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Web Note

A COMPARISON OF THE WATSON-WATT AND PSEUDO-DOPPLER DF TECHNIQUES

This Web Note discusses and compares the primary features of the Watson-Watt and pseudo-Doppler DF techniques. The material is presented in an informal, easy-to-read format suitable for readers more interested in practical applications rather than a highly technical discussion of purely theoretical issues.

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In keeping with RDF Products' business philosophy that the best customer is well informed, RDF Products publishes Application Notes from time to time in an effort to illuminate various aspects of DF technology, provide important insights how to interpret manufacturers' product specifications, and how to avoid "specsmanship" traps. In general, these Application Notes are written for the benefit of the more technical user.

RDF Products also publishes Web Notes, which are short papers covering topics of general interest to DF users. These Web Notes are written in an easy-to-read format for users more focused on the practical (rather than theoretical) aspects of radio direction finding technology. Where more technical discussion is required, it is presented in plain language with an absolute minimum of supporting mathematics. Web Notes and Application Notes are distributed on the RDF Products Publications CD and can also be conveniently downloaded from the RDF Products website at www.rdfproducts.com.

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I OVERVIEW

In view of the fact that RDF Products DF systems employ the Watson-Watt DF technique with Adcock DF antennas, customers sometimes inquire as to the relative merits of Watson-Watt versus pseudo-Doppler DF systems. Although this is a complex subject and is somewhat application dependent, useful and informative comparisons can nonetheless be made. Furthermore, there is a certain amount of "pseudo-knowledge" associated with this topic that this paper attempts to dispel. These and related issues are addressed in the Sections that follow.

II HISTORICAL BACKGROUND

Radio direction finding is nearly as old as radio itself. The earliest commercially manufactured DF systems were built in Great Britain just after the turn of the century when vacuum tubes became commercially available as radio frequency amplification devices. These early systems generally employed two or more bi-directional loop antenna arrays. Their outputs were then amplified and fed to the deflection coils of a "goniometer" (a typical goniometer was a two- or three-phase mechanical resolver that employed an electromagnetically-driven pointer). A prominent DF system employed in those early years was the Bellini-Tosi system, followed somewhat later by the Watson-Watt "twin-channel" system (named after its inventor Sir R. A. Watson-Watt of Great Britain, who is perhaps better remembered for his key role in the development of the early British radar technology that proved so decisive in the Battle of Britain in 1940).

Loop-based DF systems were used for many years, but suffered from what was known as the "night-effect". Although these systems worked reasonably well for vertically-polarized signals during daylight hours, the horizontally-polarized signal components received at night as a result of skywave reception (which did not occur at these low frequencies during daylight hours) resulted in very erratic and unreliable bearings.

This problem was solved by Adcock, an Englishman who developed and patented (British Patent No. 130490) the Adcock DF antenna in 1919. Essentially, the Adcock antenna relied upon suitably spaced difference-phased vertical elements (aerials) to obtain the desired bi-directional antenna gain pattern with circular lobes. Since these vertical elements could be made nearly immune to the effects of horizontally-polarized signal components, good bearings could be obtained even on skywave signals. The invention of the Adcock DF antenna was a major breakthrough in DF technology.

Watson-Watt DF systems further improved in tandem with the rapid improvement of radio technology in general after World War I. When cathode ray tubes became available in the 1930s, CRTs eventually replaced the mechanical pointer displays used until that time (at least in the more sophisticated systems). The incorporation of the real-time polar CRT bearing display was another major breakthrough in DF technology, since the CRT trace length allowed the DF operator to much more easily discriminate between desired legitimate signals and undesired noise and multi-path. Both single- and multi-channel Watson-Watt DF systems were built during this time, some operating at frequencies well into the VHF range.

Doppler and pseudo-Doppler DF systems did not come into prominence until after World War II. The concept was first formally introduced in a 1947 paper written by Earp and Godfrey of Standard Telephones & Cables, Ltd. (a then-prominent British DF company). Pseudo-Dopplers are actually special single-channel implementations of interferometer DF systems (multi-channel interferometers did exist before World War II). The primary advantage of the pseudo-Doppler over the Adcock cited by that paper was the ability of the pseudo-Doppler antenna to be implemented as a wide-aperture array capable of reducing site errors induced by multi-path reception. With the passage of over 50 years, this contention by those authors has been well-validated as will be explained in the Sections that follow.

III DF TECHNOLOGY OVERVIEW

In the most general sense, all non-rotating radio direction finding systems employ a DF antenna having an array of spatially-displaced aerials (also referred to as "elements", three or more being required for non-ambiguous operation) that are illuminated by the received wavefront. The resulting output voltages produced by these aerials exhibit characteristics (phase, amplitude, or both) that are then measured. Since these characteristics are unique for every received azimuth in a properly designed DF antenna, the wavefront angle-of-arrival (bearing) can be ascertained by appropriately processing and analyzing the aerial output voltages.

To be more specific, modern non-rotating DF systems tend to fall into one of two broad categories. In *phase-comparison* DF systems, three or more aerials are configured in such a fashion that the relative *phases* of their output voltages are unique for every wavefront angle-of-arrival. Bearings can then be computed by appropriately analyzing the relative phases of these output voltages. Phase-comparison DF systems include interferometers and their Doppler and pseudo-Doppler derivatives.

In *amplitude-comparison* DF systems, two or more directive antenna arrays are configured in such a fashion that the relative *amplitudes* of their outputs are unique for every wavefront angle-of-arrival. Bearings can then be computed by appropriately analyzing the relative amplitudes of these output voltages. Amplitude-comparison DF systems include Adcock/Watson-Watts and Wullenwebers.

Although there are many different DF techniques available to the DF system designer, the only two that are truly capable of meeting the minimum performance requirements of a truly professional-quality DF system at low to moderate cost are the single-channel Adcock/Watson-Watt and pseudo-Doppler techniques (when properly implemented). The comparative advantages of these two DF techniques are addressed in depth in subsequent Sections of this paper.

IV OVERVIEW OF THE WATSON-WATT DF TECHNIQUE

As mentioned above, the Watson-Watt DF technique falls into the amplitude-comparison category. Users not familiar with this DF technique should refer to RDF Products Web Note WN-002 ("Basics Of The Watson-Watt DF Technique"), which can be downloaded from the RDF Products website or obtained from your sales representative. As of this writing, all RDF Products DF systems employ the single-channel implementation of the Watson-Watt DF technique using Adcock DF antennas.

V OVERVIEW OF THE PSEUDO-DOPPLER DF TECHNIQUE

A. MULTI-CHANNEL INTERFEROMETERS

Since pseudo-Doppler DF systems are actually single-channel implementations of interferometers as mentioned above, it is useful to first review the basics of interferometer DF systems in general. Fundamentally, a multi-channel interferometer DF antenna array typically comprises three or more omni-directional antennas that are appropriately spatially-displaced in the horizontal plane. The outputs of these antennas are each fed to identical phase-matched receivers that convert their received signals to a much lower intermediate frequency (IF) for subsequent convenience of processing. The IF output of each receiver is then fed to a common bearing processor that first examines the relative phase of the receiver IF outputs and then computes the wavefront angle-of-arrival (bearing) using an appropriate algorithm.

The computational algorithm employed can range in complexity from very simple to very elaborate, depending upon the number of antennas employed, their relative positions, and other factors. In all but the simplest configurations, a computer or microprocessor is necessary to implement the algorithm, which is one of the reasons that multi-channel interferometers were not widely used until well after World War II. (Although the interferometer concept was well-known before World War II, the absence of digital computers forced reliance upon analog-based resolvers, which allowed only the simplest and most basic implementations.)

Multi-channel interferometers are very elegant DF systems that are capable of excellent performance. When a large number of aerials and receivers are employed, multi-channel interferometers can be implemented as wide-aperture DF systems capable of suppressing bearing errors caused by multi-path reception (i.e., reflections off nearby towers, buildings, and other structures).

On the down side, multi-channel interferometers require a separate receiver for each aerial employed, and are thus very expensive, bulky, and cumbersome. As a result, they are employed primarily for high-end fixed-site DF applications where their expense and bulk can be justified. In general, they are not cost-effective for mobile and other DF applications where size and economy are important.

B. SINGLE-CHANNEL INTERFEROMETERS (TRUE-DOPPLER IMPLEMENTATION)

As mentioned, the concept of the Doppler DF system was first formally introduced in a 1947 paper written by Earp and Godfrey of Standard Telephones & Cables, Ltd. Although the authors may not have recognized it, the Doppler DF system is actually a single-channel implementation of the interferometer.

The concept of the Doppler DF system is based on the well-known "Doppler effect" whereby the *apparent* frequency of a transmitted wavefront received by a moving object is affected by its velocity. If the moving object is *approaching* the transmitter, the *apparent* frequency *increases* due to *compression* of the received wave. On the other hand, if the moving object is *receding from* the transmitter, the *apparent* frequency *decreases* due to *rarefaction* (expansion) of the received wave. As one would expect, the Doppler effect is proportionately more pronounced at greater velocities.

A practical example of the Doppler effect familiar to most people is the pitch (frequency) of a railway crossing warning bell as heard by a passenger on a moving train. As the train approaches the railway crossing, the warning bell pitch apparently increases . When the train recedes from the railway crossing, however, the warning bell pitch apparently decreases.

The earliest Doppler DF systems used this effect to advantage by placing a single aerial on the edge of a fast rotating turntable (the rotation rate and aerial position being precisely established by means of a servo-mechanism controlled by a very low-frequency rotational "tone" generated in the DF bearing processor). As the aerial approaches the transmitter, the apparent frequency increases. Similarly, as the aerial recedes from the transmitter, the apparent frequency decreases. It is thus clear that the aerial signal output becomes frequency modulated at a rate equal to the frequency of the rotational tone as a result.

This frequency modulated signal is then fed to an FM receiver, which recovers a replica of the rotational tone from the receiver FM demodulator. Although the frequency of this recovered tone is exactly that of the original rotational tone, it will, in the general case, be offset in phase from the rotational tone. With a little thought, readers can convince themselves that *the phase difference between the recovered tone and the rotational tone directly corresponds to the relative azimuth (bearing) of the received signal.*

C. SINGLE-CHANNEL INTERFEROMETERS (PSEUDO-DOPPLER IMPLEMENTATION)

Although the true-Doppler implementation of the single-channel interferometer DF technique as described above is intuitive and easy to understand, it is suffers from two very serious practical limitations. First, it is very difficult to spin the turntable fast enough to generate a modulation frequency sufficiently high to obtain a reasonable signal-to-noise ratio at the output of the FM demodulator for receivers with typical IF bandwidths. In fact, it is usually impractical to achieve rotational rates that even approach AC power line frequencies. Second, a mechanically rotating antenna array is cumbersome, expensive, and unreliable.

These practical difficulties were soon overcome by eliminating the rotating turntable in favor of at least three (four being more typical) discrete aerials equi-angularly positioned along the perimeter of a circle. To simulate mechanical rotation, the individual aerials are sequentially switched (or "*commutated*"). This is accomplished by breaking up the rotational tone (now referred to as the *commutation* tone) into four (assuming four aerials) equal-duration sequential phases (components), each of which is then used to activate the aerial switches in progressive sequence. In other words, for a four-aerial antenna, first the North aerial is turned-on and then turned-off, followed by the East, South, and West aerials. This simulated rotation is continuously repeated at the commutation tone rate.

This "pseudo-Doppler" DF technique has two major advantages over its above-mentioned true-Doppler counterpart. First, the unwieldy mechanics associated with physical rotation are eliminated. Second, a much higher commutation (rotational) tone can be employed, which results in far more recovered tone output from the receiver FM demodulator (and thus better sensitivity).

The equivalence of the pseudo-Doppler DF system to a single-channel interferometer is much easier to intuitively grasp than is the case for a true-Doppler DF system. The pseudo-Doppler can be viewed as an interferometer where the aerial outputs are sequentially sampled (multiplexed) for application to a single receiver rather than continuously applied by each aerial to its own dedicated receiver. By equi-angularly positioning the aerials along the perimeter of a circle, a very simple computational "algorithm" (FM demodulation and phase comparison to the rotational tone as discussed above) can be employed to ascertain the bearing.

VI COMPARATIVE ADVANTAGES OF THE PSEUDO-DOPPLER DF TECHNIQUE

The primary comparative advantages of the pseudo-Doppler DF technique over its Watson-Watt counterpart are site error suppression, DF antenna economy, and extended high frequency capability. These advantages are conditional, however, and require a careful evaluation of the underlying assumptions before being accepted uncritically at face value. These advantages are as follows:

1. **Site Error Suppression** - Site errors are fundamentally the result of anomalous conditions at or near the DF antenna that result in various distortions in the apparent angle-of-arrival of the received wavefront. As a result, the apparent angle-of-arrival may be different than the true angle-of-arrival. The biggest contributor to site errors are usually reflecting objects causing multi-path reception.

   Unlike an Adcock-based Watson-Watt DF system whose maximum DF antenna aperture (Adcock aerial pair spacing) can be no greater than 1.22 wavelengths at the highest operating frequency, there is no theoretical limit to the aperture of a pseudo-Doppler DF antenna. The aperture can be increased without bounds provided that additional aerials are appropriately added (theoretically, the maximum separation between adjacent aerials must not exceed 0.5 wavelengths at the operating frequency to avoid ambiguity, although in practice this separation should be considerably less). A wider aperture with more aerials improves wavefront averaging, which in turn tends to average out errors caused by multi-path reception.

   This is in sharp contrast to an Adcock DF antenna which, in its classical implementation, always functions electrically as a narrow-aperture antenna regardless of its physical aperture. The classical Adcock system thus has no ability to reject site errors and is greatly inferior to the pseudo-Doppler DF system in this regard.

A word of caution is in order, however. This site error suppression claim is sometimes inappropriately made by pseudo-Doppler system manufacturers for their narrow-aperture systems. Site error suppression is strictly a function of pseudo-Doppler antenna aperture and the number of aerials, and is not significant for narrow-aperture designs. If the pseudo-Doppler antenna in question has only four aerials, then it is inherently a narrow-aperture design with little site error suppression capability. Site error suppression does not become noticeable until the aperture exceeds 0.5 wavelengths (which also requires more than four aerials).

2. **DF Antenna Economy** - The electronic circuitry required for a pseudo-Doppler DF antenna is very straightforward, requiring at minimum only appropriate high-frequency switches and the necessary driver circuitry. This is in sharp contrast to a single-channel Adcock antenna, which requires carefully balanced sum-difference hybrids, balanced modulators, phase-matched components, phase/gain correction networks, and very careful and time-consuming testing. The simpler pseudo-Doppler DF antenna is thus more easily and economically designed and manufactured.

   The reader might infer from the above statement regarding DF *antenna* economy that pseudo-Dopplers also offer an advantage with regard to DF *system* economy. Although this can be the case in a low-end pseudo-Doppler DF system, there are two very important caveats that must be considered before accepting such a sweeping generalization at face value.

   First, the relative economy for the pseudo-Doppler DF antenna cited above applies only to *narrow-aperture* (4-aerial) designs. *Wide-aperture* pseudo-Doppler antennas (which require many more aerials, additional circuitry, and more complicated mechanics) are at least as expensive to manufacture as Adcocks.

   Second, the pseudo-Doppler DF technique (as explained in the "Adaptability To Non-DF Receivers" discussion in the next Section) is not well-suited to DF systems that rely upon general-purpose low-cost consumer-market communications receivers. The better of these receivers offers very good performance. As a result, they are extremely cost-effective for use in DF systems (even professional-quality ones) *provided that the DF technique employed is commensurate for use with receivers that have not been specifically designed for DF applications*. Unlike Watson-Watt DF systems, pseudo-Dopplers are unforgiving of the various performance anomalies encountered when using such general-purpose receivers not specifically designed for DF. Although many pseudo-Doppler DF systems employ these low-cost receivers anyway, the performance trade-off is of such magnitude that these systems can no longer be considered as truly professional-quality. If professional quality is to be maintained, it is therefore necessary either to perform extensive (and costly) modifications to the "low-cost" receiver, or (even worse from a cost standpoint) manufacture a receiver in-house that has been specifically designed to minimize receiver-induced bearing errors. In either case, the overall *DF system* cost will likely exceed that of a comparable Watson-Watt DF system employing a consumer-market receiver.

   The only exception to this might be pseudo-Doppler DF systems that are not required to provide wide frequency coverage - such systems could function with a simple receiver that could be cost-effectively manufactured in-house, even in small quantities. In the general case, however, most DF requirements demand wider frequency coverage that cannot be accommodated at low cost, and it is this more general case that this paper primarily addresses.

It is clear then that the pseudo-Doppler's advantage in DF antenna economy translates into overall DF system economy only for low-end sub-professional-quality systems. The many low-cost pseudo-Doppler DF systems on the market today all fall into this category.

3. **Extended High Frequency Capability** - The more complex electronic circuitry required by the Adcock DF antenna is such that as a practical matter, it is not feasible to design a *manufacturable* wideband DF antenna capable of good and consistent performance at frequencies over 1000 MHz or so. The simplicity of the electronics associated with a pseudo-Doppler system is such that there is no reason why a manufacturable wideband DF antenna with good performance up to 2000 MHz or more should not be possible.

In summary then, the primary advantages of the pseudo-Doppler DF technique over its Adcock/Watson-Watt counterpart are site error suppression capability, antenna economy, and the potential for extended high frequency capability. In mobile DF applications, however, where size and cost constraints generally require the use of 4-aerial narrow-aperture DF antennas, the site error suppression advantage disappears. Furthermore, the advantage of antenna economy does not translate into system economy where minimum standards of professional-quality performance must be met. In mobile DF applications below 1000 MHz then, the only remaining major advantage of the pseudo-Doppler technique is its potential for extended high frequency operation.

In a sub-professional-quality pseudo-Doppler DF system where the above-mentioned performance degradation associated with the use of a low-cost consumer-market receiver can be accepted, economy re-emerges as an advantage. *This is beyond a doubt the true reason for the current popularity of the pseudo-Doppler DF technique among most DF equipment manufacturers.*

It is probably fair to say that the pseudo-Doppler's strongest technical advantage over its Watson-Watt counterpart is the site-error suppression capability that can be obtained in its wide-aperture implementation. One of the major uses of such wide-aperture pseudo-Doppler DF systems in the United States has been for air traffic control applications at flight service stations without radar. The DF antennas employed by these systems typically employ 32 aerials with an aperture of 1.3 wavelengths.

VII COMPARATIVE ADVANTAGES OF THE WATSON-WATT DF TECHNIQUE

The Adcock-based Watson-Watt DF system has many significant performance advantages over its pseudo-Doppler counterpart, particularly for mobile or transportable DF applications where size constraints force the use of compact narrow-aperture DF antennas. These advantages are as follows:

1. **DF Sensitivity** - In order to obtain good DF sensitivity, pseudo-Doppler systems must employ a rather high commutation rate (in order to achieve sufficient FM deviation for efficient FM demodulation). Since the designer's latitude to raise the commutation rate is limited by various other system constraints, a compromise is required that results in reduced DF sensitivity. Since a Watson-Watt system relies on an AM tone encoding technique (somewhat analogous to pseudo-Doppler commutation), demodulation efficiency is unaffected by the tone frequencies (due to the inherent nature of AM demodulation). The designer is therefore free to set the tone frequencies to more favorably meet other system design constraints without compromising DF sensitivity.

   Pseudo-Doppler DF systems also suffer from bearing errors caused by aerial re-radiation. To avoid excessive bearing errors, it is necessary either to employ very short (i.e., insensitive) aerials, or use resistive loading to reduce aerial re-radiation (which also degrades sensitivity). The inherent symmetry of Adcock DF antennas is such that aerial re-radiation causes negligible bearing error, with the result that Watson-Watt DF systems are capable of excellent bearing accuracy even at the resonant frequency of the aerials. Adcock DF antennas thus do not require shortened aerials or other measures that compromise sensitivity to preserve bearing accuracy.

2. **Bearing Accuracy** - As mentioned in the discussion of DF sensitivity above, pseudo-Doppler DF systems suffer from bearing errors induced by aerial re-radiation. Recalling that the pseudo-Doppler DF system ascertains the apparent wavefront angle-of-arrival by examining the relative phase of the aerial output voltages, it is not difficult to visualize how inter-aerial shadowing and re-radiation can result in phase perturbations that degrade bearing accuracy. Although this can be mitigated by employing very short aerials or resistive loading as mentioned above, in most applications the resulting loss in DF sensitivity severely limits the designer's latitude to reduce bearing errors using this method. In fact, pseudo-Doppler DF systems almost invariably trade-off significant bearing accuracy to help mitigate the loss in sensitivity. Adcock DF antennas, in sharp contrast, do not suffer from this problem and therefore require no such trade-off.

   Another factor that degrades pseudo-Doppler bearing accuracy is variation in receiver group delay. By its very nature, the pseudo-Doppler DF technique is highly vulnerable to bearing shifts caused by receiver group delay variations (particularly in the receiver IF filter). The problem typically manifests itself as a bias error when the receiver is not tuned precisely on frequency, or as a bearing shift when a different receiver IF bandwidth is selected. The problem can also occur when changing receiver bands. Very careful receiver design is required to mitigate this problem. The magnitude of this error is proportional to the commutation rate, which unfortunately needs to be high for best DF sensitivity. In sharp contrast, the signal processing technique in a properly designed Watson-Watt DF system is such that the severity of this problem is typically several orders of magnitudes less. Watson-Watt DF systems are therefore virtually immune to bearing errors induced by receiver mistuning or IF bandwidth selection.

RDF Products VHF DF systems provide typical bearing accuracies of 1.5 degrees RMS on an ideal site. This degree of accuracy is achieved without site calibration. Of course, as with any DF system, a significant additional error factor is imposed when the system is installed on a mobile platform (or any non-ideal site).

3. **Adaptability To Non-DF Receivers** - During the past 20 years or so, it has become increasingly important in today's cost-conscious DF market that the selected DF technique be adaptable for use with the many low-cost (but highly capable) wide-coverage receivers that have become available on the consumer market. Self-contained DF receiver/processors have traditionally been very expensive as a result of low-volume production. Furthermore, the bulk of the cost is usually in the receiver (rather than the DF processor). With the appearance of low-cost wide frequency coverage consumer market receivers in the early- to mid-1980's, astute DF equipment manufacturers began to realize that major DF system cost reductions were possible by designing "stand-alone" DF bearing processors (ones without self-contained receivers) capable of interfacing with these new low-cost receivers (via an IF or audio signal interface). Since that time, the market has leaned increasingly toward such low-cost DF systems.

   This trend, unfortunately, does not play to the strengths of pseudo-Doppler DF systems (see discussion in the previous Section). As mentioned, pseudo-Doppler DF systems require very careful control of receiver group delay to prevent bearing shifts from occurring as a result of different band selection, IF bandwidth changes, or even slight receiver mistuning. In the traditional integrated DF receiver/processor, there is considerable latitude to employ special (and expensive) constant group delay IF filters and incorporate various compensation techniques to minimize this inherent weakness of pseudo-Doppler DF systems. Of course, the manufacturers of popular low-cost consumer-market receivers have no incentive to include such costly and unnecessary circuitry. As a result, manufacturers of stand-alone pseudo-Doppler DF bearing processors must either make difficult and expensive modifications to a selected consumer-market receiver, or simply accept major performance degradation. In summary then, the pseudo-Doppler DF technique is fundamentally incompatible with low-cost consumer-market receivers (at least where professional-quality performance standards must be maintained).

   The Watson-Watt DF technique, in sharp contrast, is largely impervious to these same anomalies that plague pseudo-Doppler DF system performance (see above discussion of DF bearing accuracy). A well-designed Watson-Watt DF bearing processor can interface to almost any receiver with good results.

   In most instances, the DF performance obtainable with a well-designed Watson-Watt DF bearing processor used in conjunction with a low-cost consumer-market receiver is very similar to that which can be obtained using a more traditional (and vastly more expensive) integrated DF receiver/bearing processor that has been specifically optimized for DF performance.

4. **Listen-Through Capability** - In many DF applications, it is important that the operator be able to monitor signal audio as well as obtain a line-of-bearing. The ability of a DF system to simultaneously perform these two functions is known as its "listen-through"

capability. The general problem with single-channel DF systems is that the modulation technique employed in the DF antenna to facilitate the DF process (i.e., commutation or axis tone encoding) can interfere with voice or other modulation that may reside on the received signal.

This problem is very serious in pseudo-Doppler DF systems, which are well-known for their "commutation noise". As mentioned, the commutation rate needs to be high to obtain good DF sensitivity, which places it in the voice audio range. FM voice audio is therefore badly distorted (recalling that the commutation process creates FM modulation at the commutation rate). AM audio usually sounds equally bad as a consequence of the fact that the soft-commutation aerial switches also impart AM modulation to the received signal as well as FM. Most pseudo-Doppler DF systems require that the operator disable DF antenna commutation (and thus DF capability) in order to obtain audio listen-through capability.

The Watson-Watt DF technique, in sharp contrast, provides far better listen-through capability. Since the DF antenna tone modulation technique is AM, FM listen-through capability is excellent due to the high AM rejection of most receiver FM limiter/discriminators. Listen-through capability is also good for AM signals as a result of the fact that the DF antenna modulation tone frequencies are well below the low end of the voice spectrum and can thus be easily attenuated in the audio output channel using a highpass audio filter.

All RDF Products DF systems provide full listen-through capability for both AM and FM signals. A sharp cut-off 250 Hz highpass filter is employed to filter out the DF antenna axis encoding tones. To accommodate SSB or other signals more vulnerable to tone interference, the DF antenna encoding tones can be disabled in cases where audio monitoring temporarily becomes more important than DF capability.

5. **Vulnerability To Resident Signal Modulation** - Another general problem with single-channel DF systems is their potential vulnerability to bearing interference caused by resident modulation on the received signal. In a pseudo-Doppler DF system, for example, signal modulation components falling on the commutation frequency "confuse" the DF bearing processor. In a Watson-Watt DF system, a similar problem occurs if resident signal modulation falls on either of the axis encoding tone frequencies. In both cases, bearing "jitter" results.

The problem is especially serious for pseudo-Doppler DF systems for two reasons. First, these systems typically employ high commutation rates (to improve DF sensitivity) that fall in the voice frequency range. Voice modulation therefore causes interference. Second, voice modulation in the VHF/UHF range is mostly FM. Since the pseudo-Doppler DF technique is also FM in nature, it is highly vulnerable to such interference. The problem can (and most always is) mitigated by employing longer DF bearing integration time, which tends to smooth the bearing jitter. Of course, the trade-off is that a longer bearing acquisition time must be accepted, which in turn diminishes the ability of the system to obtain good bearings on short-duration signals.

Watson-Watt DF systems are much more immune to the bearing interference problem for two reasons. First, the axis tone encoding frequencies are normally below 250 Hz, thus placing them well below the voice frequency range where they are less subject to interference. Second, since the Watson-Watt technique relies on AM (rather than FM) DF antenna tone encoding, the bearing interference problem is further reduced by the fact that the preponderant voice modulation technique at VHF/UHF is FM rather than AM.

The major exception to the Watson-Watt DF system's ability to reject modulation interference is for SSB signals. When voice-modulated SSB signals are applied to a standard envelope-type AM demodulator (as opposed to a product detector), low frequencies appear at the demodulator output that tend to fall on the low audio tone encoding frequencies, thus causing bearing jitter. RDF Products DF systems, however, mitigate this shortcoming by offering the operator the option to select longer bearing integration time and higher antenna tone encoding frequencies.

6. **DF Antenna Spectrum-Spreading** - As mentioned, all single-channel DF techniques rely upon an antenna tone modulation process to facilitate bearing encoding. As with any modulation process, sidebands are imposed on the received signal that widen its effective bandwidth. This effect is often referred to as DF antenna "spectrum-spreading". These sidebands are offset from either side of the signal frequency at the tone modulation frequency and (in general) its harmonics.

The problem stems from the fact that the DF antenna is a wideband device. Antenna tone modulation then is not confined only to just the desired signal, but to *all* signals received by the DF antenna. The above-mentioned "spectrum-spreading" results in a tendency for signals at adjacent frequencies to be widened in bandwidth to the point where these undesired new sidebands "splatter" onto the desired signal frequency. The unwanted result of this spectrum-spreading is a reduction in effective receiver adjacent channel rejection. The problem becomes most noticeable when attempting to DF on weak signals in the presence of strong adjacent channel signals.

Early pseudo-Doppler DF antennas (and even some present-day low-cost units) employed "hard-commutation" whereby the aerial output voltage is switched abruptly using saturated signal diodes. Since the resulting effective modulation waveform is nearly rectangular, large numbers of high-amplitude harmonics result that in turn cause severe spectrum-spreading.

Improved pseudo-Doppler designs employ "soft-commutation" whereby the aerial output voltage is switched more smoothly and gradually using PIN diodes or field-effect transistors. Soft-commutation generates far fewer high-amplitude harmonics, which in turn results in far less spectrum-spreading. All professional quality pseudo-Doppler DF systems employ soft-commutation.

Although Watson-Watt DF antennas employ balanced modulators rather than commutators, spectrum-spreading is still a problem unless appropriate means are taken to approximate sinusoidal modulation. The advantage of Watson-Watt DF antennas lies in the fact that since the modulation frequency is low (in comparison to the commutation rate of pseudo-Doppler DF antennas) the degree of spectrum-spreading is far less for a given number of significant sidebands created by the modulation process. To illustrate by example, if a pseudo-Doppler DF antenna employs a commutation rate of 1000 Hz and 15 significant sidebands are generated as a result of commutator non-linearity, a received CW carrier will be spread to an occupied bandwidth of plus and minus 15 kHz (30 kHz total).

A Watson-Watt DF antenna having the same amount of balanced modulator non-linearity will similarly generate 15 significant sidebands, but since the modulation frequency can be low (e.g., 160 Hz), the resulting spread will be only plus and minus 2400 Hz (4800 Hz total). This is a very significant difference that can greatly improve DF performance when attempting to track weak signals in dense signal environments.

7. **Threshold Performance** - Since pseudo-Doppler DF systems employ FM demodulation, they are subject to the advantages and disadvantages of FM reception in general. The primary theoretical benefit of FM reception for pseudo-Doppler DF systems is the FM improvement factor. It will be recalled that an FM discriminator yields an output SNR (signal-to-noise ratio) enhancement (as referenced to the FM discriminator input SNR) equal to 3•^{2} (where • •is the FM modulation index) *provided that the FM discriminator input SNR is at least 12 dB*. In other words, as long as a received signal is moderate to strong (i.e., greater or equal than the 12 dB threshold), a pseudo-Doppler DF system benefits from the classical 3•^{2} FM improvement factor.

   Unfortunately, there is less practical benefit to this enhancement than one might initially expect. First, the modulation index • •is small for a narrow-aperture DF antenna. The SNR enhancement is thus very modest. Second, since the noise equivalent bandwidth of the post demodulation bearing integrators of DF systems is very low (typically 3 Hz or less), good DF SNRs are already obtainable at the 12 dB threshold input SNR in any case.

   The primary drawback of FM demodulation for pseudo-Doppler systems is that once the FM discriminator input SNR begins to drop below the 12 dB threshold, the output SNR deteriorates very rapidly. Viewed on a real-time polar bearing display, the bearing would appear steady until the input SNR drops below 12 dB. At this point, bearing jitter would increase rapidly. A continued drop in input SNR would soon result in the disappearance of a useable bearing altogether, with the display showing only random noise bearings of large magnitude (analogous to the loud hissing sound that is audible when an FM voice signal drops below threshold). This is the basis for the familiar complaint about azimuth ring display pseudo-Doppler systems that the display "lights-up" (presents continuous random bearings) when the signal disappears.

   The AM-based Watson-Watt DF system behaves much more favorably. Although there is no SNR enhancement at the AM demodulator, a 12 dB input SNR nonethless results in a steady bearing. As the input SNR drops below 12 dB, bearing jitter increases, but much more gradually. Useable (though noisy) bearings are obtainable for an input SNR down to about 0 db. When the signal disappears altogether, random noise bearings are visible, *but at a very low magnitude* (in sharp contrast to the behavior of the pseudo-Doppler system described above where large magnitude noise bearings appear when the input signal disappears). This improved performance in the sub-threshold region is a major advantage of Watson-Watt DF systems, and is especially pronounced for those systems employing real-time polar bearing displays when tracking weak signals and ones that appear intermittently or are of short duration.

VIII SUMMARY AND CONCLUSION

All DF techniques have both strong and weak points, and it is important that users understand these comparative advantages and disadvantages and weigh them appropriately for their intended application. This is not always easy, since the issues involved are often subtle and somewhat technical.

Although the pseudo-Doppler is the best known and most widely used DF technique, its major technical strength (its site-error suppression capability when implemented as a wide-aperture fixed-site DF system) is not at all well matched to its predominant application (low-cost mobile and transportable DF stations requiring the use of compact narrow-aperture DF antennas). In fact, the Watson-Watt DF technique is far better suited to such mobile and transportable DF applications, particularly when budgetary constraints dictate the use of low-cost consumer-market host receivers.

The probable explanation for this pseudo-Doppler dichotomy that the simplicity of the pseudo-Doppler DF technique is such that many manufacturers have been lured into adopting it primarily on that basis alone (even though it is frequently not at all well-matched to their customers' applications, resulting in significant performance trade-offs). We therefore hope that this paper has been a constructive and useful tool to help illuminate these issues so that prospective DF customers can better make informed purchasing decisions. <>