50 Years of Instantaneous Frequency Measurement

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Abstract: Quadrature phase discriminators, the core of wideband instantaneous frequency measurement (IFM) receivers and multiple base-line interferometry for accurate DF, was invented in 1957, by SJ Robinson of Mullard Research Laboratories. Digital Instantaneous Frequency Measuring (DIFM) receivers have been universally used operationally for wide band monitoring of radar environments in naval, airborne and ground-based ESM systems all over the world for over 50 years. Its importance is such that many countries have developed their own IFM manufacturing capability with just minor architectural changes on the original design.
This paper describes the invention sequence[1], the development history, IFM design and performance principles, its general use and limitations in modern EW systems, and ends with a projection for the future.

List of Abbreviations

ADC	Analogue-to-Digital Converter
CRT	Chinese Remainder Theorem
CW	Continuous Wave
DC	Direct Current
DF	Direction Finding
DIFM	Digital Instantaneous Frequency Measurement
DPEWS	Design-to-Price EW System
DFT	Digital Fourier Transform
ESM	Electronic Support Measures
EW	Electronic Warfare
FFT	Fast Fourier Transform
IF	Intermediate Frequency
IFM	Instantaneous Frequency Measurement
MADGE	Microwave Aircraft Digital Guidance Equipment
MEL	Mullard Equipment Limited
MRL	Mullard Research Laboratories
S-Band	Frequency range 2GHz to 4GHz
S/H	Sample and Hold
SURC	Syracuse University Research Corporation
VSTOL	Vertical Short Take-Off and Landing

Introduction

The instantaneous frequency of an RF signal is defined by the rate-of-change of phase at the measurement instant. This can be approximated simply by measuring the phase difference across a known, short length L of delay line. If the line delay is T_d (= L/c) and the phase difference is $\varphi = 2\pi f T_d$rad, then the instantaneous RF angular frequency is approximately $f = \varphi/2\pi T_d$. When the frequency varies within the time T_d then the result more closely approximates the signal frequency at a time $T_d/2$ before the measurement instant.
The instantaneous frequency measurement (IFM) indicator exploits this principle by using a wideband vector phase discriminator to measure phase across a delay line of calibrated length. In a basic role, the sine and cosine components of the vector discriminator drive the x and y plates of an oscilloscope display. The displayed amplitude is then proportional to signal strength and the vector angle proportional to frequency.
A digital instantaneous frequency measurement (DIFM) receiver uses several wideband phase discriminators to measure the phases in digital form across a bank of different length delay lines. The lines are usually in geometric length ratios and the digitised line phases are processed to enable high precision and tolerance to system errors. The longest line defines the frequency accuracy, limited by the phase measurement performance of the basic phase discriminator, while the shorter lines progressively resolve longer line phase ambiguities. The shortest line defines the unambiguous frequency band cover. Major ambiguities in frequency measurement can occur if peak phase errors exceed the design deambiguity margin, controlled by component quality, the design delay line ratio, and the phase quantisation.

Analogue IFM: 1950-1960[P3,P4]

Work on wideband instantaneous frequency measurement was triggered in the 1950's by the outbreak of the Korean war and the perceived need to counter radar-controlled stand-off missiles.
Laboratories in the UK and USA were tasked to find suitable wide band detection and frequency measurement solutions. Over the period 1947 to 1952, waveguide components were the norm, but giving way to coaxial transmission line versions; the latter in turn being replaced by printed stripline[2] and microstrip[3] technology.
The coaxial ring or rat-race 3dB hybrid, Figure 1, was described by Tyrrell[4] in 1947; this unit opened options for IFM systems using coaxial delay lines. At the design frequency (wavelength), power entering port 1 divides equally in-phase between ports 2 and 4.

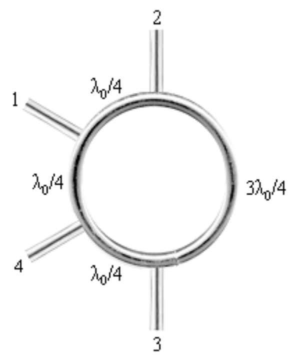

Figure 1 The Rat-race 3dB Hybrid

Conversely power entering port 3 divides equally but 180° out of phase. Away from the design frequency, both power level and phasing varies, so limiting the useful operating bandwidth to about 30%.

$$\frac{D2}{D1} = tan^2\left(\frac{\pi L f}{c}\right)$$

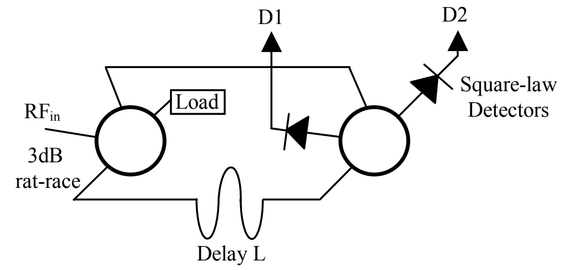

Figure 2 Early Instantaneous Frequency Indicator

Figure 2 shows an early instantaneous frequency indicating circuit based on rat-race hybrids sensitive to phase delay across a known length of delay line. The first hybrid splits the input signal equally between a direct and delayed path to the second hybrid. One crystal diode detects the sum of the input signals, whilst the second detects the difference. The square-law detected outputs are approximately (ignoring coupling amplitude-frequency dependence):

$$D1 \sim V\left(1 + cos\left(\frac{2\pi Lf}{c}\right)\right) \sim cos^2\left(\frac{\pi Lf}{c}\right)$$

$$D2 \sim V\left(1 + cos\left(\frac{2\pi Lf}{c} + \pi\frac{\lambda_0}{\lambda}\right)\right) \sim cos^2\left(\frac{\pi Lf}{c} + \frac{\pi}{2}\frac{\lambda_0}{\lambda}\right)$$

The ratio of the detector outputs generates an amplitude independent tan^2 monotonic function of signal frequency over a limited range about the design frequency. Log-video subtraction also produces a monotonic result. Detectors feeding square-rooting amplifiers and applying the video signals to X and Y plates of an oscilloscope produces a vector, angle proportional to frequency over a quadrant.

Various alternative circuits were being worked on at other laboratories,[5] some involving analysis of the standing wave along short-circuited or open-circuited lines or the interference between opposing signals in a transmission line medium. All these circuits were band-limited with poor indicated accuracy, exhibited DC offsets and signal amplitude dependence.

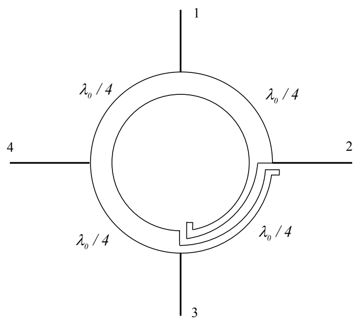

Figure 3 Phase Reversal 3dB Hybrid

In four key steps, engineers led by SJ Robinson at the UK Mullard Research Laboratories, transformed this simple system into the Digital IFM Receiver, the core component of modern ESM systems, still being commissioned today.

The first step was the invention by SJ Robinson[6,7] in 1955 of the phase reversal ring hybrid (Figure 3,4), after NE Goddard pointed out the phase reversal property of twin lines. A similar conclusion came to EM Hicken.[8]

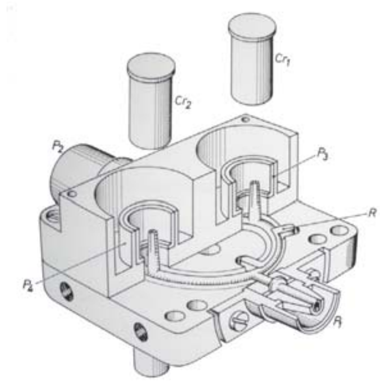

Figure 4 Phase Reversal Mixer Construction (MRL, 1956)

This involved replacing the long arm of the rat-race with what was eventually recognised as a short-circuited 90° 3dB coupler. Relative to the other arms this component inserts a frequency insensitive 180° phase change. A coupling amplitude-frequency dependence remains but the constant π phase shift significantly improves the useful operating bandwidth.

The second key development step was the invention,[9,10] by SJ Robinson in 1957, of the quadrature phase discriminator (Figure 5) as used in the MEL ESM equipment called 'Pendant'.

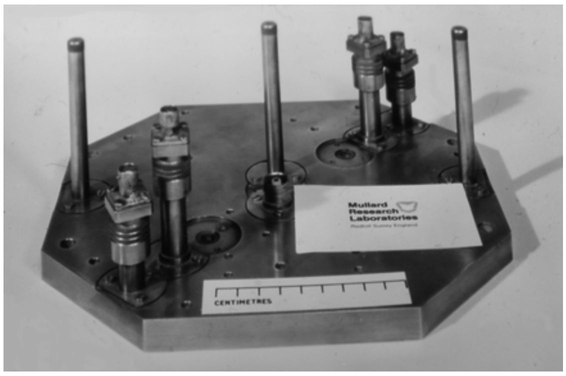

Figure 5 The Robinson Quadrature Discriminator (MRL, 1957)

Subtracting the outputs from the detectors 1,2 and 3,4 in Figure 6 produces linear vector X,Y components with no DC offsets, and angle proportional to frequency valid over the full 360°,

$$V_{12} \sim cos\left(\frac{2\pi Lf}{c} - \frac{\pi}{4}\frac{\lambda_0}{\lambda}\right)$$

$$V_{34} \sim cos\left(\frac{2\pi Lf}{c} + \frac{\pi}{4}\frac{\lambda_0}{\lambda}\right)$$

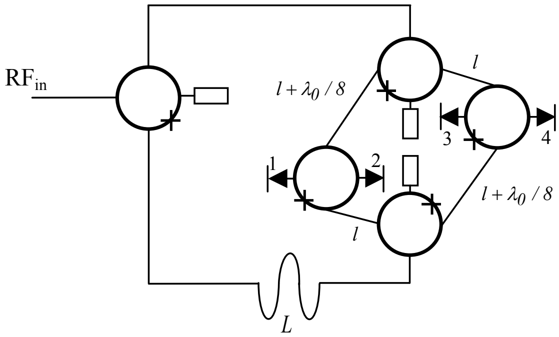

Figure 6 The Robinson Quadrature Discriminator Schematic

The only feature this discriminator invention lacked was true frequency-insensitive orthogonality. In early discriminators 90° phase difference was achieved by inserting $\pm\lambda_0/8$ extensions in feed lines, as shown in Figure 6. Later, the 90° quadrature 3dB coupler was substituted to improve the operating bandwidth.

Application to EW receivers in an analogue form followed almost immediately. Early analogue indicators exploited this by applying the detected orthogonal video components to the *X* and *Y* plates of an oscilloscope, producing a vector whose amplitude reflected the input signal power and angle from a prescribed datum was linearly proportional to the signal frequency. Video outputs are produced synchronously with input pulsed RF signals.

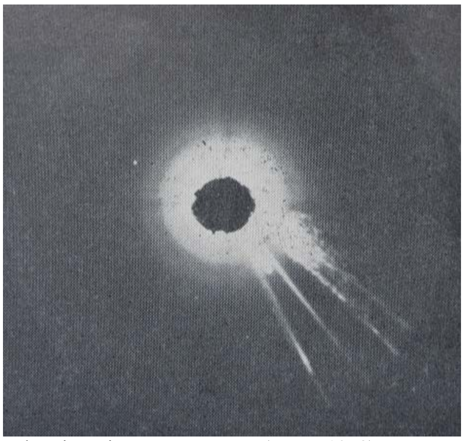

Figure 7 The First Live IFM Intercept (MRL, 1958)

Figure 7 shows a vector display photograph taken from a 'Pendant' equipment in 1958. This was the first instantaneous frequency indicator deployed operationally.

The attractions of this type of indicator for real-time radar pulse analysis rapidly became apparent. Also, exotic radars employing multiple components, pulse-to-pulse agility and within-pulse frequency chirp could be recognised immediately. Initially, the accuracy of frequency measurement was limited by component errors and calibration, but the technique of x10 line switching developed for Pendant soon improved this by an order of magnitude against the more persistent signals.

In 1959, as part of UK-US collaboration, a Pendant system was supplied to Syracuse University Research Corporation for assessment by US EW engineers.[5] This event aroused tremendous interest and was to seed the US and world-wide exploitation of IFM and DIFM development. Whilst the technique was protected by UK restricted patents, publication was permitted in the US. Two companies, Curry Mclaughlin and Len, Inc. (later to become Microwave Systems Inc.) and Anaren Microwave Inc, were set up in 1963 and 1967 respectively by Pendant evaluation engineers, who went on to develop and market IFM component and system products. Another SURC worker WR Kincheloe actually filed an unclassified US patent[11] in 1965 covering phase and instantaneous frequency discriminators of the Robinson design with no acknowledgement of prior art. It was probably this release that encouraged other major US companies to develop similar products for the EW market, soon followed by the EW industries in many other countries.

Pendant was derived from an ESM system named 'Porker', ordered for the Royal Navy from Mullard Equipment Ltd, which was widely fitted as outfit UA8/9 from 1962 (Figure 8).

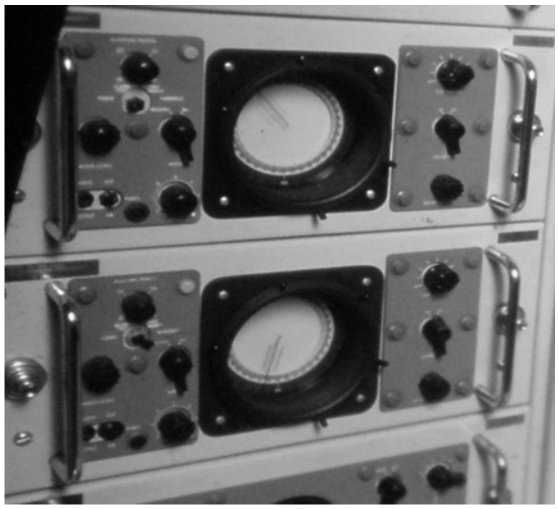

Figure 8 Porker ESM Equipment (MEL, 1962)

Digital IFM Inception: 1960-1970[P5-P10]

DIFM development continued at MRL. By 1962, the final two key steps in IFM transformation were the digitisation of video signals and unambiguous combining multiple parallel discriminators with various delay line lengths and ratios.[13,14,15] Up until 1967, workers in the US at SURC and Stanford Electronics Laboratories concentrated on producing single, compact stripline, discriminators that were linearised for each frequency band up to 18GHz and suitable for analogue displays.[5] Sinking of the Israeli destroyer Elath in October of that year by a Soviet Styx missile fired from an Egyptian torpedo boat, plus recognition of the superior performance of UK-deployed multi-discriminator digital IFM, was to change their minds.

At MRL, redundant digitisation, careful selection of delay line ratios, and fast deambiguity logic enabled useful tolerance to component errors, system noise and overlapping signals, providing excellent frequency measurement performance operationally.

In 1962, a two-discriminator breadboard system using a pair of Pendant discriminators, (JL Cook) in 1:4 delay line ratio, proved the viability of coarse digitisation deambiguity schemes. Following this success, and the upcoming availability of low-loss copper-clad dielectrics, a four-discriminator system, using a rat-race printed stripline design (R Levy) with delay lines in the ratios 1:4:16:64 was tested (RN Alcock, PW East) successfully against live radars in 1964 using a high-speed (<1μs) digital cathode-ray tube electromagnetic display[16] enabling real-time intercept presentation. Figure 9 shows the display of several such radar intercepts with frequency (vertically) versus pulse width (horizontally). With pulse-by-pulse DF data available, the synchronised frequency/bearing presentation proved an even more powerful sorting and analysis combination.

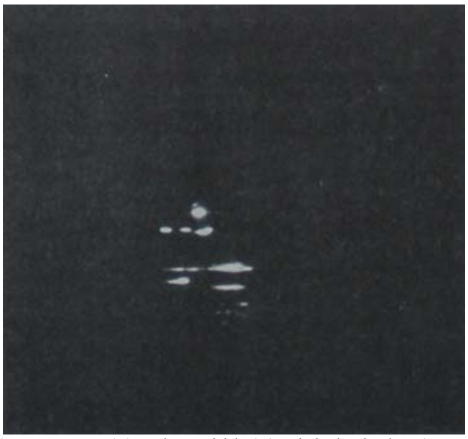

Figure 9 Frequency (*Y*) Pulse Width (*X*) Digital Display (MRL, 1971)

The equipment was very large by today's standards, filling a 19" rack. Experiments and analysis of the effects of simultaneous signals and limits of receiver sensitivity highlighted the technical advantages of using delay lines in binary ratios (1:2:4 etc:). Deambiguity analysis undertaken in 1964 predicted the architecture phase tolerance to digitisation, component and system noise errors for both geometric and prime factor ratios.[17]

The DIFM trials success was rewarded by a contract to supply an S-band unit built to production standards being placed by MoD in 1965. This became the first Digital Instantaneous Frequency Measurement (DIFM) Receiver used operationally first in 1966. The binary design comprised six 1/4 ATR boxes housing seven discriminators, suitable for flight trials. The equipment also formed part of the Abbeyhill prototype sea trial in summer 1967. It demonstrated 2MHz accuracy on pulses down to 250ns over the band 2.5 to 4.1GHz. With travelling wave tube amplification it operated close to tangential signal sensitivity.[18]

The binary design proved very effective against random simultaneous signals and although work on beat frequency detector and edge-detection flags was successful it was not found necessary to include these flags in a receiver design. Simultaneous signals were never a serious problem for MRL’s DIFM's.

The suppression effects of limiting amplifiers and the predictable frequency offsets, if these occurred, limited the effect on emitter analysis. In real scenarios, due to radar scanning varying the propagation/sidelobe characteristics together with helpful compression effects in limiting RF amplifiers, most components of multi-frequency radars could be intercepted and correctly analysed in practice. CW was more of a problem, partly coped with by AC-coupled or DC-restored video amplifiers. CW emitter scan amplitude variations, intermodulations and suppression of wanted signals could seriously affect field performance. Tracking on a front-end bandstop filter was found the most economic solution.

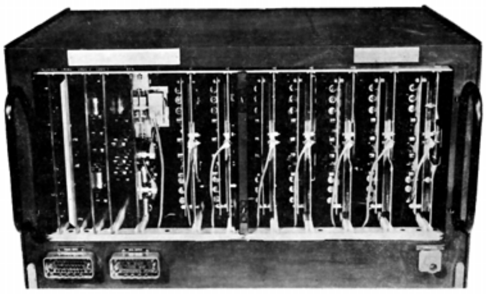

Figure 10 IFM3 S-Band Digital IFM (MRL, 1967)

Development at MRL moved rapidly and by the end of 1967 a more compact system using a new design (Figure 10) of 7 strip-line plug-in discriminators.[19] Around this time better quality low-loss laminates were becoming available enabling more compact consistent component design. The discriminators (designed by LW Chua, Figure 11) were configured with 90° overlap couplers. Some of the delays were printed and adjustable using a trombone section. This unit demonstrated 1MHz accuracy on 150ns pulses in the band 2 to 4GHz.

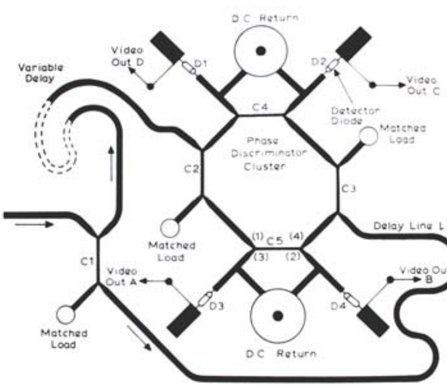

Figure 11 IFM3 Stripline Discriminator (MRL, 1967)

The design was subsequently used by Mullard Equipment Ltd as the basis for the development of four other units to cover the 1-18GHz band.

Patent applications for this and subsequent discriminator designs were impeded by the company and authorities in an attempt to prevent further loss of intellectual property design rights; in the event, to no avail.

Digital IFM Receiver Design[20,21]

All DIFM receivers produced since 1967 are largely based on the architecture shown in Figure 12. A filter at the RF input, followed by RF amplification, coarsely defines the receiver's operating band. The RF amplifiers ideally demonstrate good limiting characteristics at high signal levels, wide dynamic range, good pulse fidelity and low harmonic levels. Flat gain/frequency characteristics and low noise figures are, of course, equally desirable.

The receiver typically comprises a number of frequency discriminator channels and a threshold channel fed from a multi-way power divider.

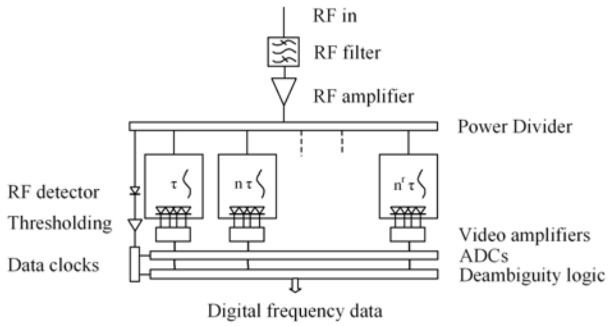

Figure 12 Multi-discriminator IFM Architecture.

The choice of the number of discriminators used in a design is dictated mainly by the specified performance required for the application. A digital measure of the delay-line phase is extracted. Fine digitisation is worth striving for since quantisation adds the equivalent of ±0.5-bit uncertainty to the discriminator phase estimation and reduces the design phase-tolerance accordingly.

Video amplifiers prior to digitisation can be AC-coupled, DC-restored, or DC amplifier types. AC-coupled amplifiers are the simplest and cope with different detector standing DC levels and variations due to biasing, but present problems when CW or high-duty cycle signals are intercepted. DC amplifiers or DC-restored types respond accurately to CW but are affected by RF amplifier noise levels and, unless special account is taken in the threshold detector channel, may be blocked while CW signals are present.

The threshold channel detects the presence or arrival of signals and level for reliable frequency measurement; it triggers timing circuits to initiate the analysis process.

After a short delay to allow the signal to propagate along the longest discriminator delay line, all discriminator phases are sampled, digitised, and stored. The phase data drive a logic network that outputs an unambiguous frequency code while accommodating discriminator phase-measuring errors.

The processing described above is the minimum necessary to indicate the frequency of a fixed-frequency pulsed signal of any duration. For more complex frequency- or pulse-modulated signals, a long-line spectrum analyser discriminator-based circuit with continuous sampling was developed to quantify within pulse modulation. Simultaneous or overlapping signals can cause problems with large line ratios, but their presence can be determined by various beat-frequency or edge detection means.

Resolving Ambiguities[17,20,21]

Phase measurements in IFM discriminators may be ambiguous since the true phase across long delay lines can contain unknown multiples of 2π. Also, given a limit to the accuracy with which the phases from multiple discriminators can be determined, there is a finite limit to the number of ambiguities that can be resolved.

When ambiguity-resolution processing fails, large errors corresponding to one or more 2π cycles of the faster discriminator occur.

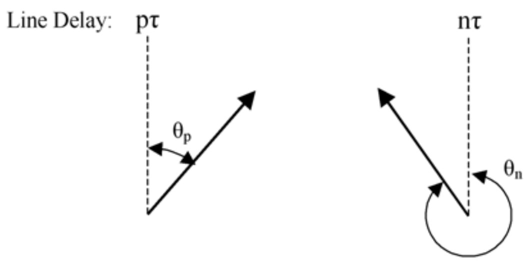

Figure 13 Adjacent Discriminator Vector-Phase Relation.

Ambiguity resolution can be understood, with reference to Figure 13, by considering two adjacent frequency discriminators with delay-lines in the ratio $\tau/n\tau$, where n is an integer (and $p = 1$).

Over a frequency range equal to $1/\tau$, the $n\tau$ discriminator vector rotates n times. At a given input-signal frequency the discriminators produce vectors defined by the discriminator sine and cosine outputs whose angles (phases), assuming no RF component errors, are related by

$$n\theta_p = 2\pi I_n + \theta_n$$

I_n can now be found either arithmetically, logically, or by means of a look-up table.

Errors in measurement of θ_p and θ_n ($d\theta_p$, $d\theta_n$) can occur and the value of I_n can still be derived providing that the result does not deviate by more than ±0.5 from its true integer value. Taking worst-case sign errors, the corresponding error-correction limits formula becomes

$$|\, n\, d\theta_p + d\theta_n | < \pi$$

This equation is fundamental to multiple-vector ambiguity resolution and can easily be checked by observing that the hour and minute hands of a clock

represent a twin-vector system with n = 12, and that the hour hand can move up to ± 15° (π/ 12 = 2.5 min on the minute scale) without the correct time being in doubt.
When the equation is satisfied, all ambiguities can be resolved and I_n evaluated. Design phase tolerances ($d\theta_n \approx d\theta_p$) for commonly used discriminator delay-line ratios are given in Table 1.

Delay-line ratio n/p	2	3	4	5	8	10
Phase tolerance	60°	45°	36°	30°	20°	16.4°

Table 1 Phase Tolerance for Typical Delay-Line Ratios

Large delay-line ratio designs are more economical in microwave components, but the lower phase tolerance can lead to unsatisfactory operation in field use.
Digitisation of vector angles in the channels reduces the phase tolerance, the amount depends on the degree of quantisation, the delay line ratio and the relative phasing between discriminators.
In the general case, where p is also an integer, both measurements may contain unknown integer multiples of 2π, these integers I_n, I_p can, however, be determined providing and n and p are mutually prime. The calculation is an application of the Chinese Remainder Theorem (CRT). The unambiguous range is $1/\tau$ and the error-correction limits formula becomes

$$| n\, d\theta_p + p\, d\theta_n | < \pi$$

Measurement Accuracy
Frequency measurement accuracy defined by the longest line is constrained by,

1. Discriminator component errors, φ_{disc}.
2. Phase digitisation errors, φ_q of up to ±0.5 the phase quantisation.
3. System noise, φ_{sn}.
4. The presence of interfering signals, φ_i.

The phase noise error distribution can be assumed to be Gaussian with an rms value given by $\varphi_{sn} = 1/\sqrt{S_q}$ rad

Where, S_q is the vector quadrature signal-to-noise ratio[22]. The probability of system noise-induced ambiguity failure (per sample or pulse) is estimated from,

$$p_{amb} = 1 - erf\left(\varphi_{res}\sqrt{\frac{S_q}{2}}\right)$$

where φ_{res} is the residual system phase tolerance after error sources 1 to 4 above are taken into account.

Simultaneous Signals[21]
By their nature, IFM receivers can analyse only one signal at a time. With simultaneous signals, treating the largest component as the wanted signal and other lower-level signals as interference, the receiver-design efficiency can be judged by the level of interference necessary to produce significant measurement errors.

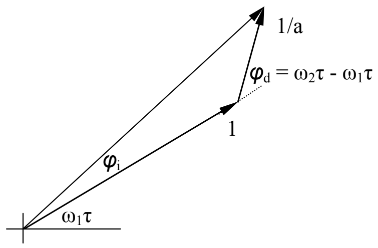

Figure 14 Interfering Signals

If a is the relative amplitude ratio (a>1, Figure 14). The phase error in estimating the large signal phase is

$$\phi_i = tan^{-1}\left(\frac{sin\,\phi_d}{a + cos\,\phi_d}\right)$$

where ϕ_d is the phase difference ($<2\pi$) between the two RF components in the discriminator considered.
The interference phase error ϕ_i has a maximum of,

$$\hat{\phi}_i = sin^{-1}(1/a)$$

when $\phi_d = cos^{-1}(1/a)$.

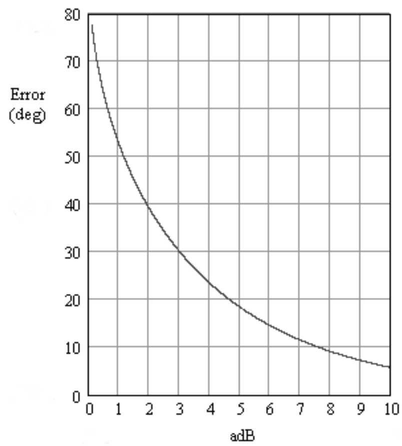

Figure 15 Phase Error - Simultaneous Signals.

Figure 15 shows that the absolute peak phase error in any one discriminator is 90°, and reduces to 30° for interference 3dB down on the main wanted signal. Referring this error to the longest line discriminator, assuming no major tracking errors, the effect on measurement accuracy can be estimated.
In addition, tracking errors can occur; the measured vector summation phases in adjacent discriminators will not in general remain in the same ratio as the discriminator line lengths.

Decca Discriminator
A competing company, Decca in the UK developed a 3-phase interference mode discriminator (Figure 16) using initially 120° transmission line phase sections replacing these later by Schiffmann[12] phase shifters to extend the frequency operating band. These units operated successfully in an airborne jammer, firstly designed in stripline circa 1968 (V Youel, T Woodley) and later

converted to the more compact high-dielectric constant microstrip substrate (AWD Ludgate).

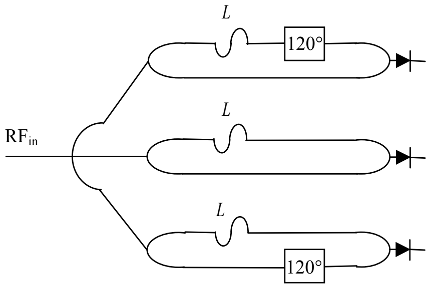

Figure 16 Decca 3-phase Discriminator

DIFM Deployed: 1970-1980[P11-P18]

The Abbeyhill ESM system, code-named Outfit UAA(1) was fitted with MEL DIFM's in Invincible class carriers, Type 42 destroyers and Type 21 and Type 22 frigates in the early 1970's. This represented the first defence deployment of production standard DIFM's in the world.

Anaren Microwave Inc and Microwave Systems Inc in the US were striving to lead the race to supply IFM systems to the world EW market. Largely using the discriminator circuit of Figure 17, but designed using proprietary in-house stripline technology. These companies sold discriminator assemblies mainly for analogue displays although the larger prime companies such as Litton, Raytheon, Hughes and Sanders soon began to procure discriminator sets from them, presumably for DIFM solutions. It is not clear how knowledge of the multi-discriminator digitisation and deambiguity technique reached the US EW industry, although DIFM procurement specifications were circulating in Europe at this time.

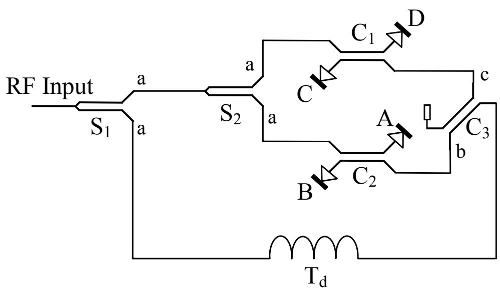

Figure 17 Frequency Discriminator Circuit

New technology becoming available (particularly for RF amplification) improved both manufacture and mechanical footprint, but the performance and principles remained largely comparable to that of the early MRL systems. By the late 70's, digital IFM became the preferred subsystem for ESM frequency measurement in all major platform fits across the world.

In the US, several small systems companies such as, Argosystems, EM Systems, Amecon, and Probe produced IFM-based EW systems. DIFM receivers were also specified in the more comprehensive versions of the DPEWS competition, won by Raytheon. In Europe, Selenia and Elettronica in Italy also offered Naval EW systems using IFM receivers.

Continuing development at MRL began to exploit microstrip discriminator designs on high dielectric constant alumina substrates.

In 1960, Wilkinson published[23] his work on the N-way in-phase splitter networks. This allowed realisation of a frequency discriminator using only Wilkinson splitters and 90° couplers, allowing true orthogonality between the sine and cosine hybrids so extending the operating frequency range and linearity. A discriminator circuit of this form is shown in In Figure 17.

90° 3dB couplers C_1 and C_2 and associated detectors function as multipliers. Coupler C_3 and power divider S_1 share the input power ideally equally between the mixers. The feeds to C_1 and C_2 are equal in length.

A microstrip discriminator based on an alumina substrate, Wilkinson splitters and mica-based overlap couplers[24] was developed at MRL (LW Chua) in 1970 (Figure 18).

The cluster $S_2\ C_1\ C_2\ C_3$ is a phase discriminator and it is made frequency sensitive by the addition of power divider S_1 and the delay line.

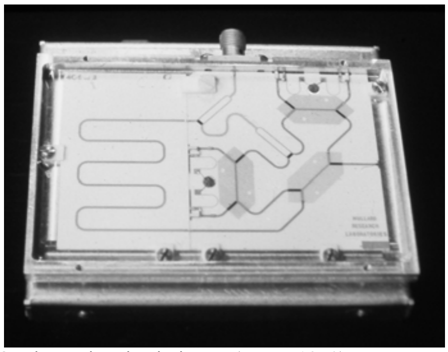

Figure 18 Microstrip Discriminator (MRL, 1970)

Some of the limitations of the circuit can be identified by a simplified analysis. Assuming that the voltage transfer coefficient of the in-phase splitter is *a* to either output port and that of the quadrature coupler is *b* to the direct port and c to the coupled arm, the low-frequency outputs from square-law detectors *A, B, C* and *D* are,

$$V_A \propto a^4b^2 + L_d a^2b^2c^2 + 2\sqrt{L_d}\,a^3b^2c\,\sin\theta$$
$$V_B \propto a^4c^2 + L_d a^2b^4 - 2\sqrt{L_d}\,a^3b^2c\,\sin\theta$$
$$V_C \propto a^4c^2 + L_d a^2b^2c^2 + 2\sqrt{L_d}\,a^3bc^2\cos\theta$$
$$V_D \propto a^4b^2 + L_d a^2c^4 - 2\sqrt{L_d}\,a^3bc^2\cos\theta$$

where, $\sqrt{L_d}$ represents the delay-line attenuation and θ is the line phase ($\theta = 2\pi fL/c$).

Subtracting detector outputs on each coupler, we obtain

$$V_A - V_B \propto \frac{1}{4}\left(\frac{b}{c}-\frac{c}{b}\right)\left(\frac{a}{\sqrt{L_d}\,b}-\frac{\sqrt{L_d}\,b}{a}\right)+\sin\theta$$

$$V_C - V_D \propto \frac{1}{4}\left(\frac{b}{c}-\frac{c}{b}\right)\left(\frac{\sqrt{L_d}\,c}{a}-\frac{a}{\sqrt{L_d}\,c}\right)+\cos\theta$$

This result shows that perfect operation of the discriminator requires that the quadrature power division be equal. If this is not so, then line attenuation will further affect the accuracy of phase determination. The maximum error in determining θ from the inverse tangent $(V_A - V_B)/(V_C - V_D)$ can be evaluated from equation by differentiation. Substituting theoretical values for a, $(1/\surd 2)$ and b and c, the bandwidth performance can be estimated.
For lossless, $\lambda/4$ length 3dB couplers,

$$b = \frac{1}{\sqrt{2 - \cos^2 \beta}} \qquad c = b \ \sin \beta$$

and $2\beta = \pi f/f_0$, where f_0 is the design centre frequency.
This simple theoretical model predicts phase-estimation errors of about 1° for octave-band operation, which rise to 5°, 12° and 21° for bandwidth ratios 3:1, 4:1 and 5:1, respectively. In practice, there are many other sources of phase error. Component match and isolation are never perfect, and, to achieve anywhere near this quality of performance, the detection sensitivities of the detectors need to be matched very closely. In addition, it is necessary to ensure that the delay line loss is balanced by an equal loss in the direct path.

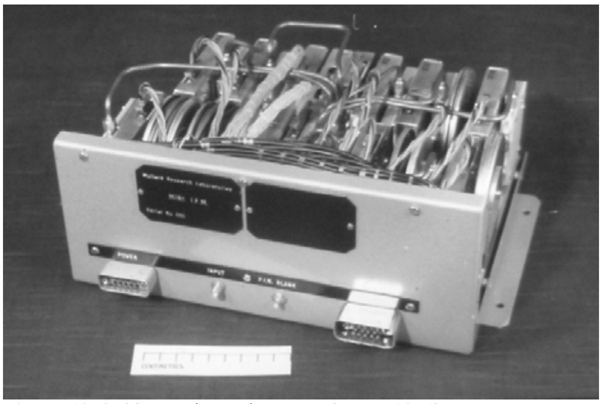

Figure 19 2-6GHz Microstrip DIFM (MRL, 1971)

New DIFM Developments: 1980-1990[P19-P27]

In this period DIFM receivers became established as the core frequency measurement unit in ESM fits of all major countries. Many patents appeared in this era describing techniques to solve the simultaneous and complex signal problems of basic DIFM.
The microstrip 8-discriminator cluster shown in Figure 20 was the IF basis for a superhet DIFM version in the MEL system range.
Many more microwave component and EW systems companies in the US also jumped on the DIFM design and manufacturing bandwagon including Aertech Industries, Sanders, Condor, NSL, TRW, Amecon, E systems, Kuras-Alterman, Plamic and Watkins Johnson to name a few. The larger US systems companies Lockheed, ITT, GE, Westinghouse, Raytheon and Northrop procured DIFM's for their prime systems. In Europe, Thompson, Dassault, AEG, Saab and HSA also developed DIFM design capability.

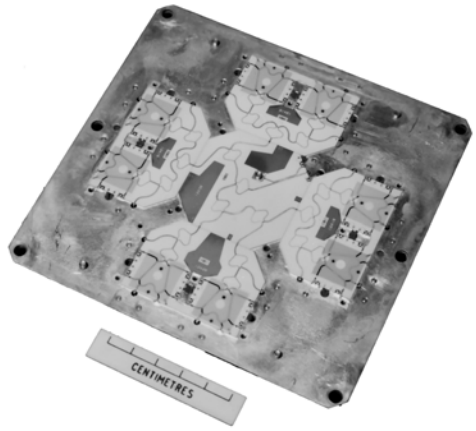

Figure 20 8-Discriminator Cluster (LW Chua, MRL, 1978)

In other parts of the world, Avitronics in South Africa, Saab in Sweden and Elisra, Rafael in Israel also acquired in-country competence. There is no doubt that in this period, all nations around the globe recognised the importance of DIFM for EW and developed their own design capability. All new defence procurements for major ESM systems for naval, land and airborne applications specified DIFM as the core frequency measuring component.
Most of the DIFM systems produced were based on the MRL quadrature discriminator with minor design and processing differences. However, an innovative alternative 3-phase reflection-mode discriminator was invented by JD Rhodes of Filtronic Ltd in 1983.[25]

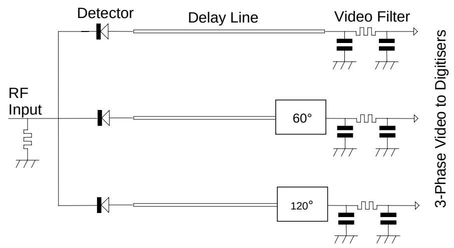

Figure 21 Filtronic 3-Phase Discriminator

This discriminator, unsurpassed in simplicity, is shown in Figure 21. In operation, the delay lines are effectively short-circuited, setting up a standing wave. The two other lines with inserted phase shifts of +60° and 120° so moving the standing wave phase by +120° and -120°. Interpolating the signals between the three detected standing waves provides instantaneous frequency information.
Another architectural modification aimed at adapting DIFM performance in simultaneous signal or blocking signal environments involved preceding a bank of similar narrow-band DIFM's with a switched RF multiplexer.[26]

DIFM Matures: 1990-2000[P28-P36]

Over this period there was much rationalising of the microwave EW industry. Whilst Anaren Microwave, remained the most successful of suppliers, having sold some 5000 units, there was insufficient new ESM systems demand to sustain so many suppliers. Technology was also improving. By incorporating multi-section couplers, bandwidth extensions up to 10:1 became practical, however the rising complexity of the radar environment ensured that conventional band split systems were still preferred for larger platforms.

In 1989, Thorn EMI purchased MEL and in rationalising, the combined company made the decision to no longer employ development resources to customise DIFM receivers for new contracts. They opted to specify new builds and procure these in open competition. It was a difficult decision as they had developed custom thin-film video hybrids by 1980 and designed an advanced high-speed multi-sample clocking system (MW Keeping).

For the larger platform ESM systems, progress was being made in the US to add capability to identify and analyse simultaneous signals and cope in high power CW environments.

With the ability to produce small 2-18GHz, DFD's some suppliers opted to increase functionality to the extent of producing compact DFD/ESM systems able to measure bearing amplitude and pulse width. Figure 22 is an example marketed by Teledyne Defence (Filtronic)[27].

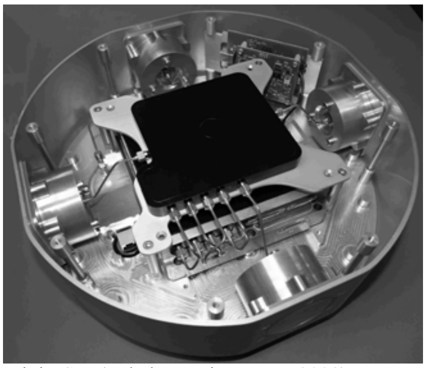

Figure 22 Mini ESM (Teledyne Microwave, 2009)

DIFM and Digitisation: 2000+ [P37-P39]

Although DIFM's are still widely deployed, very few traditional IFM manufacturers remain in 2010. In the UK, Teledyne Defence are still active in the market, and in the US, Anaren Microwave, Wideband Systems, Akon and LNX Corp survive, although some of the larger US and European systems suppliers have maintained an internal capability.

Within the past ten years, with the development of GHz clocked digital circuits and fast sample-and-hold/ADC's, the frequency measurement position of conventional DIFM receivers for Electronic Warfare has been challenged. These fast digital developments have opened the way for direct digitising of RF and processing by either the IFM algorithm or the fast Fourier spectrum analysis technique. Or indeed a combination of both; examples are described below.

The need for multiple IFM delay lines can be avoided by digitising the RF signal (or quadrature RF signals) and using relevant clock sampling intervals to collect the series of DIFM phases for deambiguity processing within the signal dwell (Figure 23). The sample intervals are no longer constrained to the original DIFM hardware delay line ratios and can be linear, fixed integer ratios or in prime factor sets. Linear sampling recovers sufficient data to enable analysis of several simultaneous signal components. Samples in prime factor sets can extend the overall unambiguous bandwidth to the limit of the ADC performance rather than the memory clocking speed.

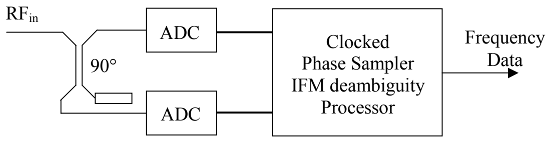

Figure 23 All Digital DIFM

For fast Fourier transform spectrum analysis, usually a binary number of equi-spaced samples of quadrature data are collected at the clock rate. The FFT algorithm is then applied to the number set and if this is processed by the time the next number set has been collected then the spectrum analysis process is continuous. With sufficiently fast sample-and-hold and ADC's, then information on RF signals higher than the clock rate is preserved but ambiguous (Figure 24).

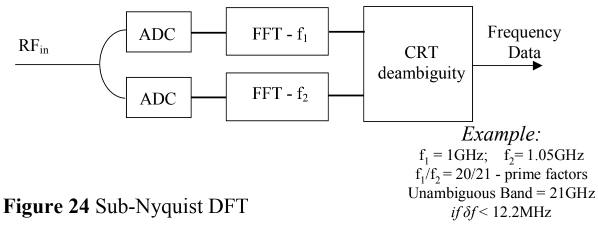

Figure 24 Sub-Nyquist DFT

Termed sub-Nyquist sampling; ambiguities can be resolved by collecting further sets of data using clock ratios f_1,f_2 that are mutually prime.[28] Reference 28 (MJ Underhill, MRL, M Sarhadi, CS Aitchison, MRL/Chelsea College, 1978) appears to be the first publication to describe the use of mutually prime clocks for unambiguous sub-Nyquist frequency analysis. The key component controlling operating frequency range is the sample-and-hold circuit preceding the ADC's; the sample aperture time must be very much shorter than the period of the highest frequency analysed.

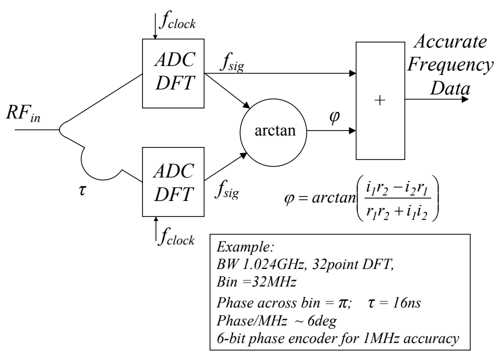

Figure 25 DFT+IFM Combination

A combination of DFT pre-filtering followed by IFM processing is shown in Figure 25. A signal appears in the same bin number in each DFT. Comparing the bin real and imaginary components provides a measure of the phase shift across the delay line from which the signal frequency offset from the DFT bin, can be calculated.

It is interesting to note that a recent innovation is to apply photonic technology to produce a frequency discriminator using optical modulation and delay[29].

Other Applications - Interferometry

The multi-discriminator phase processing concept described for IFM was also applied in parallel developments to multiple baseline interferometry - another important MRL innovation. Melodious, a two-interferometer technique (SJ Robinson, RN Alcock) used waveguide discriminators for passive ranging by measurement of phase-front curvature in land trials in 1964.

Figure 26 Waveguide Az-El Interferometer (MRL, 1965)

More successful was the application to multiple baseline interferometers to achieve high bearing accuracy and confidence for aircraft landing. To cover a wide field-of-view and a broad frequency band, prime factor baseline ratios were proposed to accommodate the finite antenna element aperture. A waveguide azimuth-elevation prototype as demonstrated (RN Alcock, RH Johnston) at MRL in the 1960's is shown[30] in Figure 26. Further development culminated in the MADGE - Microwave Aircraft Digital Guidance Equipment[31,32] (RN Alcock, RP Vincent, DA Lucas); an aircraft landing aid manufactured by MEL Equipment Ltd for guiding helicopters and VSTOL aircraft in confined landing sites. It used IF discriminators to achieve very high direction accuracy and prime factor ratios to achieve adequate azimuth field-of-view.

In the USA, between 1967 and 1977, CW Gerst and HA Hair of Anaren Microwave, with the assistance of S Rehnmark, developed another important innovation for EW while working in the IFM field. They demonstrated a digital bearing measurement system[33,34] comprising a 16-port circular array of directive elements followed by a Butler matrix, processed by a set of phase discriminators/correlators in 1977. The Butler matrix generates omnidirectional phase modes related to azimuth in the far field. By suitably choosing array size and high-order mode phases for digital deambiguity processing, excellent wideband all-round DF accuracy was demonstrated.

Conclusions

Instantaneous frequency measurement methods, pioneered by Steve Robinson at Mullard Research Laboratories[35] in the 50's have served the EW industry well for over 50 years and seem certain to continue to do so for many years to come.

Advances in digital processors, ADC's and sample-and-hold technology, however, are opening up a wide field of opportunity for alternative frequency analysers with some superior characteristics. Direct digitisation of microwave signals up to 40GHz may still be some way off, but parallel DFT systems using multiple clocks in prime ratios and state-of-the-art sampling digitisers are offering a feasible alternative.

There is no doubt that the ingenuity of development engineers will be challenged to choose a worthy DIFM successor from the vast array of possible architectures.

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