Chapter 1

Too Low an SWR Can Kill You

(Adapted from QST*, April 1973)*

Sec 1.1 Introduction

Judging by what we hear on the air, nearly everyone is looking for an SWR of one-to-one. Question why, and the answer may be, "I'm not getting out on this frequency because my SWR is 2.5:1. There's too much power coming back and not enough getting into the antenna." Or, "If I feed a line having that much SWR, the reflected power flowing back into the amplifier will burn it up." Or still, "I don't want my feed line to radiate." Any of these answers shows a misunderstanding of reflection mechanics, and are symptomatic of the present state of thinking on this subject. Rational and creative thinking toward antenna and feed-line design practice has been absent for a long time. Such thinking has been replaced with an unscientific and thought-inhibiting attitude, as in the days before Copernicus persuaded the multitudes that the universe did not revolve around the earth. This situation originated with the introduction of coaxial transmission lines for amateur use around the time we got back on the air after World War II. It gained momentum since SWR indicators appeared on the scene and since the loading capacitor of the pi-net tank replaced the swinging link as an output-coupling control, decades ago. We are in this state of mind because much misleading information has been, and is still being published concerning (1) behavior of antennas which are not self-resonant, (2) feed-line performance in the presence of reflections when mismatched to the antenna, and especially (3) the meaning and interpretation of the SWR data.

Articles containing explicitly erroneous information and distorted concepts have found their way into print, became gospel, and continue to be propagated with chain-letter effectiveness. These include such gems as (1) always requiring a perfect match between the feed line and the antenna, (2) evaluating antenna performance or radiating efficiency only on the basis of feed-line SWR—the lower the better, (3) pruning a dipole to exact resonance at the operating (single) frequency and feeding with an exact multiple of a half-wavelength (1/2–λ) coax—no other length will do, (4) adjusting the height—perhaps just lowering the ends into an inverted-V dipole—to make the resistive component of the antenna terminal impedance equal to the line impedance, or (5) subtracting percent reflected power from 100 to determine usable percentage of transmitter output power. Nomographs have even been published for this erroneous method *(Ref 102)*.

As a result of these misdirected concepts, we have been conditioned to avoid any mismatch and reflection like the plague. One-to-one all the way! Sound exaggerated? Not if your receiver is tuning the same amateur bands as mine! In the current vernacular, you could say we have a severe SWR hang-up! In many instances, from the viewpoint of good engineering practice, this hang-up is inducing us to concentrate our impedance-matching efforts at the wrong end of the transmission line *(Ref 16)*.

It is ironic that we should be in this situation, because the amateur is generally quite practical when it comes to following theoretical considerations. In this case we have been following the perfect-match theory down the narrow path because many of the aforementioned articles have misled us to believe that all reflected power is lost. They've given never an inkling that, properly controlled, reflections can be turned to our advantage in obtaining increased flexibility concerning operating frequencies which we are presently throwing away.

That so much misinformation gained a foothold is surprising in view of the correct teachings of *The ARRL Handbook (Ref 1), The ARRL Antenna Book (Ref 2)*, the works of Grammer *(Refs 3 through 5)*, Goodman *(Ref 7)*, McCoy *(Refs 8 through 13 and 41)*, Drumeller *(Ref 14)*, Smith *(Ref 15)*, and especially two articles addressed to a subject nearly identical to this one by Grammer *(Ref 6)* and Beers *(Ref 16)*. One objective of this book, therefore, is to identify some of the many erroneous concepts concerning reflection principles, with sufficient clarity to make you question your own position on the subject. Once we correctly understand mismatch and reflections, we can obtain improvement in operational antenna flexibility, similar to going VFO after being rock-bound with a single crystal. And when we discover how little we gain by achieving a low SWR on the average feed line, we will avoid unnecessary and time-consuming antenna modifications. Such modifications often involve hazardous climbing and precarious operations on a roof or tower, which can result in injuries or even death. Let's kill SWR misconceptions—not ham operators!

Sec 1.2 Open-Wire Versus Coax Feed Lines

The theory behind the transmission of power through a feed line with minimum loss by eliminating all reflections—terminating the line with a perfect match—is equally valid, of course, for open-wire and coaxial lines. But in the days of open-wire lines prior to our widespread use of coax, theory was tempered with practical considerations. Open-wire line was, and still is, used with high SWR to obtain tremendous antenna flexibility relative to operating over a wide range of frequencies with high efficiency. This is because all power reflected from the feed-line-to-antenna mismatch which reaches the input source is conserved, not dissipated. The power is returned to the antenna by re-reflection in the antenna tuner (Transmatch) at the line input. But, although the loss from reflections and high SWR is not zero, this additional loss is negligible because of the low attenuation of open-wire lines. If the line were lossless (zero attenuation), no loss whatever would result because of reflections. (This is discussed further in Chapter 6, in connection with Fig 6-1.)

The error in our thinking that standing waves on coaxial line must always be completely eliminated originated quite naturally, because the permissible reflection and SWR limits are much lower than in open-wire lines. When using coax for truly single-frequency operation, it makes sense to match the load and line to the degree economically feasible. But it makes no sense to match at the load in many amateur applications where we are chiefly

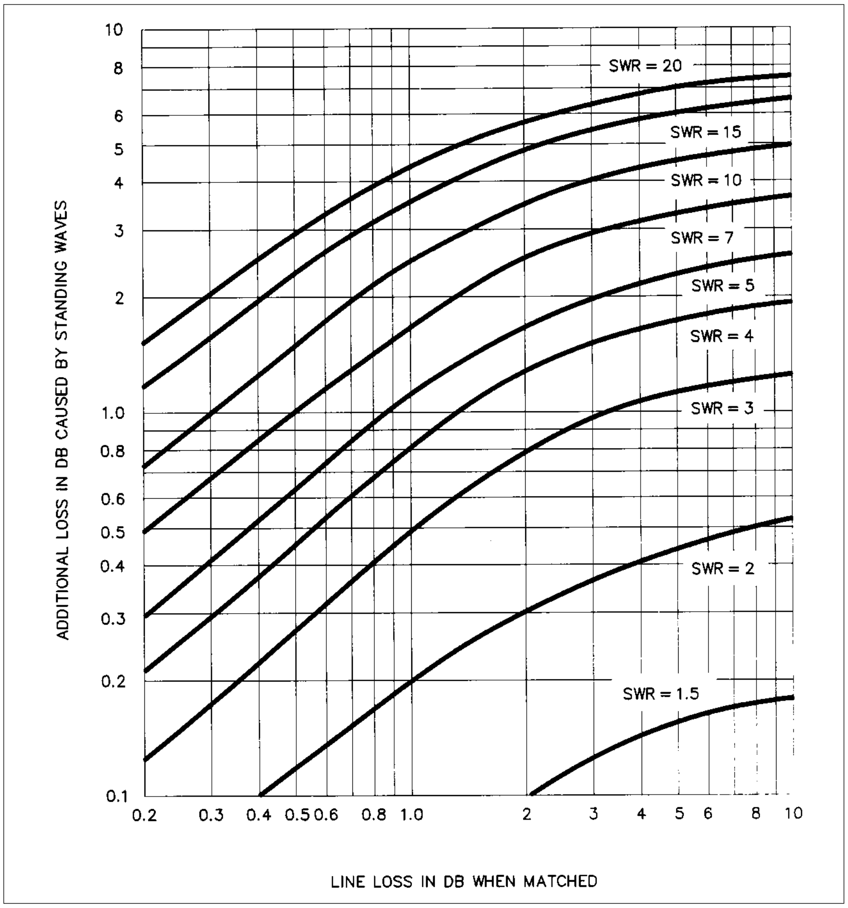

Fig 1-1—Increase in line loss because of standing waves (SWR value at the load). To determine the total loss in decibels in a line having an SWR greater than 1, first determine the loss for the particular type of line, length, and frequency, on the assumption that the line is perfectly matched. Locate this point on the horizontal axis and move up to the curve corresponding to the actual load SWR. The corresponding value on the vertical axis gives the additional loss in decibels caused by the standing wave. (Also see Fig 6-1.)

interested in operating over a band of frequencies! Single-frequency operators we are not, except as our misguided concern over increasing SWR restricts our departure from the resonant frequency of the antenna.

Many authors are responsible for perpetuating the unscientific and erroneous viewpoint that the coax-fed antenna must be operated at its self-resonant frequency. They have continually overemphasized the necessity for the antenna being matched to the line within some arbitrary, low SWR value to preserve transmission efficiency, and by implying that efficiency equals 100 minus percent reflected power. The viewpoint is wrong and unscientific because it neglects the most important factor in the equation for determining efficiency—line attenuation. And it is also erroneous because efficiency does not relate to reflected power by simple subtraction. Setting an SWR limit alone for this purpose is meaningless, because the amount of reflected power actually lost is not dependent on SWR alone. The attenuation factor for the specific feed line must also be included. This is because the only reflected power lost is the amount dissipated in the line because of attenuation—the remainder returns to the load. Some authors have so wrongly conditioned us concerning what happens to the reflected power that many of us have overlooked the correct approach to the subject. It is clearly presented in both *The ARRL Handbook* and *The Antenna Book* that transmission efficiency is a two-variable function of both mismatch and line attenuation. With this knowledge and by using a graph of the function appearing *The ARRL Handbook*, presented here as Fig 1-1, the amateur can determine how much efficiency he will lose for a given SWR with the attenuation factor of each specific feed line. He can then decide for himself what the realistic SWR limit should be.

Sec 1.3 Unimportance of Low SWR Values

In our efforts to obtain low feed-line SWR values of 1.1, 1.2, or even 1.5 to 1, we have gone far past the diminishing-returns point with respect to efficient power transfer, even for single-frequency operation. It is like installing no. 4 or no. 6 wire in a house-wiring run where no. 12 wire is sufficient. Reference to the basic transmission-line equations, which have always been readily available in engineering texts and handbooks *(Refs 1, 2, 17, 18, 19 and 33)* verify this analogy. In addition, such references make it clearly apparent that authors who simply insist on low SWR, or find 1.5 or 2 to 1 objectionably high, have failed to comprehend the true relationship between reflected and dissipated power. From the viewpoint of amateur communications, it can be shown mathematically, and easily verified in practice, that the difference in power transferred through any coaxial line with an SWR of 2 to 1 is imperceptible compared to having a perfectly matched 1:1 termination. This is true no matter what the length or attenuation of the line. Further, it can be shown that many typical coaxial feed lines we use in the HF bands with an SWR of 3 or 4, and often as high as 5 to 1, have an equally imperceptible difference at the receiving end. When feed-line attenuation is low, allowing such higher values of SWR permits operating over reasonably wide frequency excursions from the self-resonant frequency of the antenna with the imperceptible power loss just described, in spite of the prevalent impression to the contrary.

The relative unimportance of low SWR when feed-line attenuation is low is demonstrated rather vividly in the following two examples of spacecraft antenna applications. First, NOAA's TIROS-ESSA-ITOS-APT weather satellites, of which the design of the entire antenna system fed by four transmitters operating simultaneously on different frequencies, was the work of the author. (See the accompanying story at the end of this chapter.) The terminal impedance of each of four crossed dipoles (radiating circular polarization) at the beacon-telemetry frequency (108 MHz in early models) was $150 - j100$ ohms, for an SWR of 4.4, and reflected power of 40%. Matching was performed at the inputs of four separate feed lines by a complex stripline matching network fed by two 30-milliwatt telemetry transmitters. (We can't afford much power loss here!) The combined attenuation of the feed line and matching network was 0.2 dB, and the additional loss from the SWR on the feed line was 0.24 dB (5.4%), for a total loss of 0.44 dB (only 9.6%). On the prevalent but erroneous assumption that all reflected power is lost (40%), only 18.1 milliwatts would reach the antenna. Efficiency determined on the same erroneous basis would only be 60%. But 27.1 milliwatts was measured at the antenna. Of the 2.9 milliwatts lost in total attenuation, only 1.6 milliwatts was lost because of the 4.4:1 SWR. So the real efficiency would have been 95.5% if the feed lines had been perfectly matched at the antenna, but reduces only to 90.4% by allowing the 4.4 SWR to remain on the feed line. Second, in the Navy Navigational Satellite (NAVSAT), which is used for precise position indications for ships at sea, the antenna terminal impedance at 150 MHz is 10.5 – *j*48 ohms, for an SWR of 9.3, reflected power 65%. Also matched at the input to the feed line, the matched-line attenuation is 0.25 dB, and the additional loss from SWR is 0.79 dB, for a total system loss of 1.04 dB. This equates to approximately 1/6 of an S unit. This is an insignificant amount of loss for this situation, even in a space environment where power is at a premium.

Why did we match at the line input rather than at the antenna? Because critical interrelated electrical, mechanical and thermal design problems made it impractical to match at the antenna. Line-input matching (which is exactly what we do in using an antenna tuner, or transmatch) provides a simple solution by permitting the matching elements to be moved to a noncritical location. This design freedom afforded tremendous saving in engineering effort with negligible compromise in RF efficiency, in spite of SWR levels many unenlightened amateurs would consider unthinkable.

Another factor which has contributed to misunderstanding concerning power lost because of mismatched loads is the confusion between three different conditions of line usage: (1) one in which the incident, or forward *voltage* on the line is constant, independent of the load terminating the line; (2) one in which the forward *power* is constant, also independent of the load, and (3) one in which the forward power *varies* with changes in the load. (For the relative amplitudes of the SWR and line voltage in the first two cases, *(see Ref 19, Fig 1.3, p 6 and Fig 3.6, p 29)*.

The first condition involves laboratory and experimental work, which generally requires holding the forward *voltage* constant with variations in the load terminating the line. A constant-voltage source is usually obtained for this purpose by using a signal generator having a pad of from 20 to 30 dB of attenuation between its source and output terminals to absorb the reflected power. Absorbing the power in the pad prevents it from reaching the source in the generator where it would otherwise alter the line coupling and cause the output voltage of the source to vary. Consequently, the generator sees a perfect match for all terminating load conditions, and *all reflected power is lost* in the pad. This is a condition which is required to obtain certain laboratory test data.

The second condition involves a power source, or generator which maintains a constant forward *power* on the line independent of the load. The distinguishing feature of this condition is that the generator has an internal source impedance Z_S that is equal to the characteristic impedance Z_C of the transmission line into which it delivers its power. If the line is lossless, conservation of energy demands that power reflected from a mismatched load termination must cause the generator to deliver less power to the line by exactly the amount of power reflected. This is because the arrival of the reflected waves of voltage and current at the input of the line causes a change in line-input impedance from the characteristic impedance Z_C to a new value that presents a mismatch to the generator equal to the mismatch appearing at the mismatched termination of the line. However, the phasor voltage appearing at the input terminals of the line is the sum of the reflected and source phasor voltages at that point. The result is that, the addition of the reflected power to the reduced source power equals the original source power, thus the power entering the line remains the same as before the reflected power returned. Consequently, the forward power remains constant, but the power absorbed in the load is still reduced by the amount of the power reflected. However, *the reflected power is not lost*, because the reduction of the power absorbed in the load is simply because the source is now delivering less power to the line. *(See Ref 70, pp 204-205.)* The fact that reflected power is mistakenly thought to be lost under these conditions is probably the chief reason many have been misled to believe reflected power is also absorbed in the plate resistance of the output amplifier of our transmitters, which is not true for the reason explained above.

The third condition involves the power amplifiers in our transmitters, or transceivers, in which the forward power in the transmission line varies directly in response to the power reflected from a mismatched load, such as a mismatched or non-resonant antenna. The reason is that for whatever power we adjust the amplifier to deliver, any power reflected from the mismatched load is returned, either to the tank circuit of the amplifier or to an external line-matching network. There, by the action of re-reflection, the reflected power is added to the power delivered by the amplifier and returned to the mismatched load. In this third case, *no reflected power is dissipated in the plate circuit* of the amplifier because it doesn't reach the plate circuit, and with lossless line (and an ideal lossless tuner), *no reflected power is lost!*

As a result of these various misunderstandings, many amateurs never even wonder whether there are any benefits to be gained by not matching at the junction of the feed line and the antenna. Many even shun the use of open-wire lines (not the old-timers). They completely miss the joy of a QSY to the opposite end of the band with only a simple readjustment of the antenna tuner. The fear of reflections engendered by the exaggerated application of the theory to coax has crept into their thinking concerning any form of mismatched connection.

Adding still further to the confusion is the old-wives' tale that the reflected power is dissipated in the transmitter, causing tube and tank-coil heating and all kinds of other damage. This myth developed out of ignorance of the true mechanics of reflections and became the easy, but fallacious, explanation of what seems to be abnormal behavior in the transmitter when feeding a line with reflections. What really happens at the transmitter in the presence of reflected power is simply a change in coupling caused by a change in impedance at the input terminals of the feed line. This is explained in detail as we proceed from chapter to chapter. Then we may understand how to operate with absolutely no danger of damaging the amplifier while feeding into a line with high SWR. Although some rigs having solid-state output amplifiers have no provision for working into any load other than 50 ohms, rigs with tubes and pi-network output coupling circuits can work into impedances that far exceed the 2:1 SWR limits the manufacturers put on their warning labels. Hence, the manufacturers are also somewhat guilty of perpetuating the low-SWR myth.

Sec 1.4 Engineering an Antenna System

Engineering is the process of making workable compromises in design goals where theories and practical applications guiding different aspects of the design are in conflict, making it impossible to optimize all the goals. Good engineering is simply recognizing the correct choices in the compromises and relaxing the right goals, as in the spacecraft-antenna design described earlier. We amateurs spend many hours building and pruning antenna systems. Wouldn't it be worthwhile spending some of that time learning how to engineer the design in order to make correct trade-off decisions among related factors instead of letting old King SWR dictate the design?

FIRST, we need to improve our knowledge of reflection mechanics and transmission-line propagation to understand:

1) why reflected power by itself is an unimportant factor in determining how efficiently power is being delivered to the antenna.

2) the effect of line attenuation to discover why it is the *key* factor which tells us when and how much to be concerned with reflected power and when to ignore it.

3) why *all* power fed into the line, minus the amount lost in line attenuation, is absorbed in the load *regardless of the mismatch at the antenna terminals.*

4) why reflection loss (mismatch loss) is canceled by reflection gain through re-reflection obtained by the impedance matching device at the input of the line *(Ref 19, p 38, Ref 25 Part II, p 33, and Ref 136, p 17).*

5) why a low SWR reading by itself is no more a guarantee that power is being radiated efficiently than a high SWR reading guarantees it is being wasted.

6) why SWR is not the culprit in transmitter-loading problems—why the real culprit is the change in line-input impedance resulting from the reflected power, and why we have complete control over the input impedance without necessarily being concerned with the SWR.

7) the importance of thinking in terms of *resistive and reactive components of impedance instead of SWR alone*, and why SWR by itself is ambiguous, especially from the viewpoint of the selection and adjustment of the coupling and matching circuitry of an external line-matching network.

SECOND, we need to become aware that with moderate lengths of low-loss coax, such as we commonly use for feed lines, loss of power because of reflected power in the HF bands can be insignificant, no matter how high the SWR. For example, if the line SWR is 3, 4, or even 5 to 1 and the line attenuation is low enough to ignore the reflected power, reducing the SWR yields no significant improvement in the radiated power because practically all the power being fed into the line is already being absorbed in the load (the antenna). This point has especial significance for center-loaded mobile whip antennas, because of the extremely low attenuation of the short feed line, which is explained in detail in Chapter 6.

THIRD, we should become more familiar with the universally known, predictable behavior of off-resonance antenna-terminal impedance and its correlation with SWR *(Ref 2, Fig 2-7; Ref 71, p 2-6)*. This knowledge provides a scientific basis for evaluating SWR-indicator readings in determining whether the behavior of our system is normal or abnormal, instead of blindly accepting low SWR as good, or rejecting high SWR as bad. The following two examples emphasize the importance of this point by showing how easily one may be misled by a low SWR reading.

1) A ground system having 100 properly installed radials has negligible loss resistance *(Ref 20)*. AM broadcast stations

operating in the 540 to 1600 KHz band use either 120 or 240 radials, while the FCC requires a minimum of 90. With such a ground system the terminal impedance of a thin quarter-wave (1/4–λ) vertical is approximately the theoretical value of 36.5 + *j*22 ohms, and becomes approximately 32 ohms resistive when the antenna is shortened to resonance. Thus when fed with a 50–ohm line, the SWR at resonance will be close to 1.6, rising predictably on either side of resonance. But a ground system having only 15 radials has approximately 16 ohms of ground-loss resistance with this antenna. So if we remove a few radials at a time from the 100-radial system, the increasing ground (loss) resistance adds to the fixed radiation resistance, increasing the total resistance terminating the feed line. Hence, as each radial is removed, the terminating resistance comes closer and closer to 50 ohms, reducing the SWR. When enough radials have been removed for the ground-loss resistance to reach 18 ohms, the terminating resistance will be 18 + 32 = 50 ohms, for a perfect one-to-one match! But while the SWR went down, so did the radiated power, because now the power is dividing between 32 ohms of radiation resistance and 18 ohms of ground resistance! In cases where losses are very small, it is unnecessary to improve an impedance mismatch that produces an SWR of only 1.6:1, because only a 0.24 dB increase in power will result by reducing the 1.6:1 mismatch to 1:1. However, in this antenna situation, reducing the 1.6:1 mismatch to 1:1 by removing radials will cause a 36% decrease in radiated power, a loss of 1.93 dB in the ground resistance.

Ground resistance with 100 to 120 radials is typically in the range of 1 to 2 ohms, or less. However, ground systems having from two to four radials may have a loss resistance as high as 30 to 36 ohms, so now the SWR at the resonant frequency will be around 1.3 or 1.4. But when operating at other frequencies, instead of rising from this low value of SWR, as it should at frequencies away from resonance, the ground-loss resistance holds the off-resonant SWR to lower values than would result with a good ground. The low SWR simply indicates that the line is well matched, but it offers no clue that approximately half the power is heating the ground. Thus the low SWR in this case is misleading; instead of verifying that the antenna system is efficient over a wide frequency band, it is actually telling us that the efficiency is very poor indeed!

2) Some amateurs who employ a one-to-one balun believe that "one-to-one" means it provides an impedance match between the feed line and the antenna. This is an erroneous concept, because "one-to-one" only specifies the output-to-input impedance ratio of the balun. No matter what antenna impedance terminates the output of the balun, approximately the same impedance is seen at the input, depending on the quality of the balun. Nevertheless, these amateurs are convinced the baluns are matching the feed line to the antenna, because the SWR sometimes goes down dramatically when the balun is inserted. When using some baluns having ferrite cores, the SWR is less than 2:1 over the entire 75-80 meter band, where somewhat over 5:1 is normal at the ends of the band when the antenna is cut to resonate at the center of the band. Off-resonance SWR is sometimes reduced with these baluns because the ferrite core saturates while attempting to handle the reactive current which exceeds the maximum core-current level. Thus, the full excursion of the reactive component of antenna impedance is prevented from appearing at the input of the balun. All power above the saturation level is lost

in heating the balun, while the low SWR is deceiving the unsuspecting amateur. The true SWR will be unchanged by a 1-to-1 balun if it has a core capable of handling the current without saturating and if it has no significant leakage reactance. However, most transformer-type baluns having a ferrite core do have significant leakage reactance, and less than perfect coupling. Hence, these baluns cannot provide a true 1-to-1 impedance transfer, and the resulting SWR will not be the same as it would if the balun did have a true impedance transfer ratio. This is because when the leakage reactance is inserted between the antenna and the feed line, this reactance can either improve or worsen the match, depending on the magnitudes and signs of both the leakage and antenna-terminal reactances. In addition, an SWR indicator may not show the true SWR without a balun if antenna current on the outside of the coax is present at the SWR indicator *(Ref 36)*. These aspects of the balun problem, and how to avoid them, are discussed in detail in Chapter 21.

So it is important to know approximately what SWR to expect—if it is low, determine whether it should be low. Don't assume that a low SWR indicates success, or that it guarantees a great system! Be especially suspicious if the SWR remains low or relatively constant over a moderate frequency range, unless specific broadbanding steps have been performed on the radiating system. This knowledge is elementary and routine for an antenna engineer, but too little information in this area has been available for the amateur, considering the degree of his involvement with antennas. The variation of antenna-terminal impedance versus frequency is shown in *The ARRL Antenna Book (Ref 2, Fig 2-7, and Ref 71, p 2-6).* In addition, correlation of the impedance change with SWR is covered in detail in Chapter 12 in this book, to enable us to predict normal SWR, within limits with a non–resonant antenna terminating the feed line.

FOURTH, we need to re-examine the use of open-wire feed lines as tuned lines *(Ref 3, Part III, p 20; Ref 10; Ref 21, p 23)*, to discover that the principles used there are exactly what we have been discussing. Remember, with tuned lines we completely ignore the mismatch at the junction of the feed line and the antenna. Then we compensate for the mismatch with the tuner at the input of the line, over the entire frequency range of the band. The SWR may run as high as 10, 15, or even 20 to 1, but the power reflected from the mismatch is re-reflected back to the antenna by the tuner. Adjusting the tuner to obtain maximum feed-line current simply adjusts the phase of the reflected waves to re-reflect back up the line in phase with the forward wave, again reaching the antenna. Thus, the reflection *loss* from the mismatch is canceled by the reflection gain of the tuner. The phenomenon of reflection *gain* is explained in detail in Chapters 4 and 7.

Many of us older amateurs know from age-old practice that a 600 ohm line made of two no. 12 wires with six-inch spacing would work every time. We had little incentive in the earlier days to learn how they worked and why they transferred power *efficiently* with such high reflected power and SWR. Nor did we particularly care that tuning the plate tank for a dip in plate current was really canceling the reactance appearing at input of the feed line, or that the plate-current dip was just another way of viewing the phase adjustment of the reflected waves to coincide with the waves emanating from the source. And we didn't realize that, at the current dip, the reflected waves of voltage and current would add in phase with the voltage and current supplied by the source to obtain maximum feed-line and antenna current. This is probably one of the reasons for our misunderstanding of the similarity between open-wire and coaxial-line operation with mismatched loads. The principle is the same in both; only the degree of mismatch is different. In other words, for many applications, *coax can be used as a tuned line in precisely the same manner as open wire,* especially with lines of low loss that are not unreasonably long. The spacecraft antenna systems mentioned earlier are typical examples.

Thus, coax connected directly into the antenna may be operated successfully with substantial mismatch, in which case the SWR limits while operating away from the self-resonant frequency of the antenna are determined entirely by power lost because of line attenuation. Voltage breakdown and current heating is not a problem at our legal power limit with RG-8, RG-213 or RG-11, or with RG-58 or RG-59 at lower powers. This is because voltage at an SWR maximum is only the *square root* of the SWR times the voltage appearing on the line when the line is matched. The impedance at the input of the line will no longer be 50 ohms, but we can determine whether the output tank of the transmitter has sufficient impedance-matching range to permit feeding the line directly. This depends on the magnitude of the mismatch and the length of the line. The range is surprisingly high in some rigs, little in others *(Ref 4, Part III)*. If the matching range of the rig is insufficient, an external matching device (antenna tuner, transmatch, or ATU) can be used to obtain an impedance match and the correct coupling between the input of the feed line and the transmitter *(Refs 9 through 12 and 22)*. The point I am emphasizing here is that within the limits mentioned, *all required line matching can be transferred back to the operating position* instead of forcing the match to occur at the antenna feed point, without suffering any *significant* loss in radiated power. The use of this technique, which may come as a surprise to many, does not contradict any theory. It is actually an embodiment of the fundamental principle of network theory called conjugate matching *(Ref 17, p 243; Ref 19, p 38; Ref 35, p 49; Ref 69)* which is the basis for all antenna tuner, or transmatch operation with either open-wire or coaxial lines.

After learning of the benefits obtained with line-input matching in the two spacecraft examples described earlier, it is interesting to compare the results using this same input matching technique in typical 80- and 40-meter situations. The 80-meter amateur band is the widest in terms of percent of center frequency, and thus suffers the greatest SWR increase with frequency excursion to the ends of the band. A dipole cut for resonance at 3.75 MHz yields a mismatch, or SWR in a 50-ohm feed line somewhat above 6:1 at 3.5 MHz and about 5:1 at 4.0 MHz. As shown in Fig 1-2, in a 100-foot length of nonfoam RG-8, an SWR of 5:1 adds only 0.46 dB loss to the matched (that is, flat) line loss of 0.32 dB at 4.0 MHz. So out almost to the ends of the band, less than 1/12 of an S unit is lost because of the SWR, an imperceptible amount at the receiving end. This further verifies the principle and proves that full-band, coax-fed dipole operation on 80 meters also is practical. Even with the high SWR at the ends of the band, the loss cannot be distinguished from what it would have been had the SWR been a perfect one-to-one! On 40 meters, with the dipole resonated at 7.15 MHz, something is amiss if the SWR exceeds 2.5 at the band ends. And from Fig

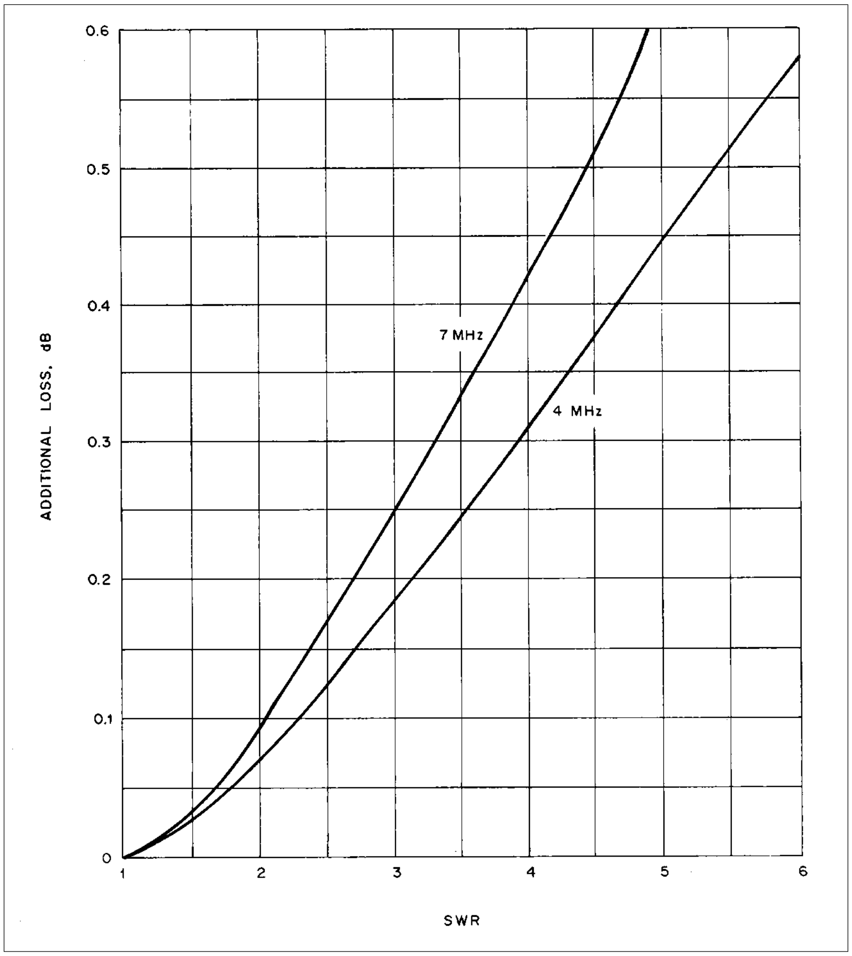

Fig 1-2—Effect of standing-wave ratio on line loss at 4 and 7 MHz. The ordinates show the additional loss in decibels over those for a perfectly matched 100-foot length of RG-8 line for the SWR values shown on the horizontal scale

1-2 it may be seen that this SWR adds only 0.18 dB to the matched loss, which at 7 MHz is 0.44 dB for 100 feet of RG-8 coax.

Sec 1.5 Non-reflective Load Versus Line-Input Matching

Now is a good time to contemplate the distinction between the no-reflection, perfectly matched load , requiring an inaccessable matching network at the antenna-feedline junction, and matching at the input of the feed line. From the standpoint of good engineering, as long as the SWR does not exceed the value above which one cannot afford to compromise further power in exchange for improved operating flexibility, the convenience and increased bandwidth afforded by matching at the line input is obvious.

But line-input matching also presents a real challenge to learning more about complex impedance, because in the presence of reflections, the line-input impedance is no longer simply the characteristic impedance ZC, but now has resistive and reactive components, both of which vary with changes in line length and with frequency. Thus, we need to understand complex impedance in order to choose and adjust corrected external conjugate-matching circuitry to couple the transmitter to the line, or to adjust the transmitter directly to the line if sufficient matching range is available. Practically all problems encountered while attempting to obtain proper coupling or loading to a line with reflections can be traced simply to not understanding the correlation of line length and relative phase of the forward and reflected waves with the resulting complex impedance seen at the input terminals of the feed line.

A detailed discussion of reflection mechanics and feed-line propagation is presented in subsequent chapters. Included is a novel means for explaining impedance transformation along the line in direct relation to forward and reflected waves, that simplifies the understanding of what does and what does not happen when a line length is changed, and how to select the correct length for given conditions. The relation of line attenuation to permissible SWR while using conjugate matching techniques, along with details on how to obtain proper coupling and loading of a transmitter to a line for which the input impedance has changed because of reflections, is also presented.