}$$

The dimension x_1 is typically taken as the launch stand height.[1] Program liftoff.cpp, ver 6.0 is different from previous versions in this respect; it considers a family of cases beginning at the launch stand height and continuing at successive height increments until a certain upper limit is reached. This is necessary due to the following factors with respect to ascent:

1. The axial position x remains constant.
2. x_1 increases.
3. x_2 decreases.
4. Theta decreases and beta increases.
5. The directivity changes as a function of theta. The directivity may either increase or decrease as theta increases.
6. The radius r changes.

The directivity has a significant enough effect on the sound pressure level that the analysis must be repeated at successive ascent heights. The change in r is another reason, although to a lesser extent.

Furthermore, there is a Wilby correction factor for blocked surface reflections that changes as a function of beta.

The height at which the peak level occurs varies with frequency.

Program liftoff.cpp, ver 6.0, thus takes a maximum envelope for each frequency.

Now continue the example. Determine the directivity using Figure 10.

Again,

$$x_1 = 6.1 \text{ meters}$$

$$f = 20 \text{ Hz}$$

$$S = 0.0138$$

$$\theta = 144.9^\circ$$

The directivity from Figure 10 is thus

$$DI = -15.5 \text{ dB}$$

[1] An exception was the analysis performed for VAFB SLC-8 which has a flame duct.

Next, determine the correction factor for surface reflections using the method in Appendix C. The result for the 20 Hz case is W_c =3.6 dB. The calculation details are omitted for brevity.

Determine the sound pressure level in the band of interest. Continue with the 20 Hz case (b=1).

$$SPL_{1,p} = L_{w,1} - 10\log r^2 - 8 + DI(1,\theta) + W_c \qquad \text{(A-19)}$$

$$SPL_{1,p} = 179.8 - 10\log[(65.4^2)] - 8 - 15.5 + 3.6 \ = \ 123.6 \text{ dB} \qquad \text{(A-20)}$$

Note that the -8 factor corresponds to radiation into a hemisphere with a flat ground plane.

Repeat Steps 5 through 7 for each band of interest

Note that the result in equation (A-20) is the sound pressure level at 20 Hz for x_1 = 6.1 meters, which is the launch stand height.

The peak response at 20 Hz actually occurs at x_1 = 60.07 meters, above the ground. A comparison is shown in Table A-2.

Table A-2. Comparison at Two Altitudes, 20 Hz (b=1)		
x_1 (meters)	6.1	60.07
$L_{w,1}$ (dB)	179.8	17.8
r (meters)	65.4	91.5
$-10\log r^2$	-36.3	-39.2
Theta (deg)	144.9	86.7
Beta (deg)	31.1	88.3
DI (dB)	-15.5	-11.1
W_c	3.60	4.36
$SPL_{1,p}$ (dB)	123.6	125.8

The higher altitude:

1. increases the radius thus decreasing $SPL_{1,p}$
2. increases the directivity DI thus increasing $SPL_{1,p}$
3. increases the Wc factor thus increasing $SPL_{1,p}$

The net gain is an increase in the $SPL_{1,p}$ by 2.2 dB relative to the starting case.

Note that this difference diminishes as the frequency increases. The concern is thus mainly at the lower frequencies.

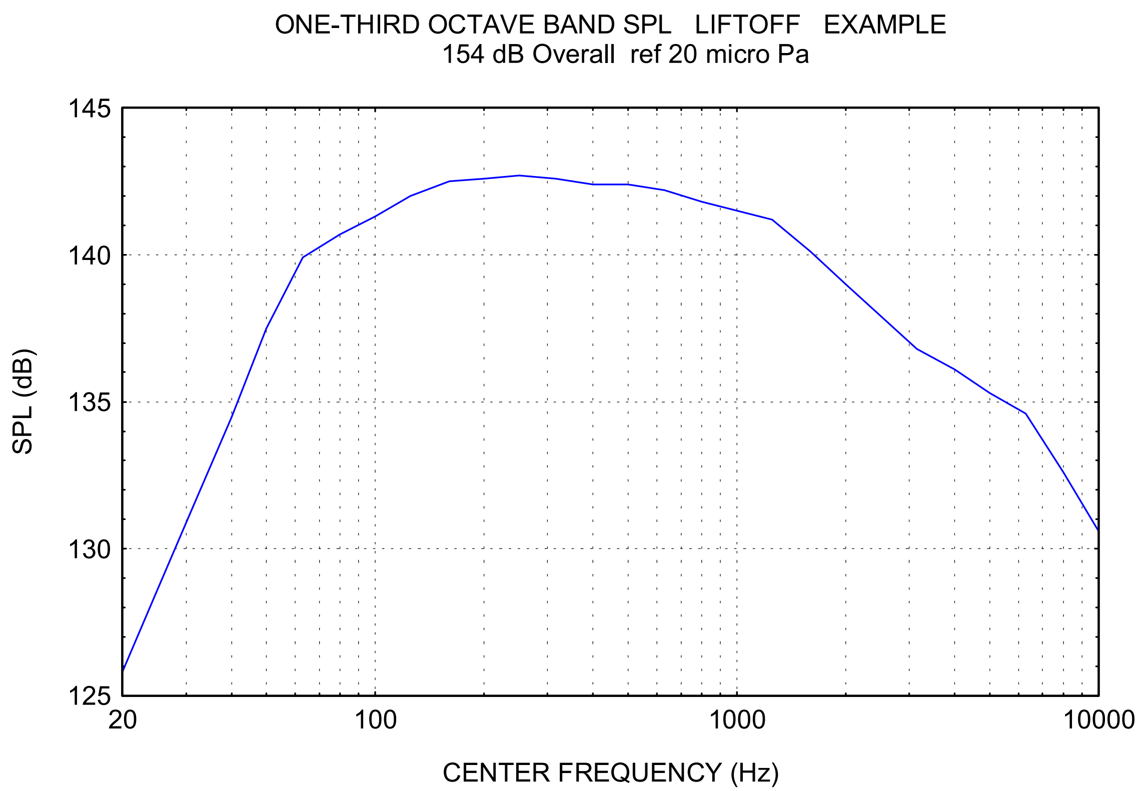


Figure A-3.

Finally, the maximum envelope SPL is shown for the entire frequency spectrum in Figure A-3.

APPENDIX B

<u>Eldred-Wilby Method for Source Allocation</u>

The Eldred-Wilby method is appropriate for the following two geometry configurations:

- deflected, single 45 deg plate
- deflected, 90 deg flat plate, conical diffuser, or wedge

```
void source_allocated_Eldred_Wilby()
{
    double sigma;
    double yn;

     printf("\n\n source allocation (Eldred & Wilby)\n");

     for(i=0; i<= ilast; i++)
     {
          strouhal = freq[i]*de/U;

          if( strouhal <= 1.87)
          {
               sigma=log10(strouhal) - 0.5645;

            yn=1.61273 + 1.550865/( exp(sigma)-exp(-sigma) );

               samp[i] = pow(10.,yn);
          }
          else
          {
               samp[i]=0.1;
          }
     }
     for(i=0; i<= ilast; i++)
     {
          samp[i]*=de;
     }
}
```

APPENDIX C

<u>Wilby Blocked Correction Factor</u>

```
void blocked()
{

// Wilby correction factor for pressure reflections at the
surface of the vehicle.
// Wilby document, equation 15, page 30.

     double sinB;

// strouhal, stationdiam, cspeed,beta

     sinB=sin(beta_rad);

    ZZ=sinB*PI*freq[i]*stationdiam/cspeed;

//   printf("\n ZZ=%12.4e  sinB=%12.4e  beta=%12.4e
freq[i]=%12.4e  stationdiam=%12.4e  cspeed=%12.4e
\n",ZZ,sinB,beta,freq[i],PI,stationdiam,cspeed);
//   exit(1);

     if(ZZ <= 0.1){delta=3.;}

     if(ZZ > 0.1 && ZZ < 12.8)
     {

          ZZ=2.*log10(1.25*ZZ)/log10(10.);

          delta=1.5*(3.+tanh(ZZ));
     }

     if(ZZ >= 12.8){delta=6.;}

}
```

APPENDIX D

<u>Question</u>

02/28/2008

Tom -

In the routine step7(), for the special case where source occurs before deflection you have total distance to apparent source as

```
r = xs + x1_alt ;
```

If this flow region is undeflected wouldn't that be

```
r = xs + samp[i] ;   ?
```

Isn't the first expression for r just the distance from the vehicle station to the point of deflection?

Thanks,

- Bob

<u>Answer</u>

Bob,

This is a good question.

The occurrence of the apparent source between the nozzle exit plane and the ground is a special case. The theta angle is 180 degrees for this case. The corresponding directivity factor is -12 to -16 dB, meaning that relatively little sound travels back to the vehicle. Furthermore, this sound would be partially blocked by the aft end of the vehicle.

So instead we set the source at the ground but with the flow deflecting upward at its rho angle. The corresponding theta angle is < 90 degrees, with a directivity of -2 to - 7 dB. As a result, a relatively greater amount of sound energy propagates forward to the various vehicle stations.

Directivity is a greater factor than radius in these cases.

Tom