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Development of model radar systems between 30 and 900 GHz

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This paper, in a slightly fuller form and entitled 'Review of two decades of experience between 30 GHz and 900 GHz in the development of model radar systems', was presented at the 25th Meeting of the Electromagnetic Wave Propagation Panel of AGARD held in Munich on 4th–8th September 1978.

SUMMARY

Practical use has been made of frequencies above 30 GHz for the last 20 years in the UK National Radar Modelling Facility to investigate the characteristics of radar reflections from typical radar targets. This paper discusses the purposes, principles and methods of radar scale modelling. It also describes the several different types of measuring radar which are being used at frequencies up to 890 GHz to investigate various aspects of radar scattering. Some comments are made on methods of data reduction to simplify their use in the investigation of real radar problems. Possible future trends towards operation at frequencies up to 2 THz are indicated.

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1 Introduction

A National Radio Modelling Facility, developed and used by EMI Electronics Limited for the Ministry of Defence (Procurement Executive) and the Royal Signals and Radar Establishment[1,2] has been in operation for the last two decades to obtain detailed data on the scattering characteristics of radar targets. Continuous development is necessary to increase the scope of measurements and to extend the range of radio frequencies available. This development provides, as it has for 20 years, a stimulus for the advancement of technology at frequencies above 30 GHz up to 2 THz.

The initial interest of EMI Electronics Limited arose from a need to design, test and assess its own novel operational radar systems and it quickly became evident that the target reflection characteristics, required for such assessments, could only be obtained in sufficient detail by modelling methods. In order to perform modelling at scaled wavelengths, special purpose mm and sub-mm radars were designed and developed for use as reliable measuring instruments. .Many of the components needed for such radars were not available so that the development of passive components, and also of some of the sources and mixers, was necessary. The aim has always been the practical one of obtaining, in the most economical way, the target scattering information needed to assess the behaviour of a full-scale radar in operational conditions. To this end, considerable emphasis has been given, first, to stability and reliability in the measuring equipment and, second, to rapid and economical processing of the data.

Initial measurements were made in 1958 with a non-coherent pulsed radar at 35 GHz. The facility now covers three decades of frequency from 800 MHz to 890 GHz and comprises more than 30 different specialized radars. At any one time, seven of these radars may operate without mutual interference. Models of many different types of target have now been made using a wide range of scaling factors.

2 Radar Target Reflection Characteristics

Any target which reflects radar power imparts several characteristics to the received signal which may be of considerable significance to the operation of the radar. Signal strength is an obvious feature since, if this is inadequate over the radar integration period, the radar will fail to detect the target. The target aspect may not be constant over that period, however, and, as shown in Fig. 1, the signal strength from a typical aircraft target varies rapidly with aspect angle and may change by 30–40 dB for very small angular changes. Furthermore, even if the signal is detected, the modulation of signal strength as the aspect of the target varies may have an

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important effect on the operation of the radar, and the modulation frequency and depth would then be significant.

The target will also impart Doppler frequency and radar polarization characteristics to the signal and some radars may be sensitive not only to these but also to their modulations with respect to time. The directional data derived by a radar can be in error because of the glinting characteristics of the target, and the radar signal can even appear to come from a point outside the envelope of the target. To assess the performance of a given radar properly, a quantitative knowledge of all such target reflection characteristics is essential.

Most man-made targets are made of conductive metals or of substantially lossless dielectrics and these will be represented in the model by lossless metal or by dielectric materials of the same dielectric constant. However, if the target does contain lossy materials in its outer structure, i.e. either resistive conductors or dielectrics with loss, then these have to be represented in the model by more highly conducting materials. This is because the dimensions of electrical resistance require that it be scaled down by the same scaling factor S.

All the scattering effects, including interference effects, polarization effects and travelling-wave phenomena are correctly represented by such scale modelling.

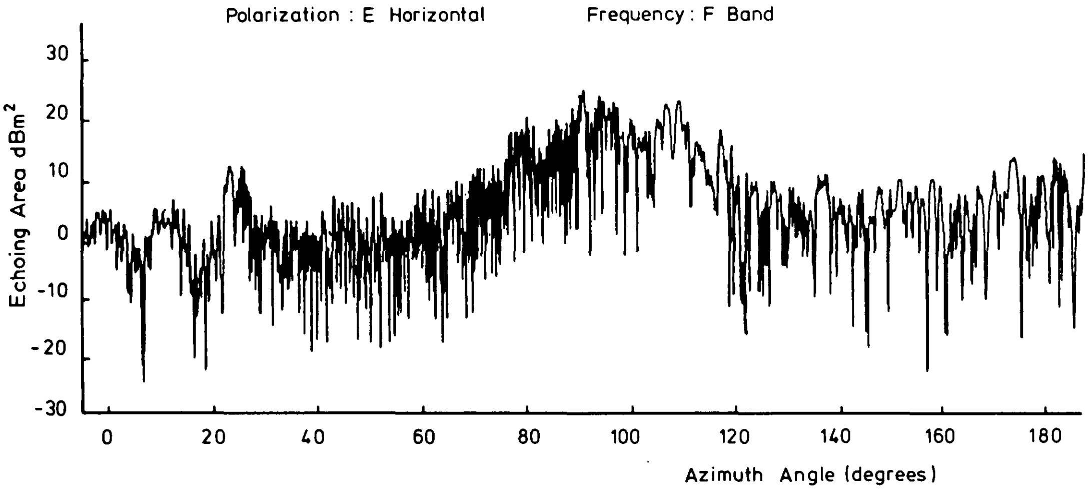

Fig. 1. Typical echoing area of HS125.

The determination and use of radar scattering characteristics was the subject of an AGARD lecture series.[3] This series considered three methods of determining the data: full-scale trials, calculation, and scale modelling. Results from some full-scale trials have been used to validate the scale modelling technique. Scale modelling is the only method which provides sufficient data efficiently and economically to permit an adequate assessment of modern radar.

3 Methods of Radar Scale Modelling

The properties of electromagnetic waves are such that, if all the linear dimensions are scaled down in the same proportion, S, then the fields will be of the same form. The echoing area of a target, in the modelled system, will be reduced by the square of S. Radar modelling makes use of these scaling properties; an accurate scale model of the target is made and viewed by a radar whose wavelength and modulation parameters have been appropriately scaled by the same factor as the target.

3.1 Model Targets and Their Support

Experience has shown the need for attention to detail in the model target. Any orifices and the cavities behind them are particularly important, as are those internal corners which cause multiple reflections. As an example, the internal parts of a jet engine may be more important than the external parts of the aircraft which it propels. Likewise any airscoops, landing lights, flaps, etc., are also significant. Signals 40 dB, or even 50 dB, down on peak reflections may still appreciably affect the performance and design of a radar. Also, the important detail of the backscatter signal is usually dependent more on the multiple small features than on the gross features of the shape.

For convenience and economy, the maximum dimension of a model target is usually in the range from 0·5 m to 5 m. This is large enough to permit correct modelling of the important small detail and yet is still convenient for handling. As a consequence, the scaling factor used for aircraft targets will usually be in the range from 1 : 4 to 1 : 20, while for ship targets a scale of 1 : 100

or even 1 : 200 may be used. The models must be supported in a manner to permit precise control of their attitude with respect to the model radar and to minimize the radar backscatter from the supporting system. This may be achieved either by the use of a tapered column to support the target or by suspending it on dielectric strings. Stability of the target requires isolation from wind and weather, achieved by operating indoors.

3.2 Elimination of Background Clutter

Interference between the backscatter from the building and that from the model target is avoided by using sharply-defined aerial beams on the radars and by pulse range-gating whenever possible. This is more effective than the use of radar absorbent materials and permits the operation of several radars in the one building without any mutual interference so long as p.r.f. interleaving is employed. The model radar pulse usually corresponds to at least three times the model target length, thereby ensuring a period when returns from all parts of the target coexist. As a result, the central part of the received signal is equivalent to that from a radar of longer pulse length (or even c.w.) and this central portion is extracted by gating in the receiver. If the full-scale radar uses a pulse which is shorter than three times the target length, then this pulse length is correctly scaled in the model radar.

3.3 Frequencies Used for Radar Modelling

Full-scale radars are in use from 0·4 GHz to 94 GHz and possibly beyond this range, but the greatest use is made of frequencies between 3 GHz and 10 GHz. Consequently, with scaling factors from 1 : 200 to 1 : 4 in the model targets (and even 1 : 1 sometimes), model radars from 0·8 GHz to 890 GHz have been required and built with a predominant interest in the upper region of this band, 30 GHz to 890 GHz.

Precise and stable radars for measurement purposes are now available throughout the band. The chart in Fig. 2 indicates how the model radar frequency and the scale factor of the model target may be chosen to simulate any given full-scale application.

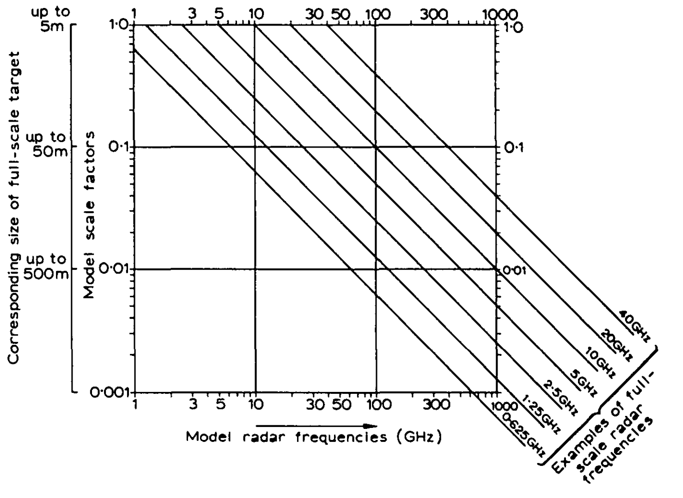

Fig. 2. Choice of model radar frequency and scale factor.

4 Radar Modelling Facility

The first measurements with the facility were made in 1958 and 1959 using 30 ns pulsed radars at 35 GHz and 70 GHz respectively. Scale model targets at scales 1 : 100 and 1 : 4 were used and sensitivities were adequate to measure 10^{-6} m^2 echoing area anywhere in a 5 m cube. This initial work was aimed at plotting the radar echoing area amplitude as a function of target aspect. For this type of measurement, the target is hung from dielectric strings and is then rotated about a vertical axis as radar measurements are being made. The radar sightline is slightly elevated so as to avoid any orthogonal reflection from the suspension strings and the radar is calibrated by measuring the reflection from an accurately made metal sphere which can be substituted for the target. The facility has been expanded in terms of frequency coverage, as was indicated in Fig. 2, and also of the type of measurement which can be made.

4.1 Non-coherent Radars

Many full-scale radars have non-coherent receiver systems so it is still necessary to make scale model measurements appropriate to these by using non-coherent model radars.

4.2 Coherent Radars

Operational radars using coherent reception are also common. Most of our model radars include coherent receivers and, typically, may be used to measure either the monostatic or the bistatic reflection characteristics of a model target as it is rotated in front of the radar.

4.3 Directional Glint Measurement Radars

The directional indication of a radar is subject to variations, i.e. to angular glint of the apparent target direction, caused by interference between reflections from different parts of the target. Model radar systems have been designed to measure these effects. One method uses a coherent radar which measures r.f. phase as well as amplitude and such systems are being used from 35 GHz to 890 GHz. The information from these radars may be used to construct mathematical representations of the target as described in Section 6.1.

4.4 Polarization Measurement Radars

During the last decade there has been a growing appreciation of the importance of polarization of the reflected signal and many measurement radars now incorporate facilities for transmitting and receiving any type of linear or circular polarization. Recently, a model radar system has been developed for measuring the relative phase and amplitude of orthogonally polarized signals received from a target which is illuminated by plane polarized radiation.

4.5 Doppler Measurement

Model radars have been made which are specialized for measuring the Doppler signal variations. These may be caused either by gross movement of the target itself or by the relative movement of elements within the target.

4.6 Overall Facility

With so many different types of data required, it has been necessary to establish a number of different, separate facilities within one building. These are indicated in Fig. 3. There are nine independent radar facilities which share seven different target support equipments. In some of these systems, the radar is stationary while the target is either rotated or moved in range with respect to the radar. In other systems, the target is stationary during measurement and it is the radar which moves, either linearly past, or on arc around, the target. Bistatic radars can be modelled, if desired, with the bistatic angle as an experimental variable. One system is specialized for measurements in which a water surface, subject to a controlled amount of disturbance, is at least a part of the target scene.

5 Model Radars

A diagrammatic representation of the radio modelling measurement system is given in Fig. 4. For pulse range gating, the transmitter has a pulse length of about 10 ns to 50 ns so as to envelop the model target completely. These pulses have sharp rise and fall times of order 1–3 ns and, consequently, a wide bandwidth intermediate frequency receiver is required. The i.f. is usually in F-band (3–4 GHz).

5.1 Non-coherent Receiver

A typical non-coherent pulsed radar with range gating is shown in Fig. 5. The transmitter source can be a magnetron at frequencies up to 80 GHz, but, increasingly, impatt or Gunn devices are being employed. Between 140 GHz and 280 GHz, either a pulsed extended-interaction oscillator (EIO) or a carcinotron is used. A reflex klystron or solid-state source provides the local oscillator signal. Schottky barrier mixer diodes, which have been specifically developed by EMI Electronics, operate in radar systems up to 280 GHz.

In past years, 4 GHz travelling wave tubes provided i.f. amplification. Range gating was achieved by pulsing the first anode of one of the tubes. Currently a solid-state i.f. amplifier is used and range-gating is accomplished by means of a diode gate operating at i.f. In the non-coherent receivers, the range-gating is in the video circuitry. To ensure fidelity in all cases, the detector is operated at a substantially constant level by preceding it with a voltage controlled diode attenuator incorporated in an a.g.c. loop. This diode attenuator has a logarithmic law and its control voltage is used as the receiver output. Thus echoing area on a decibel scale can be measured over a range of about 40 dB.

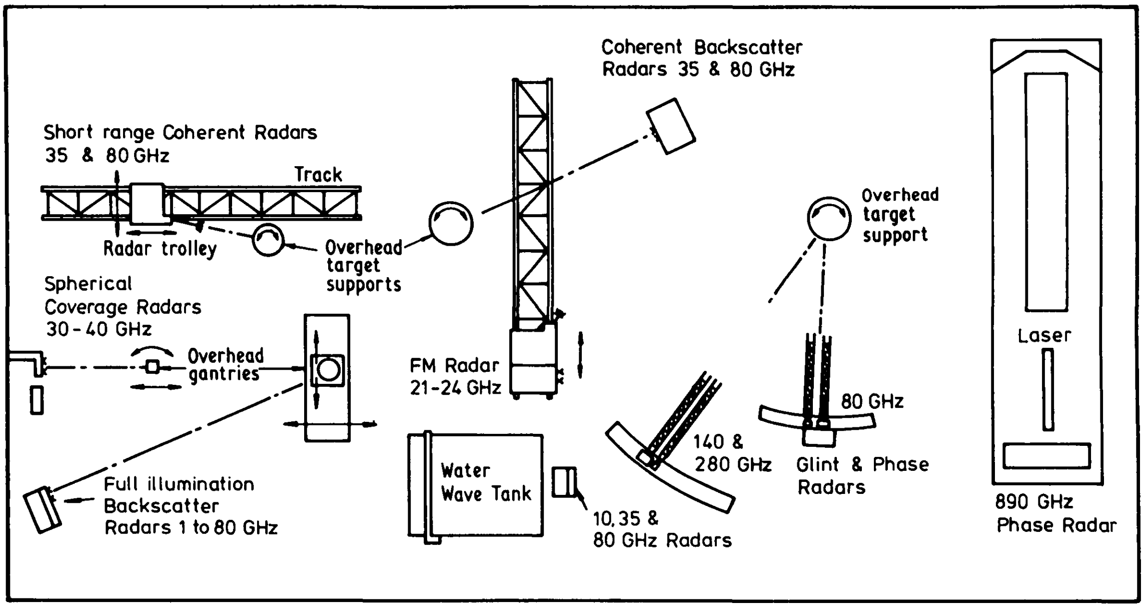

Fig. 3. Plan of radar modelling facilities.

5.2 Coherent Receiver

In a coherent radar (Fig. 6), to obtain a reference, a fraction of the transmitter power is delayed to coincide with the reception of the signal reflected by the target. The frequency of the reference signal is displaced by introducing a continuous change in its phase. Both the reference and the received target signals are mixed down to the first i.f. using separate mixers driven by the same local oscillator. The two mixer outputs, both in F-band (3–4 GHz), are separately amplified before being mixed together in a balanced detector. Due to the modified frequency of the reference signal all the Doppler components generated by the target appear as positive frequencies at the detector output. Values of instantaneous amplitude, a, and phase, ϕ, can be derived by processing the Doppler information in an on-line computer.

In an alternative coherent arrangement, a $\frac{1}{2}\pi$ phase shift can be injected into the reference channel periodically so that the in-phase and quadrature components can be determined in time multiplex. Such a radar will faithfully reproduce Doppler signals caused by target motion relative to the radar.

5.3 Direction Finding Receiver

Interference between radar waves reflected from different parts of a target can lead to perturbation of the associated phase fronts. This can result in angular glint errors in the directional indication given by the radar. An early form of a model radar operating at 80 GHz had a two-port aerial system in which the apertures were very tiny and were positioned side by side. A servo arrangement was used to align and maintain the aerial system normal to the phase front as the target aspect was changed. Currently a radar, such as that described in Section 5.2 is used to measure phase and amplitude.

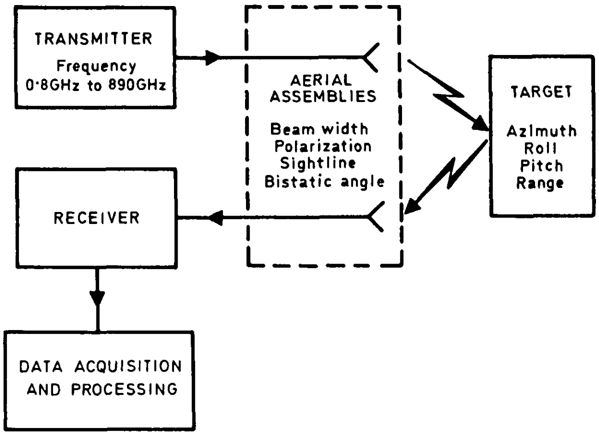

Fig. 4. Radar modelling measurement system.

Angular glint is then derived from the rate of change of phase with target aspect, using an on-line computer. Pulsed radars designed in this way are available up to and including 280 GHz.

Beyond 280 GHz optical technology becomes applicable and a laser source has been developed for use at sub-mm wavelengths.

5.4 Sub-millimetre Modelling

A homodyne coherent c.w. radar, operating at 890 GHz, has been in continuous use over the past five years. It is based on an HCN laser which is excited by gas discharge. This laser has been developed into a reliable, stable 30 mW source for radar modelling. The system can be used with models of large targets to determine angular glint or to identify echo sources within a target by using angular spectral analysis as discussed below. The radar system is shown in diagrammatic form in Fig. 7. Power is extracted from both ends of the laser, using coupling holes in the confocal mirrors which form the laser optical cavity. Most of the power is radiated

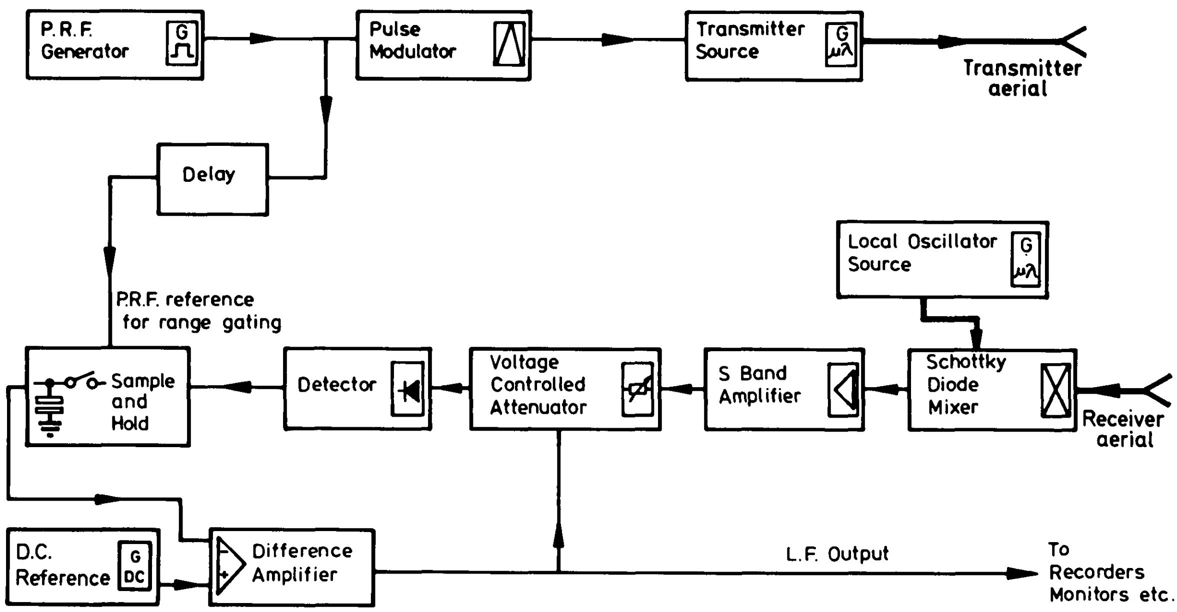

Fig. 5. Measurement radar with non-coherent receiver.

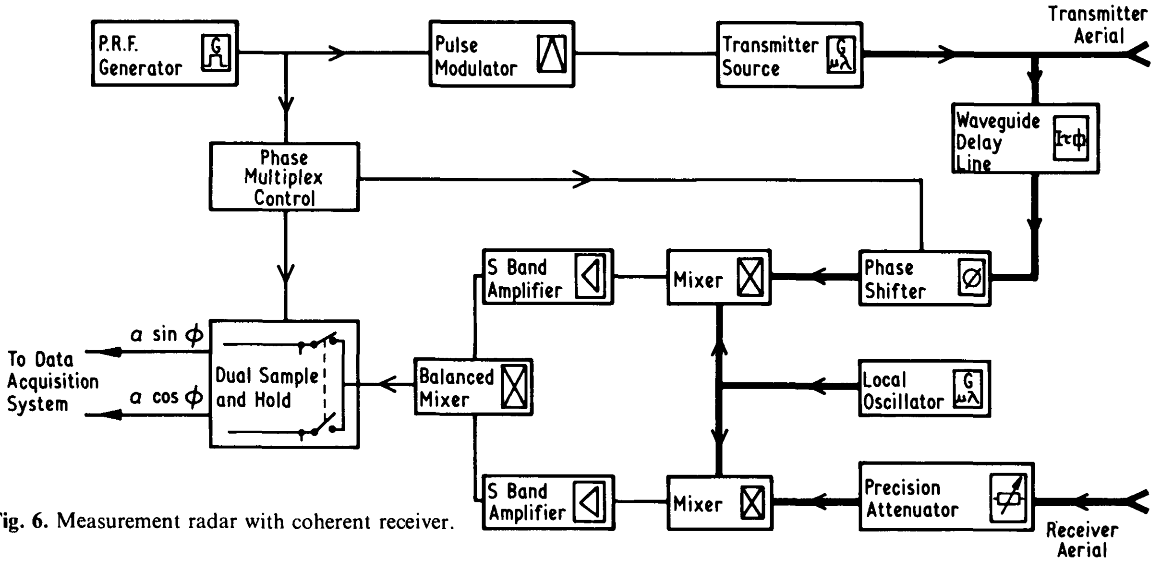

Fig. 6. Measurement radar with coherent receiver.

from the end pointing at the target and this is phase modulated ($0/\pi$) at 500 Hz, using a toothed dielectric wheel. The unmodulated signal from the back end of the laser provides the reference signal in the radar receiver. The balanced mixer uses indium antimonide photoconductors which require to be cooled in liquid helium to a temperature of 4·2 K. In the helium Dewar, the photoconductors are placed back to back and each is illuminated by the reference signal through its respective window. Diffraction gratings and mirrors are used to divide and direct the reference signal along the two separate paths. The received backscatter signal from the target is directed onto one mixer only, using a lens receiver aerial. The difference between the mixer output voltages is coupled out using a transformer and, in order to minimize its noise contribution, the transformer also is included in the Dewar. The selected signal component at 500 Hz is amplified and then translated to base-band using a phase-detector and a 500 Hz reference derived from the $0/\pi$ phase-modulator drive. Quadrature detection of the coherent return is achieved with a $0/\frac{1}{2}\pi$ phase-modulator in the receiver path immediately before the mixer. Time multiplexed, in-phase and quadrature components are therefore provided by the receiver. An output bandwidth of 1 Hz is used in each channel and a signal-to-noise ratio of 30 dB is obtained from a target having a 10^{-4} m^2 echoing area when aerials of 3 deg beamwidth are used. (See Fig. 8.)

6 Organization and Validation of Data

Digital computer processing is essential to handle the outputs from the seven independent measurement

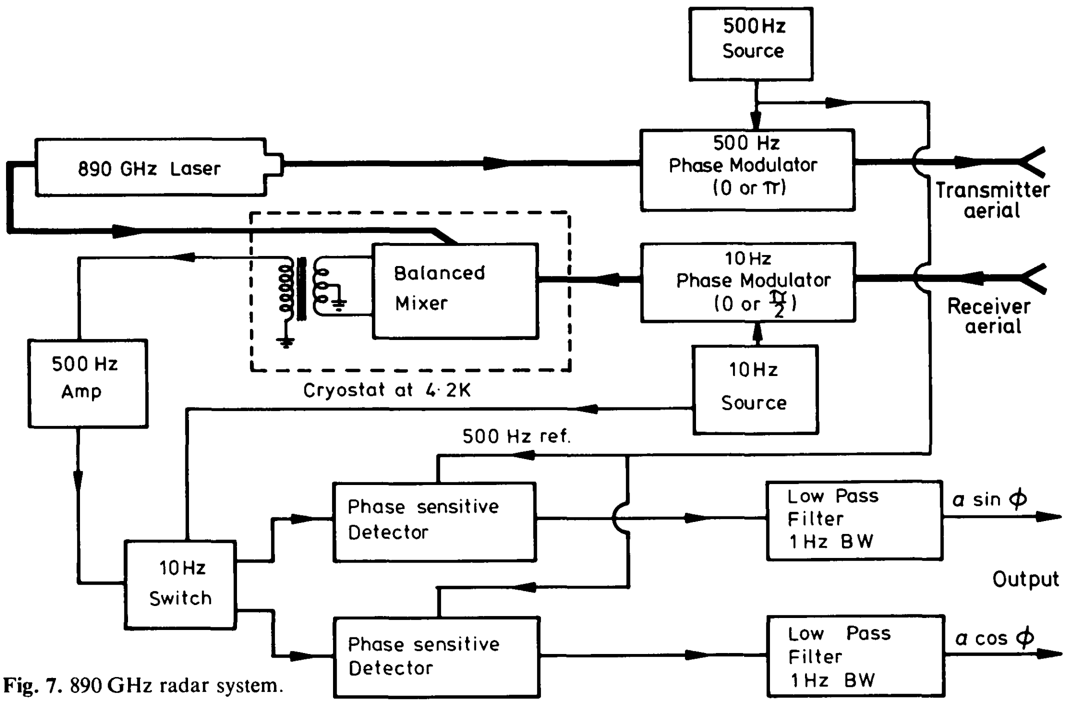

Fig. 7. 890 GHz radar system.

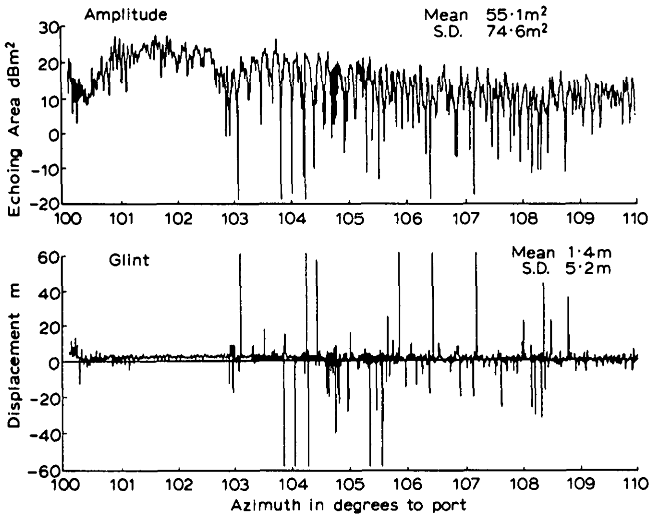

Fig. 8. Amplitude and glint plots from radar modelling.

radars. A mini-computer is provided at each site and Fig. 9 indicates how it is used to provide suitable monitor displays so that the experiment operator can confirm the validity of the experiment and of its data. The computer is also used to monitor target and radar settings and to add measurement conditions in the form of a header block, thus facilitating subsequent additional processing of the data in an off-line g.p. computer.

6.1 Processing and Use of Data

For some purposes, it is necessary for all of the data collected to be used in an analysis of the performance of an operational radar system. However, for many assessments, the quantity of raw data is embarrassingly great and suitable summaries have to be devised and computed. Sometimes these summaries consist merely of mean, median and standard deviation values of, say, the echoing area or the angular glint error within a given aspect angle region around the target. Often a much fuller summary is needed.

For many years, angular spectral analysis techniques have been used at EMI Electronics for interpreting backscatter data.[4] Information from an azimuthal scan around a target with a coherent radar is processed, using the appropriate weighting and 'window aperture', to obtain an angular spectrum. An angular spectrum gives the cross-range location and intensity of the elementary reflectors within a target. Further, by moving the window through the data recorded as a function of target aspect, the polar diagram of these sources can be determined. Figure 10 shows an angular spectrum for an aircraft viewed near 10 deg from head-on. A very succinct digital representation of a complex target can be derived from such information. It is often more efficient to store such a 'multi-source' representation of a target and compute the signal amplitude and glint at any aspect, than it is to store the initial data. The effectiveness of this method is illustrated by Fig. 11 which shows how well glint data calculated from a multi-source model compares with the measured data. It is possible, using the mathematical model, to compute the radar signal characteristics for ranges between target and radar other than that which was modelled. Thus, time-varying backscatter signals for an approaching target can be predicted by computation. To study the performance of

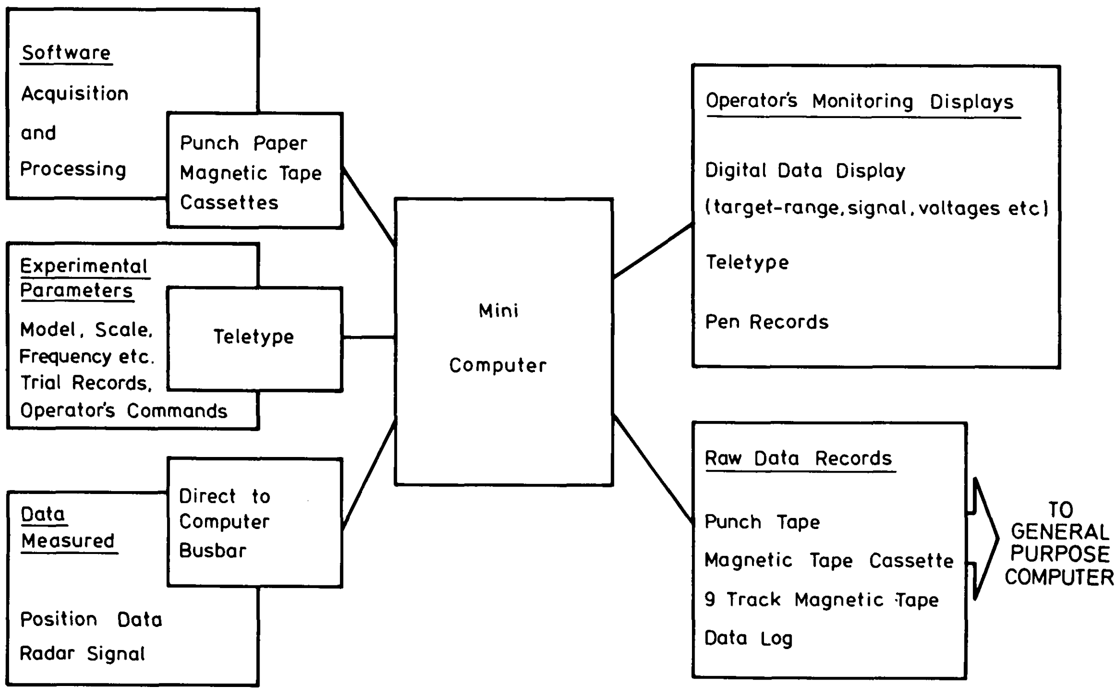

Fig. 9. Data collection and validation.

coherent radars with a computer, a multi-source model of the 'skin' Doppler backscatter would be derived as above and then a mathematical representation of Doppler components from turbines, compressors and propellors would be added.

7 The Nurturing of Near-millimetre Wave Technology

Greater exploitation of the band between 0·2 THz and 2 THz for radar modelling is anticipated and, as a consequence, new and improved sources and detectors are still being developed. EMI Electronics are presently using photons from CO_2 lasers to excite other gas molecules which provide stimulated emissions at any one of many frequencies in this band; methanol is a particularly fruitful molecule.[5] Suitable outputs have now been achieved at 30 different frequencies. Several transitions have a sufficient bandwidth to promise pulsed sources suitable for 50 ns range gating.

8 Conclusions

The UK National Radar Modelling Facility has for 20 years served a dual purpose. It has improved the understanding of radar scattering phenomena and provided much essential data for the design and proving of British and of American radars. It has also encouraged the progress and consolidation of technology in the frequency band from 30 GHz to 1 THz. In both of these respects its service to engineering, to design and to science is expected to continue.

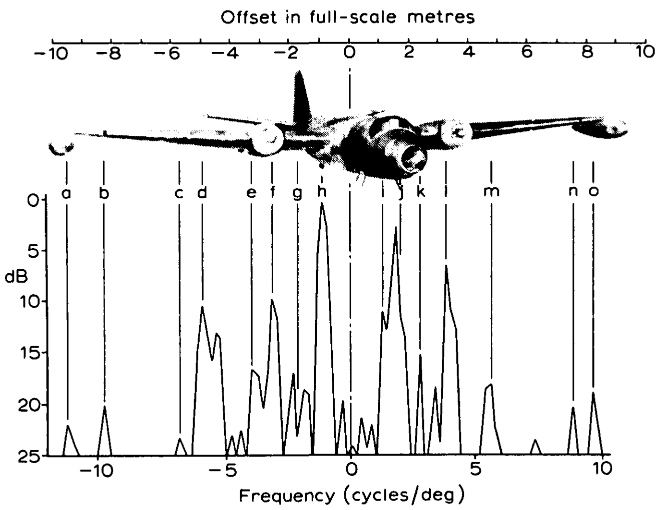

Fig. 10. Identification of sources by angular spectrum analysis.

a Starboard wing tank
b Starboard wing aerial
c Starboard inner aerial
d Starboard outer wing edge
e Starboard engine outer lip
f Starboard engine
g Tail
h Corner reflector—Starboard inner wing + Fuselage
i Cockpit
j Nose
k Corner reflector—Port engine + Inner wing
l Port engine
m Port wing control surface
n Port outer aerial
o Port wing tank

Radar wavelength, 3 cm equivalent; azimuth window, between 7 deg and 17 deg to starboard.

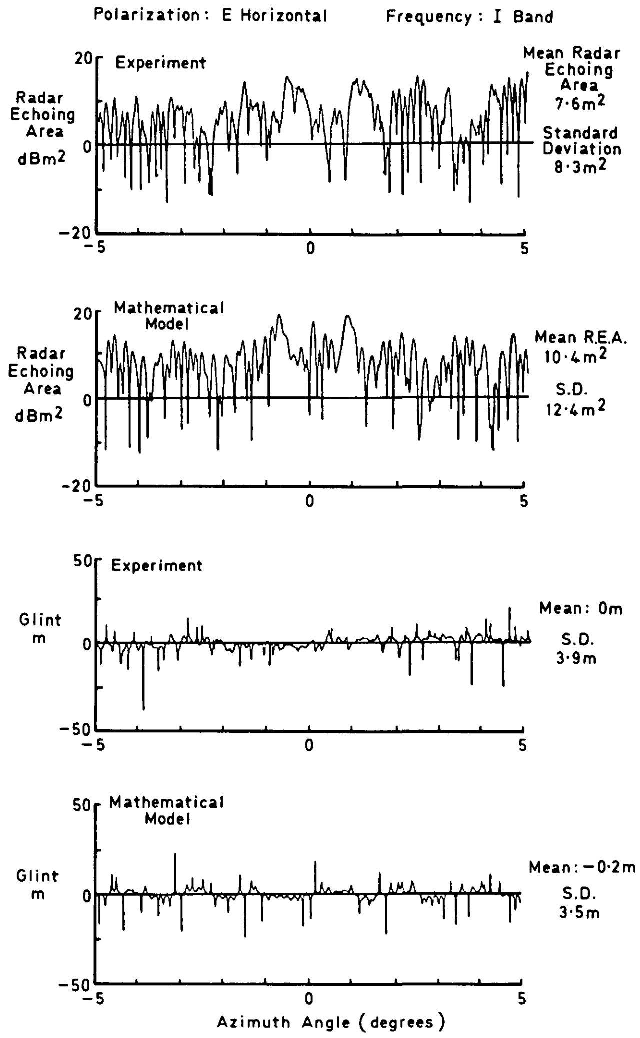

Fig. 11. Comparison of mathematical model predictions with experimental results.

9 Acknowledgments

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