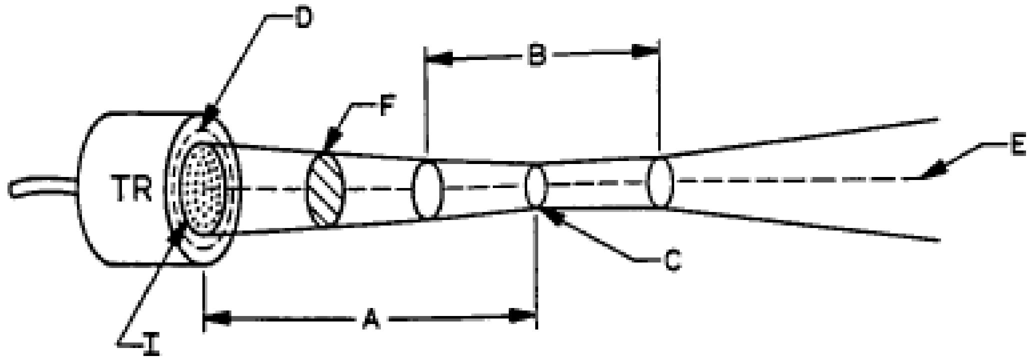
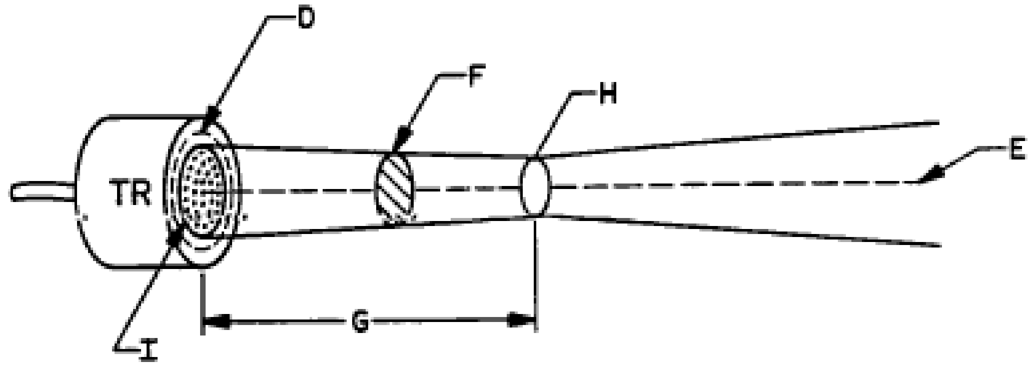


FOCUSED



UNFOCUSED

A = FOCAL LENGTH
B = DEPTH OF FOCUS (CM)
C = FOCAL AREA (CM^2)
D = RADIATING CROSS-SECTIONAL AREA, S
E = BEAM AXIS
F = BEAM CROSS-SECTIONAL AREA (CM^2)
G = TRANSITION DISTANCE = $\frac{S}{\pi \lambda}$
H = BEAM CROSS-SECTIONAL AREA AT TRANSITION DISTANCE (CM^2)
I = ENTRANCE BEAM DIMENSIONS (CM^2)

Figure 5-6
BEAM PROFILE PARAMETERS FOR FOCUSED AND UNFOCUSED SINGLE-ELEMENT TRANSDUCERS

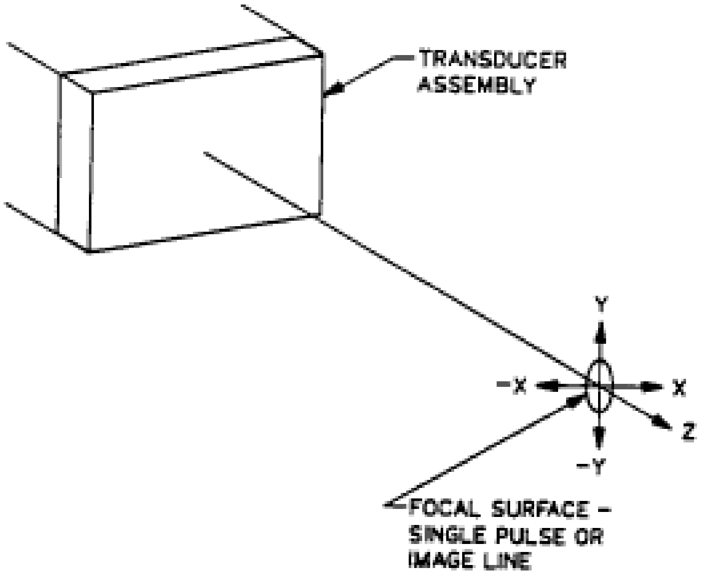


Figure 5-7
BEAM GEOMETRY AT THE FOCUS OF ONE PULSE (I.E., IMAGE LINE) FOR THE SECTOR SCANNING RECTANGULAR TRANSDUCER ASSEMBLY

The z axis is the **beam axis** for the image line being depicted. The x-y plane is the image plane.

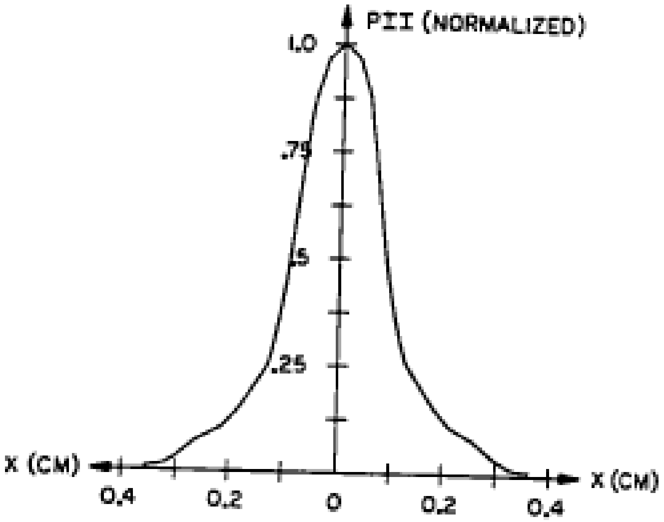


Figure 5-8a
PLOT OF PII (NORMALIZED J/CM^2) ALONG A DIAMETER THROUGH THE FOCUS OF A CIRCULAR SOURCE TRANSDUCER

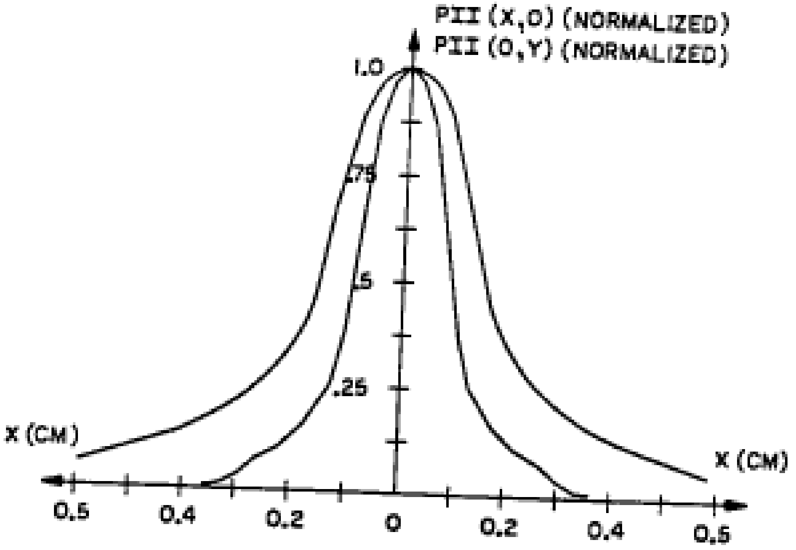


Figure 5-8b
PLOTS OF PII (NORMALIZED J/CM^2) THROUGH THE FOCUS OF A RECTANGULAR TRANSDUCER ASSEMBLY

The x and 7 axis plots are taken along lines that intersect and are parallel to the sides of the transducer assembly. See Figure 5-7.

5.4.11 Measure the Ultrasonic Power

The **ultrasonic power** (W) shall be measured according to the procedures of Section 5.6.

5.4.12 Find the Spatial Maximum Derated Pulse Intensity Integral

The maximum derated **pulse intensity integral** $PII_{.3}(j,v_{mj},z)$ and the position at which it occurs shall be determined by moving the hydrophone along the z-axis, toward the transducer under test, in an iterative fashion, searching for the maximum derated $PII_{.3}(j,v_{mj},z)$, where derated parameters will now be indicated with a .3 subscript. In order to avoid near-field variations, this axial scan shall be made no closer to the surface of the **active aperture** than the **minimum measurement depth** z_{min}. The location at which the derated **pulse intensity integral** $PII_{.3}(j, v_{mj},z)$ is maximized over the range $z = z_{min}$ is denoted $z_{mjPII.3}$.

The following equation shall be used to calculate the derated **pulse intensity integral**, $PII_{.3}(j,v_{mj},z)$:

$$PII_{.3}(j,v_{mj},z) = \exp(-0.23 * 0.3 * f_c * z) * PII(j,v_{mj},z) \qquad (5.4.12\text{-}1)$$

where f_c is the frequency expressed in MHz (Section 5.4.9.2) and z is the distance (one way) in cm along the **beam axis** from the **transducer assembly** to the measurement point.

5.4.13 Verification of the Spatial Maximum $PII_{.3}(j,v_{mj},z_{mlPII.3})$

The maximum $PII_{.3}(j,v_{mj},z_{mlPII.3})$ point shall be verified by testing the surrounding points in all coordinate directions. If a maximum has not been found, the procedures beginning at step 5.4.3 shall be repeated.

5.4.14 Waveform Recording

The hydrophone **waveform** at this location should be recorded as described in Section 5.4.6.

5.4.15 Calculate the Derated Spatial-Peak Pulse-Average Intensity ($I_{SPPA.3}$)

The derated **spatial-peak pulse-average intensity** ($I_{SPPA.3}$), taken at the location ($z = z_{mjPII.3}$) for any **drive voltage amplitude**, shall be calculated by:

$$I_{SPPA.3}(j,v) = PII_{.3}(j,v,z_{mjPII.3})/PD \quad (W/cm^2) \qquad (5.4.15\text{-}1\ )$$

where PD is **pulse duration** expressed in sec and v is the **drive voltage amplitude**.

Note that while the location for this measurement was found using the **maximum drive voltage amplitude** (v_{mj}), the derated **spatial-peak pulse-average intensity** ($I_{SPPA.3}$) may be calculated for any **drive voltage amplitude**.

5.4.16 Calculate the Derated Peak Rarefactional Pressure ($p_{r.3}$)

The derated **peak rarefactional pressure** $p_{r.3}$, taken at the location ($z = z_{mjPII.3}$) for any **drive voltage amplitude**, shall be calculated using Equation 5.4.8-1, and multiplying by the **derating factor** expressed as:

$$p_{r.3}(j,v) = p_r(j,v,z_{mjPII.3}) * \exp(-0.115 * 0.3 * f_c * z_{mjPII.3}) \qquad (5\text{-}4\text{-}16\ 1)$$

where f_c is defined in Section 5.4.9.2, $z_{mjPII.3}$ is described in 5.4.12, and v is the **drive voltage amplitude**.

5.4.17 Calculate the Derated Spatial-Peak Time-Average Intensity ($I_{SPTA.3}$)

The derated **spatial-peak temporal-average intensity** ($I_{SPTA.3}$), taken at the location ($z = z_{mjPII.3}$) for any **drive voltage amplitude**, shall be calculated by:

$$I_{SPTA.3}(j,v) = PII_{.3}(j,v,z_{mjPII.3}) * PRF \quad (W/cm^2) \qquad (5.4.17\text{-}1)$$

where PRF is the **pulse repetition frequency** in Hz, as defined in Section 5.4.9.1, and v is the **drive voltage amplitude.**

5.4.18 Measurement Methods for Equipment Which Produces Continuous Waveforms

For **equipment** which produces **continuous waveforms**, the **pulse intensity integral** is not a meaningful parameter, and the maximum **temporal average intensity** $I_{TA}(j,v_{mj},z)$ shall be used instead of the **pulse intensity integral** for the measurement of I_{SPTA}, p_r, and f_c. The maximum derated **temporal average intensity** $I_{TA.3}(j,v_{mj},z)$ shall be used instead of the derated **pulse intensity integral** for the measurement of $I_{SPTA.3}$ and $p_{r.3}$. The **temporal average intensity** is defined by:

$$I_{TA} = \frac{1}{nT}\frac{\int_0^{nT} v_h^{\,2}(t)dt}{10^4 \rho c M_L^{\,2}(f_c)} \qquad (5.4.18\text{-}1)$$

where T is the period of the hydrophone voltage $v_h(t)$, and n is an integer. If an arbitrary integration time is used, (e.g., the data capture window of a digital oscilloscope) then the integration time shall be greater than 10T, to reduce the errors inherent in integrating over a nonintegral number of cycles.

At low amplitudes where the **waveform** is sinusoidal, Equation 5.4.18-1 may be simplified:

$$I_{TA} = \frac{0.5V_0^{\,2}}{10^4 \rho c M_L^{\,2}(f_c)} \qquad (5.4.18\text{-}2)$$

where V_0 is the amplitude of the **waveform**. If the **waveform** has undergone any nonlinear distortion (Appendix B), then Equation 5.4.18-1 shall be used rather than 5.4.18-2. As a guideline, if the positive and negative voltage levels differ by more than 10%, Equation 5.4.18-1 should be used.

In order to measure **equipment** which produces **continuous waveforms**, the procedures of Sections 5.4.2-6 shall be performed, with the exception that the **temporal-average intensity** $I_{TA}(j,v_{mj},z)$ shall be the parameter to be maximized. By definition, the **spatial-peak temporal-average intensity** shall be found at the location determined by this modified search procedure. Sections 5.4.8, 5.4.9.2 shall then be performed as described (Sections 5.4.7 and 5.4.9.1 have no meaning for **continuous waveforms**). The parameters described in Section 5.4.9.3 shall then be determined, again using the **temporal-average intensity** instead of the **pulse intensity integral**. The **ultrasonic power** (W) shall be measured according to the procedures of Section 5.6.

Sections 5.4.12-14 shall be performed using the derated **temporal-average intensity** defined by:

$$I_{TA.3}(j,v_{mj},z) = \exp(-0.23 * 0.3 * f_c * z) * I_{TA}(j,v_{mj},z) \qquad (5.4.18\text{-}3)$$

The derated **peak rarefactional pressure** $p_{r.3}$ shall be determined using Section 5.4.16, and the results of the modified search procedure just described. By definition, the derated **spatial-peak temporal-average intensity** $I_{SPTA.3}$ shall be found at the location determined by this modified search procedure.

5.5 MEASUREMENT FOR INTENSITY AND PRESSURE IN AUTOSCAN MODE

In **autoscan mode**, a series of interrogating beams are steered through a succession of azimuthal (i.e., in-plane lateral) directions within a single or succession of target planes. The rate at which this azimuthal scanning pattern is repeated is the **scan repetition frequency** (SRF); the inverse of this rate, the **scan repetition period**, is the time over which **intensity** is averaged in order to calculate **temporal average intensity**.

In the simplest **autoscan mode**, all transmitted beams exhibit the same focal characteristics along their respective **beam axes**; the beams differ only in the orientation of the **beam axes**. Thus, the temporal peak and pulse average parameters of all beams (considered separately), as well as the **autoscan mode** itself, are identical. The temporal average parameters for the mode are determined by the pulse-average parameters of an individual beam, the degree of spatial overlap of the beams in the formation of the overall scan, and the **scan repetition frequency**.

In more complex **autoscan modes**, the transmitted beams may exhibit two or more sets of focal characteristics. In some systems, certain scanning modes may employ two or more distinct focal patterns, each focused at a different depth, to create a single, overall scan. In still other systems, such as phased array sector devices, beam focal characteristics may vary with steering angle as well. In these more complex modes, the temporal-peak and pulse-average parameters for a given mode are determined by the maximum values that occur for any beam within the scan. The temporal average parameters for the mode are determined by the pulse-average parameters of the different beam types, the degree and pattern of spatial overlap of the different beam types in the formation of the overall scan, and the **scan repetition frequency**. In the most general case, precise measurement of temporal average parameters in these modes involving multiple focal patterns can be extremely complex, tedious, and time consuming.

In yet another class of systems, the plane of examination is automatically swept through the target space in the elevation direction. Thus, while the scanning pattern may appear to be repetitive in the range-azimuth plane, the scanning pattern is not repetitive at any point in the target volume due to motion of the scan plane. Nevertheless, as considered in this Standard, this elevation motion is disregarded and **temporal average intensity** parameters are determined over the period of repetition in the range-azimuth plane.

Stated simply, the general principles for measuring acoustic output parameters for **autoscan modes** can be summarized as follows:

a. Temporal-peak and pulse-average parameters for the mode are determined by the temporal-peak and pulse-average quantities of the individual beams considered separately. Such parameters as **scan repetition frequency, pulse repetition frequency** and such factors as spatial overlap of beams, do not affect temporal-peak and pulse-average parameters for the mode.

b. Temporal average parameters are determined by the cumulative effects of the overlap of beams generated during the **scan repetition period**. As the most important such parameter, **temporal average intensity** for an Auto Scanning mode, when measured at a point, is determined by the sum of the **energy fluences** at a point resulting from the various beams during the scan, and the **scan repetition frequency**.

5.5.1 Introduction to Autoscan Measurements in Combined Modes

Autoscan, in **combined modes**, refers to those operational conditions of the scanning instrument where the beam shape, focus, amplitude, or pulse length change within a single scan; a single scan being one cycle of a repetitive sequence of emitted acoustic pulses. More specifically, **autoscan modes** are those conditions where the scanning of the beam cannot be stopped and the beam measured with the knowledge that the measured data is consistent throughout the entire scan. A simple example would be a B-mode image with a Doppler signal interleaved through some smaller part of the overall scan plane in the form of a single point interrogation or a 2-D flow image.

By its very nature, measurement in **autoscan modes** can be, at best, difficult without detailed information regarding the sequence, sources, and direction of the transmitted beams. This level of detail may be available from the manufacturer; if not, tedious scanning of scan plane with a hydrophone becomes the required means for defining the pulse sequence of a particular front panel setting. Complex array systems using interleaved transmit foci for each of the different **combined modes** make this an undesirable, if not unreliable, approach.

Proceeding further with **autoscan** measurements without accurate pulse sequence information is not recommended. In this case, the **non-autoscan** data defining each operational mode which make up the **autoscan combined mode** as measured in Section 5.4 will suffice as an adequate definition of the acoustic output capacity of the instrument/probe under evaluation.

NOTE—The technical staff of a manufacturer is assumed to be sufficiently knowledgeable about their equipment to be able to perform complete **autoscan** measurements.

In **combined autoscan modes**, each instrument manufacturer's scheme of operation is considerably varied. Algorithms to assist in identifying the control setting "region" producing the values under search can be very useful. An example of one such algorithm is given in Appendix G. A step by step procedure unique to the individual instrument under test should be developed and followed.

Because of the difficulties and complexities described above, the remainder of this section does not detail technical and mathematical procedures for obtaining the desired values but, instead provides only guidelines.

5.5.2 Measurement of $I_{SPTA.3}$ in Combined Autoscan Modes

The basic equation determining the **derated spatial-peak temporal-average intensity** in an **autoscan mode** is given as the global spatial maximum within the scan plane of the following:

$$I_{SPTA.3} = \underset{over(x,z)}{maximum} \sum_{i=0}^{n} PII_{.3}(x,0,z)\, SRF \qquad (5.5.2\text{-}1)$$

where $PII_{i.3}$ (x, 0, z) is the **derated pulse intensity integral** (or **derated energy fluence per pulse**) of the i-th beam as measured at the point (x, 0, z), SRF is the **scan repetition frequency**, and n is the number of beams.

NOTE—For sector formats, θ is the azimuthal dimension variable, y is the elevation, and r is the range variable. Thus, for rectilinear formats, the scan plane is described by (x,0,z); for sector formats, the scan plane is given by (θ,0,r).

The summation in 5.5.2-1, indicating the contributions of all the pulses that affect point (x, y, z) during a single scan, can be defined as the **derated scan intensity integral** ($SII_{.3}$) at a general point:

$$SII_{.3}(x,y,z) = \sum_{i} PII_{i.3}(x,y,z) \qquad (5.5.2\text{-}2)$$

Thus, just as derated $PII_{.3}$ (x, y, z) is the time integral of **intensity** at a point due to a single pulse, $SII_{.3}$ (x, y, z) is the time integral of **intensity** at a point during a single scan, resulting from all the pulses during the scan that insonify the point, either on- or off-axis.

Thus, for **auto-scanning** systems:

$$I_{SPTA.3} = \underset{over\ (x,z)}{maximum} SII_{.3}(x,0,z)\, SRF \qquad (5.5.2\text{-}3)$$

analogous to the equation for **non-autoscanning** systems:

$$I_{SPTA.3} = \underset{over\ (x,z)}{maximum} PII_{.3}(x,0,z)\, PRF \qquad (5.5.2\text{-}4)$$

Certain simplifications are possible when all of the beams comprising the scan share the same focal properties (aperture size, focal depth, etc.), and are at an equal spacing in the azimuthal direction at a given range such that:

$$PII_{i.3}\ (x, y, z) = PII_{0,\ .3}\ (x\text{-}x_i,\ y,\ z) \qquad (5.5.2\text{-}5)$$

In such case, the $SII_{.3}$(x,y,z) may be expressed as the summation:

$$SII_{.3}(x,y,z) = \sum_{i} PII_{0,.3}(x - x_i, y, z) \qquad (5.5.2\text{-}6)$$

where $PII_{0,\ .3}$(x-x_i, y, z) is the **derated pulse intensity integral**, measured at (x, y, z) of a beam whose axis passes through (x = x_i, y = 0, z), where x_i = x – i Δx, Δx(z) is the azimuthal spacing between beams at range z and i is the number of lines which overlap the point during one **scan repetition period**.

Further simplification is possible in the limit as Δx(z) becomes small in comparison to the beam pattern (i.e., beam overlap factors predominate in the summation forming $SII_{.3}$ (x, y, z)), and edge effects near the lateral edges of the scan plane can be ignored. Then it can be shown that $SII_{.3}$ (x, y, z) ceases to be dependent on x, and can be approximated as:

$$SII_{.3}(y,z) = \frac{\int PII_{0,.3}(x,y,z)dx}{\Delta x(z)} \tag{5.5.2-7}$$

Thus, when all beams making up the scan share the same focal properties, and they are at a constant azimuthal spacing at a given range, and beam spacing is small, then:

$$I_{SPTA.3} = \underset{over\ z}{max\,imum} \frac{\int PII_{0,.3}(x,0,z)dx}{\Delta x(z)} SRF \tag{5.5.2-8}$$

Thus measurements can be made at one central location in the scan plane or by scanning a stationary beam.

5.6 POWER MEASUREMENTS

The measurement method shall provide acoustic **power** measurements consistent with those of a calibrated radiation force balance measurement. The measurement method of acoustic **power** shall be traceable to NIST or other comparable national standards.

Where acoustic **power** is detected using a radiation force balance, the radiation force balance shall be calibrated using a **reference source** transducer with acoustic **power** traceable to a national standards laboratory. Where acoustic **power** is determined using hydrophone planar scanning methods, the **working hydrophone** sensitivity shall be determined using a **reference source** transducer or **reference hydrophone** traceable to a national standards laboratory. The entire planar scanning system accuracy shall be verified using a **reference source** transducer for which the acoustic **power** is traceable to a national standards laboratory.

5.6.1 Force Balance Methods

5.6.1.1 Measurement Methods

Force balance systems, equations governing their operation, and procedures for testing them are described in 3.6 and 4.4. In a **local laboratory,** a calibrated force balance system should be used for periodic comparisons with **reference sources, working sources,** and pulser drivers.

It is the primary function of the force balance system to measure **ultrasonic power** emitted by diagnostic systems. While making radiation force balance (RFB) measurements, care should be taken to ensure that the radiation force balance target intercepts the total **acoustic output power** emitted by the **source transducer.** The **source transducer and** RFB target should be positioned so that the effective **beam cross-sectional area's** dimensions are less than the corresponding RFB target dimensions, and the beam is centered on the RFB target. Procedures for measuring unfocused transducers driven by diagnostic systems are the same as for measuring **reference sources** or **working sources.** When measuring focused transducers, tests should be performed to detect nonlinear response due to the saturation of the water medium. For diagnostic systems, the ultrasound is usually emitted in pulses. Whether the ultrasound is pulsed or not, it is the **ultrasonic power** that is given by Equation 4.4.1-2, since the radiation force measured is a temporal average.

It is necessary to know which aperture or ultrasound line creates the greatest intensities since some lines may carry more energy or focus more tightly than others. If measuring a **non-autoscan** mode or an **autoscan** mode with the sweep arrested, the **power** measurements must be made using this line.

It is strongly recommended that, with the exception of measurements of **power**/unit length (Section 5.6.1.6), all measurements, **autoscan, non-autoscan,** or **combined modes** be made with the beam sweep arrested, with all pulses coming from the aperture creating the greatest intensities. This ensures that all ultrasound beams strike the absorbing target at an angle of incidence of no more than 10 degrees from normal.

The PRF corresponding to the system settings being measured must be known, particularly if these measurements are to be used to compare with data collected using a hydrophone raster scan (see Section 5.6.2). Likewise, for multimode and unique systems, the sequencing of the pulses (i.e., how many B-mode, Doppler etc. lines/second/frame) must be known. For **autoscan** and **non-autoscan combined modes**, one can measure each separately, provided each portion is pulsed exactly the same way when separated as when combined.

Because ultrasound heats the absorbing target in a force balance, the buoyancy, and thus the measured weight of the absorbing target, will drift with **exposure time**. In addition, from power-on to power-off, an overshoot of the target occurs and a short, damped oscillation period follows as the target settles. Therefore, a short delay time is necessary before taking data after power-on/power-off. Since the target weight also drifts due to cooling and heating of the chamber fluid, an extrapolation technique is necessary in order to accurately determine the target weight at power-on/power-off.

One extrapolation technique is to take a weight reading and then turn power on (this is the time zero power-off/power-on) (Carson et al., 1978). Take a power-on weight reading at 10 sec and another at 20 sec. Use the 10 and 20 second readings to extrapolate back to the time zero power-off/power-on weight. If R(t) is the balance reading at time t:

$$R(0) = 2R_{10} - R_{20} \qquad (5.6.1.1\text{-}1)$$

Repeat the procedure, but going from power-on to power-off. Wait a sufficient period of time before repeating the cycle. The power-off period allows the water and target to cool down. Note that the target cools down slower than it warms up. There should be no systematic difference between the magnitudes of the power-off to power-on and power-on to power-off measurements. Any such differences may indicate a significant warm-up or shut-down time of the system under test and an alternative method of interrupting the transmitter voltage may be required. The difference between the power-off (time zero) and power-on (interpolated back to time zero) weights is then divided by the 68 mg/mW conversion factor to get the uncorrected **power** measurement. Figure 5-9 illustrates the interpolation.

Because the ultrasound beam is attenuated somewhat during travel to the target (due to fluid (Kaye & Laby, 14th ed.) and membrane attenuation), a correction factor must be applied to the measured value. Acoustic calibration of the balance over the **working frequency range** is required (see Section 4.4).

Averaging a number of measurements will produce more accurate results. In addition, the transducer under test shall be decoupled from the balance, recoupled, realigned and another series of measurements taken. The number of measurements between recouplings (N1) shall be five or more; the number of recouplings (N2), three or more. The average and standard deviation for each set of N1 readings shall be found, as shall the standard deviation between the N2 averages. The reported **power** shall be the average **power** of the N2 sets (see Appendix A).

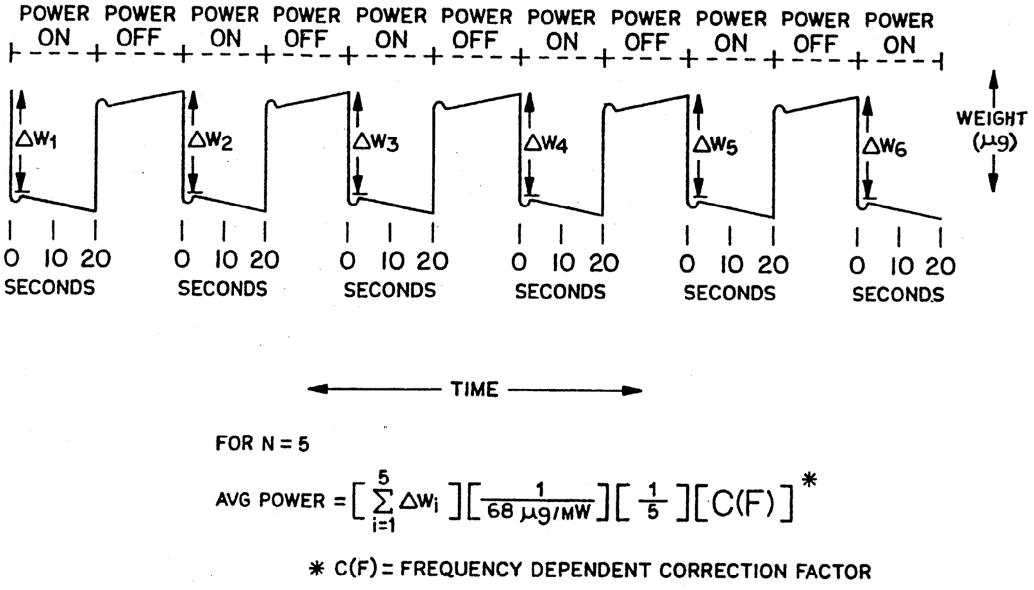


Figure 5-9
ILLUSTRATION OF AN R.F.B. MEASUREMENT OF ONE SEQUENCE OF N = 5 CYCLES

Extrapolation technique is shown. Sequence should be repeated three or more times with the transducer recoupled each time.

5.6.1.2 Aperture Considerations

For transmit apertures ≤ 3/4 of the corresponding radiation force balance target dimensions, the transducer-target separation distance shall be the smaller of 1 cm or 1/2 the distance to the focal point, where the focal point is determined as the position of maximum PII on the **beam axis** with the diagnostic ultrasound equipment operating at the **maximum drive voltage amplitude** (v_{mj}), for the **transmit pattern** (j) being tested, and such that the **acoustic output** linearity requirements of Section 5.6.1.3(b) are met.

For transmit apertures > 3/4 of the corresponding radiation force balance target dimensions, the transducer-target separation distance shall be selected so that the **beam cross-sectional area's** major and minor dimensions are less than 3/4 of the corresponding radiation force balance target dimensions, and such that the **acoustic output** linearity requirements of Section 5.6.1.3(b) are met.

Absorbing targets with dimensions on the order of 20 mm to 25 mm wide are recommended. This size permits small transducer-target distances. Targets with larger dimensions often cause unacceptably noisy measurements. For large aperture transducers, increase the transducer target distance or use a collimator (see references in Section 1) to meet the linearity requirements specified in Section 5.6.1.3(b).