MARTELLO – A MODERN THREE-DIMENSIONAL SURVEILLANCE RADAR

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A modern long range surveillance radar must give three-dimensional cover with good resistance to jamming, should be transportable, and capable of use autonomously or as part of a reporting system. This paper discusses these needs and the design philosophy of the Martello radar, which was conceived to meet them fully and economically. The design is discussed in some detail to show how it has evolved, and to illustrate its potential for further growth.

INTRODUCTION

In 1985, when Martello is entering service with NATO, half a century has elapsed since the practicability of radio-location was established. From that famous Daventry experiment, the UK wartime radar chain evolved directly, and in post-war years an international radar industry has been built up.

Ever since the lead given by CH and CHL in the war, air defence systems have continued to rely for their essential primary sensors on long range surveillance radars, the role for which Martello has been developed in the fourth quarter of the century.

Frequently such long range surveillance radars are required, like CH, to provide range, bearing and height of targets and are designated '3D' (three-dimensional) but for some purposes range and bearing data only – '2D' – is acceptable. Alternatively, nodding centrimetric height finders, figure 1, have been added in some cases to 2D radars so that separately derived heights, albeit at a data rate limited by mechanical constraints, can supplement the basic range and bearing information.

GEC companies have been involved closely in the design and supply of all these classes of radars since the war, for air defence at home and abroad, and Martello represents the current state of 3D technology.

Two versions of Martello, S713 (figure 2) and S723 (figure 3) exist currently and are described here. Whilst they differ in antenna dimensions and form of transmitter and have slightly different performance, they share many common features and employ the same principles for height finding.

Fig. 1. An example of a nodding height finder

BRIEF GENERAL DESCRIPTION

The two types of Martello radar are both transportable, long range air defence 3D sensors operating in L Band (23 cm). They feature frequency agility, pulse compression and comprehensive signal processing and both employ planar phased arrays to achieve minimum side-lobes for maximum resistance to jamming. The equipment is designed for military use and combines into complementary sets of vehicles, including main and standby diesel generators.

The 3D principle shown in figure 4 is applicable to any frequency but L Band was considered to be the best choice for the first generation of Martello radars: it offers a sensible compromise between the conflicting requirements of overall performance and transportability. Nevertheless some of the earlier experimental work on the planar array was carried out at S Band (10 cm) and the basis of a design was laid down for future application if required.

In addition to providing output data in agreed digital formats for feeding into defence reporting networks, Martello also incorporates its own radar displays. These permit the radar to be used autonomously if required, but their main function is to provide a radar management centre from which decisions can be made on selection of the operational parameters of the radar, especially when in a hostile environment. Control is effected over, for example, radiated frequency, form of agility, blind arcs and other operational modes.

Both radars employ planar arrays of co-phased dipoles; these number 1920 in the S713 and 2560 in the S723. To avoid the ultimate complexity of providing that number of transmitters, duplexers and receivers, the dipoles are grouped together in rows, with a transmitter input feed, duplexer and receiver for each row.

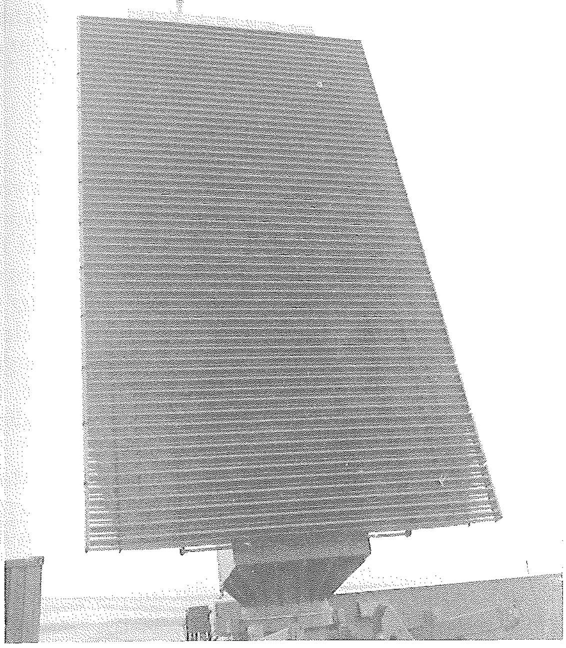

Fig. 2. The Martello S713 antenna

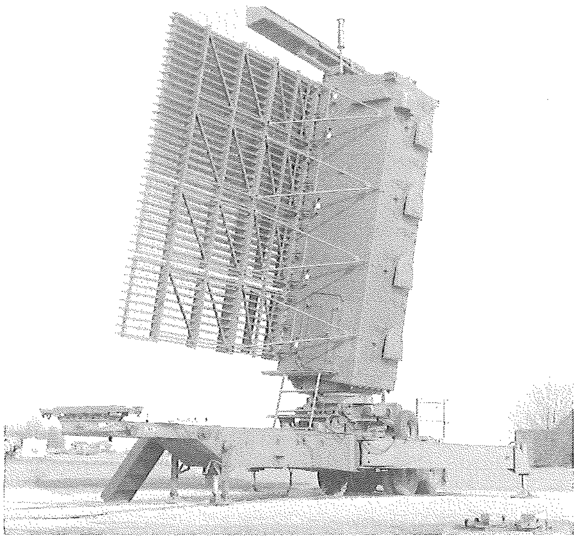

Fig. 3. The Martello S723 antenna

In the S713 there are 60 rows, each with a duplexer and receiver but the transmitter power is obtained from a power source common to all. The transmitter is a substantial equipment housed in a separate vehicle and coupled to the antenna by waveguide.

By comparison, the S723 has 40 dipole rows, again each with a duplexer and receiver, but each row now has a locally mounted transistor transmitter, all 40 of which are fed coherently from a common r.f. source.

In both cases, the planar array is built up of detachable 'antenna modules' which are accurately located in position by jigged fixings on the supporting spine. For transportation, the modules are removed from the spine and carried on a separate vehicle, but the detailed arrangements differ between S713 and S723 because of the difference in module size. S713 has 12 modules, each with 5 rows of dipoles; the modules are 20 feet in length and 3 feet wide. S723 has 4 modules, each of 10 rows, but they are 40 feet long and 6 feet wide. Power assistance for handling is built into the deployment system in both cases.

The rigid spine which is the positional reference

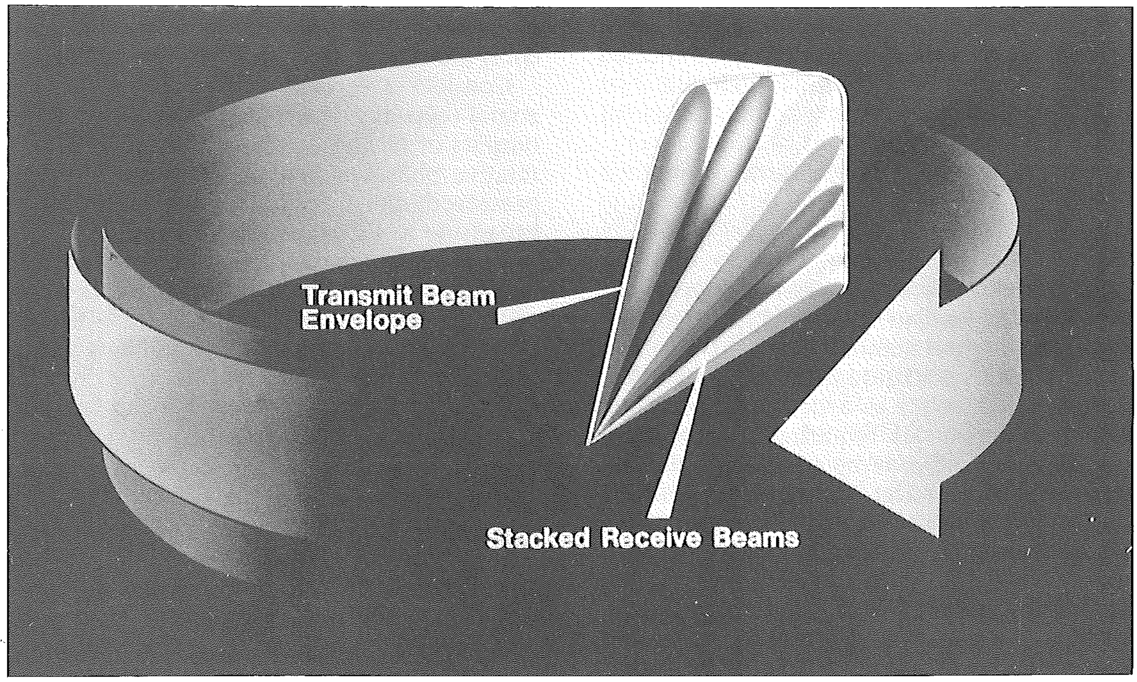

Fig. 4. Martello transmit and receiving beams

for the antenna modules is lowered hydraulically to the horizontal position during transit. The spine also forms the housing for miscellaneous electronic equipment including frequency synthesizer, beam forming networks and secondary radar system where fitted, the upper part of the assembled planar array being designed to support an SSR antenna if required.

RADAR HEIGHT FINDING

Height finding by radar is based upon the measurement of the angle of elevation of the target: thus 3D radars must ascribe an angle to every echo received. CH, because of its metric wavelengths, naturally produced a pattern of vertical lobes from the interference caused by ground reflections; therefore, perhaps curiously, the very first long range sensor had the desirable 3D capability! But, again because of its long wavelength, it was unable to detect targets at low angles of elevation.

By comparison, the radiation from microwave radars is largely independent of ground effects and can be made to produce a more complete vertical coverage pattern: by various means, this pattern can have a beam structure enabling responses from different elevation angles to be identified. It is at this point that the main design options and problems of 3D microwave radars arise, and over the years different solutions have been adopted. Many have been variants of the general concept of a number of feed horns looking into a common reflector to produce a structure of stacked beams; there is the further option of transmitting and receiving on each beam separately, or transmitting over the full elevation coverage but receiving on individual beams, as is done in Martello.

THE REQUIREMENT FOR MARTELLO

The late 60's and early 70's constituted a period of intensive air defence study in the UK, NATO and abroad. Many views were put forward but all seemed to agree that future long range sensors should

(a) be inherently 3D,

(b) have the best possible ECM resistance and

(c) be, as far as possible, mobile or reasonably transportable.

This was a clear indication that the days of the '2D + heightfinder' and of the heavy permanently installed 3D radar were numbered.

It was against this background that Martello was conceived in the mid-70's as a design to meet the requirements of countries requiring a long range sensor for air defence. From the start, it was defined as a transportable 3D radar with low antenna side lobes since, whatever other ECCM features are added, this is an essential feature in resistance to jamming.

A planar array would have to be used since there is a limit to the side-lobe level achievable with conventional feeds and reflectors, many arrangements of which had been exploited by the Company over the years. Typical 3D horn-stack radars have 'first side lobes' in azimuth in the range −20 to −25 dB depending on frequency, but Martello was designed to be around −30 dB over the entire operating band, with very low 'far-out' side lobes.

ANTENNA AND BEAM FORMING

Conventional surveillance radars sweep out a volume of space by rotating a beam, or set of elevation beams, through 360°. This is normally achieved by mechanically rotating the entire antenna. The possibilities of using static phased planar arrays facing in different directions, covering all azimuths by electronic control were not overlooked but it was thought that complexity and expense would be excessive, as indeed has been the experience elsewhere, including the USA.

Thus it was concluded that the solution for Martello still lay in the mechanically rotated planar array which would give the required performance at minimal cost but it remained to decide on the form that the height finding system should take. Many approaches were possible: some employ a change of operating frequency or phase in order to elevate the beam or to form a vertical beam structure, whilst others use discrete frequencies for each beam. All such methods increase the difficulty of achieving frequency agility – another highly desirable characteristic for the avoidance of jamming.

Martello avoids any commitment of the operating frequency for the process of elevation beam forming by employing a unique passive beam forming network (b.f.n.) operating at the second intermediate frequency of the receiving system. Beams are synthesized and the receiving system includes separate signal processing channels for each beam. The radar output thus consists of parallel data from all the elevation receiving beams, height being assessed on every return by a process of monopulse extraction, using the ratio of signal powers in adjacent beams[1,2].

Consider a vertical stack of equally spaced horizontal receiving dipoles, as viewed in figure 5. If the outputs of all the dipoles are combined so that the relative phases of the signals received by each are preserved, the direction of maximum reception is broadside to the stack, figure 5a.

If, however, a phase shift is introduced into the output of every dipole so that each is equally and progressively displaced in phase from its neighbour, signals from a common source will only add in-phase when they arrive at an angle to the array. The phase shifts now compensate exactly for the natural phase relationship of the signals arriving at the separate dipoles, figure 5b.

By introducing suitably controlled amounts of phase shift in each line a beam can be synthesized at any required elevation angle, although the beam shape becomes less well defined at the extremes. In practice, small positive and negative angles are sufficient to provide the total elevation coverage if the planar array is tilted slightly backwards.

In Martello, a row of dipoles in the same horizontal

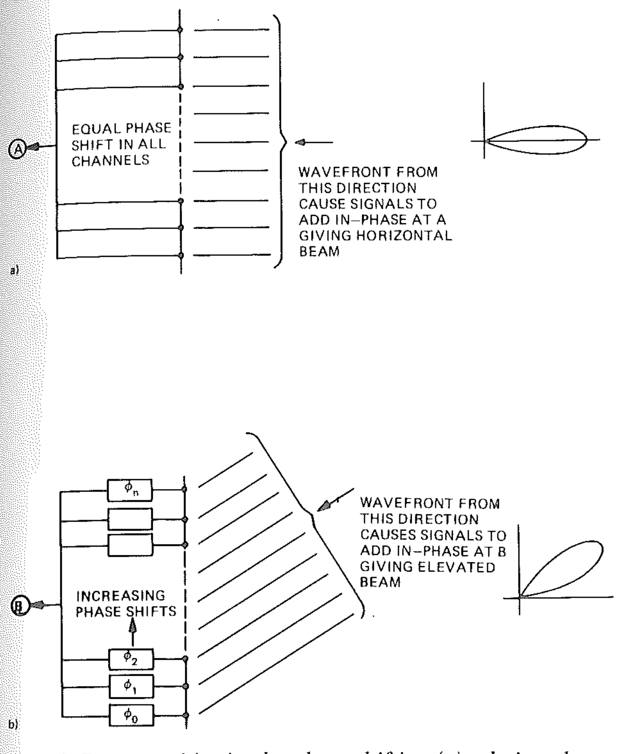

Fig. 5. Beam positioning by phase shifting (a) relative phases unchanged (b) with phase shifts introduced

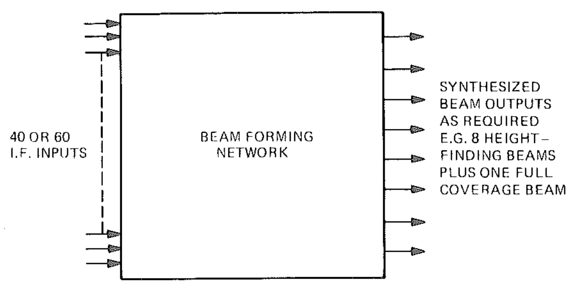

Fig. 6. Beam forming network – block diagram

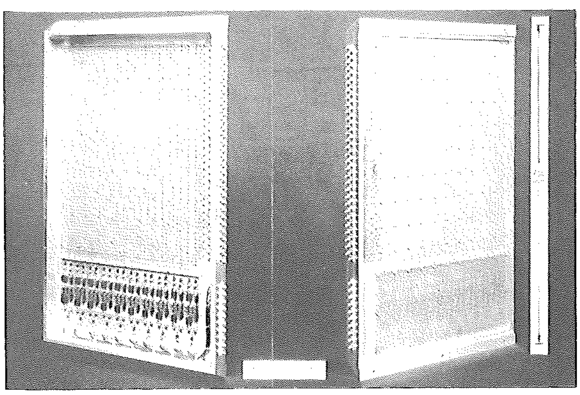

Fig. 7. Beam forming network – S713

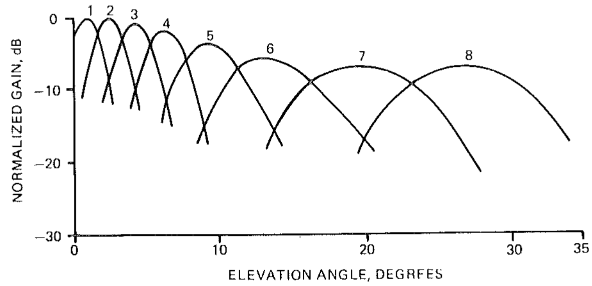

Fig. 8. Martello beam structure

plane is used at each vertical position and the output of an entire row is fed to a receiver from which a coherent i.f. signal is produced.

The 60 (S713) or 40 (S723) i.f. outputs are fed to the b.f.n., figure 6. Within the b.f.n., any required phase shift is achieved simply by choosing resistors of suitable values. This is made possible by first splitting the i.f. signal into 4 fixed phases in quadrature and then using resistors to achieve intermediate phases by combining appropriate signal amplitudes. Furthermore, the system is not limited merely to a single elevation beam but can be extended to produce several separate beams simultaneously.

Before deciding finally on the i.f. beam forming system, consideration was given to the better known techniques of r.f. beam forming: these were rejected on the grounds that they are not only more cumbersome and space consuming but once installed are quite inflexible. I.f. beam forming, on the other hand, has the advantage that the relatively compact self-contained and passive b.f.n., figure 7, may, if required, be replaced by another having different component values. Thus if the operational role of the radar should change, a different elevation beam pattern may be provided very simply, without touching the antenna itself.

Looking further ahead, the b.f.n. concept lends itself to the use of active rather than passive devices so that it is not difficult to achieve a rapidly adaptive beam forming system if required at some future time.

Generation of the multiple beams is achieved by combining the outputs of the individual receiver channels in the b.f.n. The beam shape and pointing angle is governed by a matrix which couples selected amounts of each input to the various outputs in the appropriate phase relationship. The synthesized beam contours are weighted and the crossover points controlled for optimum performance.

The b.f.n. normally provides 8 beams for the S713 and 6 or 8 for the S723. Figure 8 shows the normal 8 beam pattern for S713 and figure 4 (again) the receiving pattern in relation to the transmission pattern. Transmission occurs within an approximately $cosec^2$ radiation pattern so that all targets on a particular bearing are illuminated by every radar pulse.

Height accuracy is independent of whether the radar is operating at a spot frequency or in an agile mode and the azimuth beam position is unaffected by frequency changes within the operating bandwidth, because of the 'squintless' design of the antenna r.f. distribution system. Thus there is complete freedom to exploit the operating frequency, as required, as an anti-jamming measure.

THE SQUINTLESS FEED

At this point a brief diversion into 'squintless feeds' is appropriate to explain their relevance to Martello.

As mentioned earlier, two basic requirements in surveillance radars are that side lobes should be as low as possible to minimize the effects of jamming and that the system should be capable of frequency agility. With the widely used conventional arrangements of feed and reflector, the reflector may either be curved in both planes, figure 9, in which case a feed at the focus can cope with a broad bandwidth or it may be contoured in the vertical plane only, with a full-length horizontal feed, figure 10.

It has been shown that the latter can give superior side-lobe performance if the relative powers of the feed outputs are properly tailored but it requires special design for the feed to operate over a band of frequencies without causing an azimuthal shift of the beam with frequency.

It was to this problem that Marconi engineers(3) addressed themselves in the 60's and production examples of the waveguide squintless feed were first shown on the Marconi S600 series of transportable 2D surveillance radars at the Farnborough Air Show of 1968, figure 10 again. In essence, the feed is a waveguide distribution system in which equal path lengths are maintained between the input/output port and each of the several radiating/receiving horns. Changes of frequency cause the same change of phase to all horns and therefore the beam remains normal to the reflector. Further, several transmitters in frequency diversity may feed a common reflector with absolute beam alignment, another useful feature for long range defence surveillance radars.

Extensive design data has now been established enabling instructions for tape controlled milling machines to be raised readily for waveguide feeds to suit a wide range of reflector sizes and frequency bands. Squintless feeds have by now been used in many radars, both ground-based and naval, and, in the present context, for the vertical distribution of the transmitter power to the S713 Martello antenna. Moreover, a derivation of the same principle, but constructed in tri-plate is used in the horizontal planes of both S713 and S723 antennas to feed the rows of radiating dipoles.

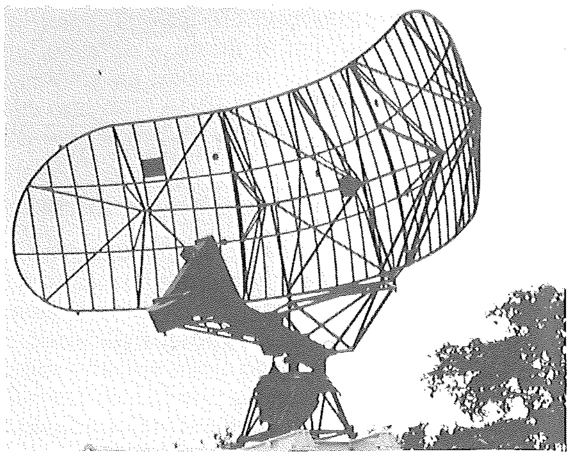

Fig. 9. An example of a double curvature antenna

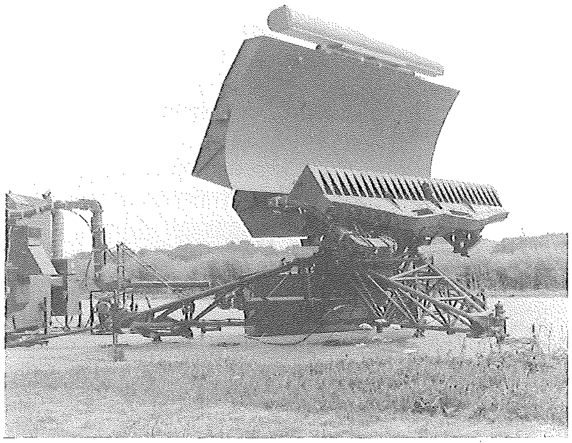

Fig. 10. An example of single curvature antenna with squintless feed

SIGNAL PROCESSING

Although wartime radars achieved excellent long range detection under favourable conditions, they were generally poor in their ability to separate wanted from unwanted targets. Probably the major achievement of post war radars has been the ability to separate targets of interest from the clutter caused, for instance, by ground returns, birds, clouds and rough seas. The requirements for reliable detection of small targets in clutter have become progressively more and more stringent and improvements have been achieved by better signal processors. It has been a long but exciting technical evolution from the original analogue m.t.i. systems of the 50's, which sensed the Doppler frequency change in returning signals to distinguish between fixed and moving targets, to the present day computer-like comprehensive digital processors, as used in Martello. But at every stage of refinement in processing, improvements in stability have become necessary in all circuits in the signal chain: there are now stringent specifications controlling timing, transmitter spectral purity and noise content.

For example, the noise content of a pulse transmitter may have to be 60 dB below the carrier throughout the entire operating band of the radar or perhaps more than −110 dB within a very narrow band. These are requirements which did not have to be considered for wartime radars.

Both S713 and S723 use similar multi-beam signal processing, figure 11. The processor applies moving target indication (m.t.i.) and non-coherent processing to each of the beams produced by the b.f.n. Each beam is subject to a single filter which is set to

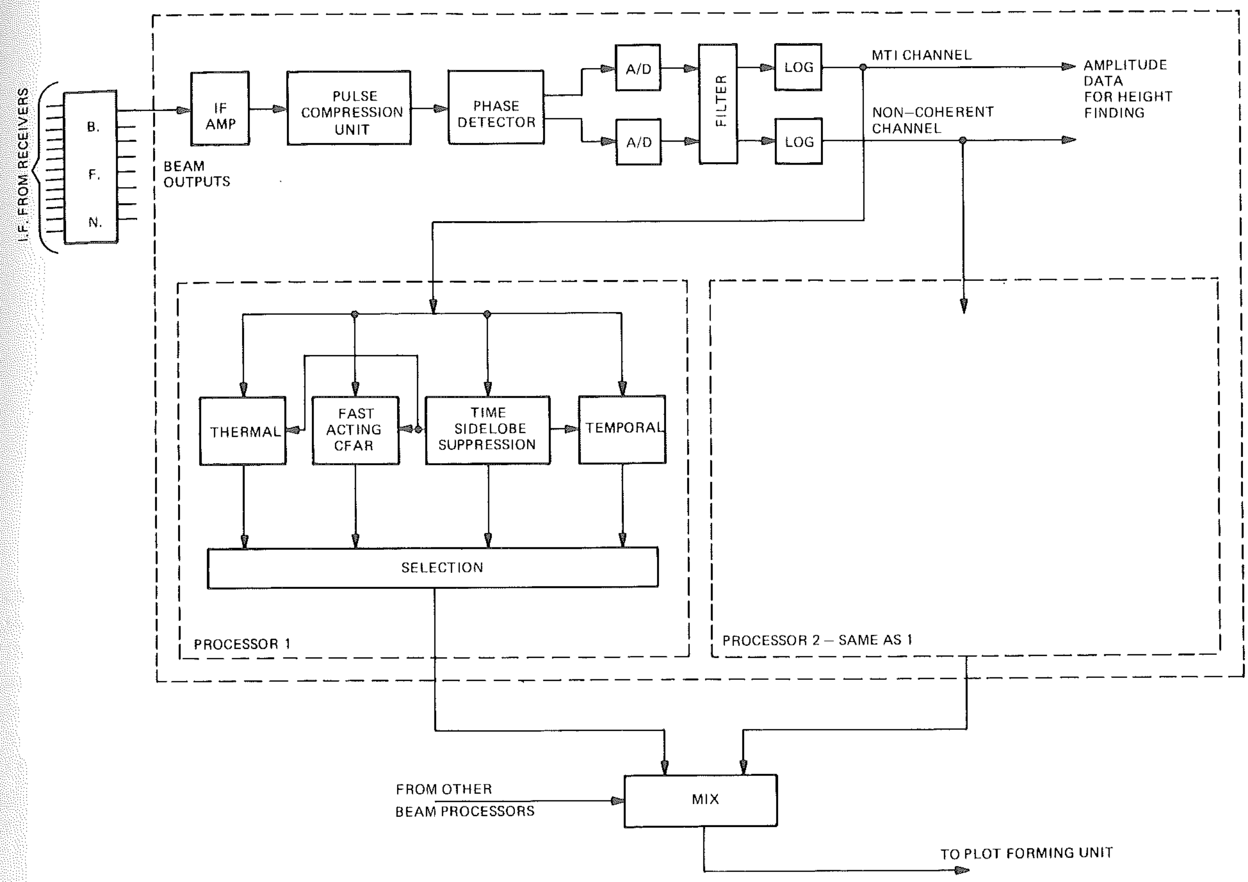

Fig. 11. Martello signal processor – block diagram

give a triple canceller response. This is followed by a time-sidelobe removal system and a choice of thresholds – thermal, temporal or fast-acting constant false alarm (c.f.a.r.). Normally, the threshold used is either 'thermal' (in clear conditions) or 'temporal' (in clutter), but when jamming is present, the fast-acting c.f.a.r. facility is switched in.

Additionally, there is a non-coherent processing channel for each beam, working on digital log video, with the same form of time-sidelobe removal and thresholding.

Each channel has an output (derived from its temporal estimator) to indicate the presence of clutter, and a full-amplitude output taken from either the m.t.i. or non-coherent channel before time-sidelobe removal and thresholding. The threshold outputs from both channels of all beams are combined to give a composite 'black and white' video output to a plot forming unit.

When a target is detected, depending on whether the detection is in an m.t.i. or non-coherent channel and whether or not clutter is present, a decision is made automatically on whether the full amplitude outputs of all beams are taken from the m.t.i. or from the non-coherent channels, and the selected information is passed to the plot forming unit for elevation extraction.

RADAR MANAGEMENT

In addition to the essential elements of frequency synthesis, transmitter drive, transmitter, receiving and signal processing chains, the S713 and S723 systems also include a display known as the Radar Management Position, figure 12. It presents the Radar Manager with complete data on the radar operating characteristics both functionally and positionally within the cover and enables him to select the most appropriate modes.

The radar signals and plot outputs are presented on a conventional p.p.i. display and equipment status and control indications on a TV monitor. The latter incorporates a Digilux touch-mask man–machine interface which enables the Radar Manager to control the radar and select data for display via the Management Processor.

GENERAL DESIGN CONSIDERATIONS

The design of transportable electronic equipment for pan-climatic operation is an established capability within the Company, built up from some 40 years experience of supplying radars to the Services. Even so, large rugged planar arrays presented a new challenge.

For the S713, the array is 20 feet wide by 35 feet high and has 60 rows of 32 dipoles: the S723 is 40 feet wide by 24 feet high and has 40 rows of 64 dipoles. Thus in both cases some two thousand dipoles have to be positioned accurately. They must be located within a dimensional tolerance of a few millimetres over the whole surface to guarantee radar performance and must maintain their relative positions in the face of winds of 100 miles per hour and survive without permanent distortion in gusts up to 150 m.p.h.

Needless to say, the intrusion of metallic supports within the radiating field of the dipoles must be avoided and the dipoles and the stripline feed protected from the weather to avoid deterioration. Add to this the requirement to withstand high explosive pressures of over 400 lb/sq. foot plus ice loading up to a distributed weight of around 2 tons without deformation and it will be appreciated that this was a design challenge somewhat out of the ordinary. Dipoles and feed are shown in figure 13.

Once the overall dimensions of the planar arrays had been decided by taking into account the horizontal and vertical radiation patterns needed for radar performance in conjunction with the constraints of transportability, thought was directed to the various ways in which the radiating elements could be grouped.

For the S713 the solution chosen was to use 12 modules, of common design and therefore interchangeable, each having 5 rows. The modules are easily removable from the main spine of the antenna structure for transportation on a separate vehicle.

For the S723, it was decided that it was impractical to break the 40-foot lengths and maintain the accuracy of assembly in the field and so the entire array is divided into four 40-foot modules each having 10 rows. Again they are interchangeable, which eases erection and logistic problems, but this feature was only achieved after careful design of the r.f. feed system whereby the relative phasing of individual rows is carefully tailored.

The design specification required the equipment to have a limited 'off road capability', yet comply with UK road transport regulations and to fulfil the requirements for roll-on, roll-off sea ferries and C130 aircraft.

The concept of the open slatted antenna array, divided into modules mounted on an upright equipment enclosure (spine) was conceived as the most cost- and weight-effective solution.

The decision to use a slatted type array with one row of dipoles per slat, rather than one which enclosed more elements within larger radomes, was taken carefully after studying the problems associated with ice loading and weather sealing in relation to wind and blast loading effects.

Both the S713 and S723 employ a stiff but lightweight equipment enclosure known as the 'spine' which forms the support for the antenna modules and houses electronic equipment as shown in the general block diagrams, figure 14 and figure 15. At the base of the spine the turning gear, rotating joint and azimuth data take-off are located, and the antenna turns on a massive single cross-roll bearing into the outer race of which the main drive gear teeth are cut, giving a compact but lightly stressed arrangement to ensure long life. The bearing diameter of some 4 feet ensures adequate clearance for the rotating joint, which passes through it. This comprises multiple slip rings together with, in the S713, a rotary waveguide joint for coupling from the external transmitter.

The turning gear assembly, which includes an existing Marconi-designed digital azimuth take-off system, is mounted on a purpose-designed mono-

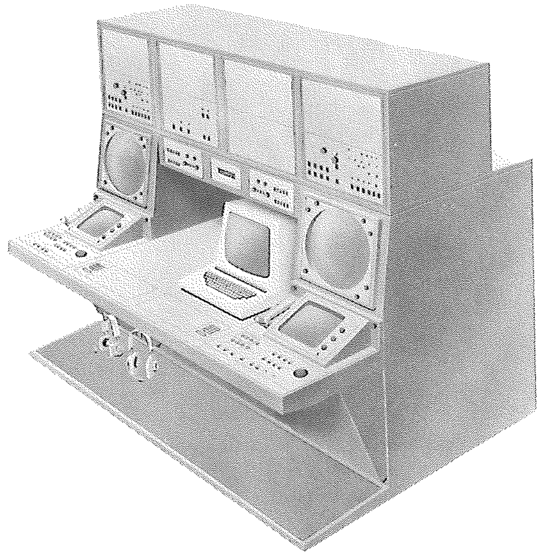

Fig. 12. Radar management position

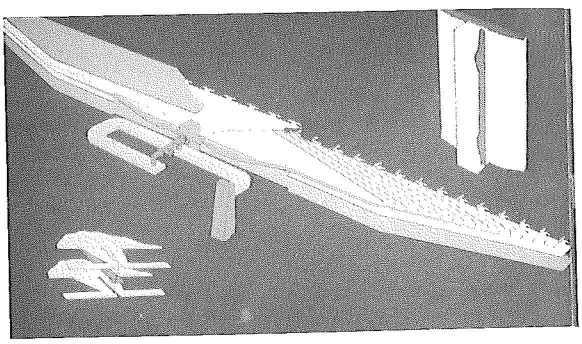

Fig. 13. Martello S713 antenna details

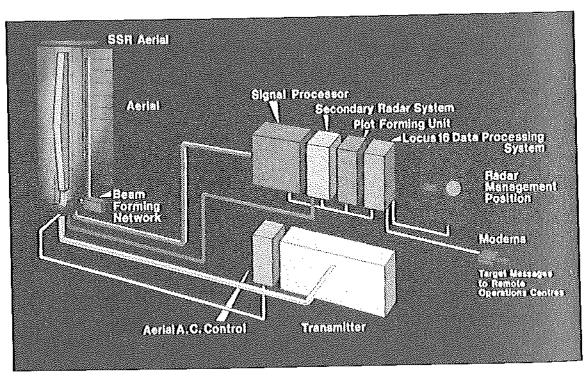

Fig. 14. Block diagram of S713 radar

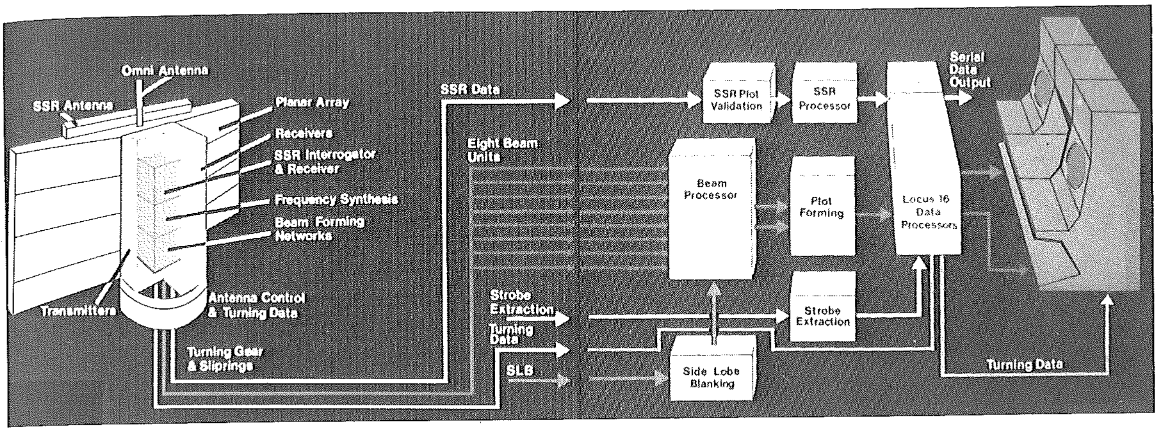

Fig. 15. Block diagram of S723 radar

coque trailer fitted with swing-out legs to form a stable deployment gantry. As quick deployment with the minimum of manpower was a design aim, the antenna and turning gear are attached to the trailer by a pivot and raised and lowered between roading and operating positions by a hydraulic ram operated from a single control panel. Levelling of the deployed gantry is achieved by additional hydraulic rams fitted on each of the three legs.

Radar height accuracy at all azimuth positions is ensured by continuous electronic monitoring of the levelling. Any deviation is fed into the height computing system together with dynamic deflections of the antenna which are measured by a gyroscopic vertical reference unit mounted in the antenna spine.

Both S713 and S723 convoys comprise a complete set of vehicles (including diesel power generators) some appropriately designed to transport the detachable antenna sections. The antenna spine and its associated vehicle are shown in transit in figure 16.

Fig. 16. S713 antenna in transit

EVOLUTION OF THE MARTELLO FAMILY

When Martello was first conceived in the 70's it was anticipated that eventually transistor technology would permit a solid state transmitter, although that stage had not then been reached. Nevertheless, the concept of separate co-phased solid state transistor output stages for each row, or set of rows, of the antenna was always kept in mind.

However, for the first Martello, S713, a conventional stable linear-beam amplifier was designed for the transmitter using a Twystron tube to give up to 3 MW peak power, 10 kW mean, at a pulse length of 10 μs, with a repetition rate around 250 p.p.s. The transmitter power is distributed to the 60 rows of dipoles by a vertical waveguide squintless feed, as shown in figure 14. Each horizontal row of 32 dipoles has a duplexer and receiver 'front-end' consisting of mixer[4] and i.f. amplifier. Gain and phase stability of the receivers is ensured at all times by an automatic pilot tone system.

After conversion to the second i.f. of 13 MHz, the signals are fed to the b.f.n. for height extraction and in subsequent stages are compressed by 40:1 to 0.25 μs to ensure adequate range resolution.

The performance of the S713, summarized in figure 17, meets many defence specifications.

Overall radar performance results from a combination of many conflicting requirements including height accuracy, data rate, susceptibility to jamming, ability to see targets in clutter and these are affected, amongst other things, by the dimensions of the antenna. S713, with its 35-foot vertical and 20-foot horizontal aperture, gives excellent height accuracy and has a horizontal beamwidth of 2.8 degrees, giving a large number of pulses per target and is ideal for many defence applications.

For some other defence requirements, however, height accuracy is somewhat less significant but a narrower horizontal beam is an advantage. Thus, in the design of the S723, which occurred when transistor transmitter power generation had reached a viable stage, it was decided to change to a 24-foot high by 40-foot wide antenna, divided into 40 dipole rows. This gives a slightly increased overall antenna aperture of 960 sq ft, compared with 700 sq ft.

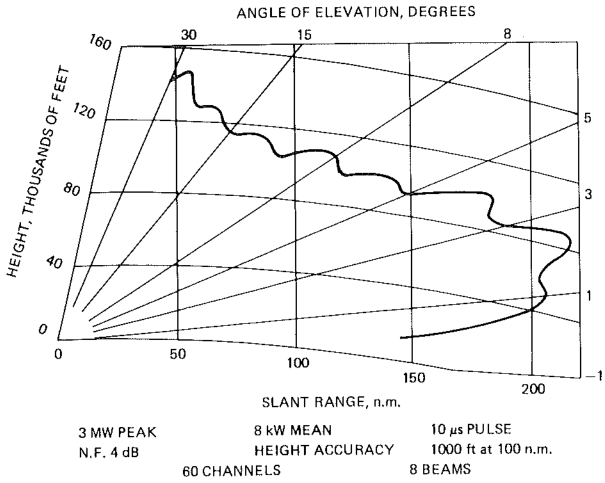

Fig. 17. Performance and data summary, S713 radar

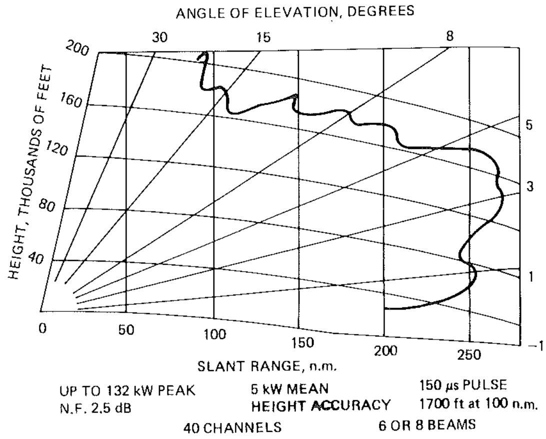

Fig. 18. Performance and data summary, S723 radar

Development of the transmitter solid state power amplifiers was based on using up to 40 (one for each row); thus the total complexity was eased in that there were now 40 rows rather than 60.

Each row may be energized by a transistor amplifier module which is mounted at the corresponding level in the central spine, the number of amplifiers fitted, and so the power radiated, depending upon the operational requirement up to the maximum of 40. Whether or not driven by a transmitter, each row has a receiver system including a low noise r.f. amplifier, and the 40 outputs at i.f. are fed to the b.f.n.

The r.f. transistor power modules have been developed after a long period of evaluating transistors from all available sources, worldwide. Life tests of complete modules indicate a very high degree of reliability even when subjected to electrical maltreatment such as badly mismatched loads. Even so, it is not yet possible to provide high peak powers with solid-state devices. Thus, in order to achieve the requisite detection performance, S723 (like other solid state radars) has to use lower peak power pulses of longer duration than in a comparable radar employing thermionic tubes. The S723 transmitted pulse length is 150 μs, compressed to 0.25 μs – the same as in the S713.

The performance of the S723 is summarized in figure 18, where it will be seen that, despite the lower transmitter power, the effects of the lower noise figure and slightly increased antenna aperture combine to give a longer range detection capability than the S713, on comparable targets.

Both S713 and S723 are in production as together they enable the Company to offer the most appropriate solution to different defence requirements.

The arguments of comparison can be complex and protracted but in the simplest terms for defence applications where utmost height accuracy and resistance to noise jamming are prime objectives, the scales may come down in favour of the S713; but where the air defence forces are able to accept slightly broader height data and the incidental advantages of solid state operation are paramount, the S723 could be preferable. Another difference is that the S723 consumes rather less power from the mains supply source; this is of varying importance, depending on the deployment of the radars and the availability of fuel.

A decision on which radar is preferable for a particular case is only reached after full consideration of details of the application, including logistic and operational aspects. In some cases a variant of the basic design embodying special features is appropriate e.g. S713A, S713B etc. However, in summary, all Martellos have the following common characteristics:

(a) Wide-band, unrestricted frequency agility (ECCM)

(b) Ease of establishing accurate beamshapes and low sidelobes across the total bandwidth of the radar.

(c) Ease by which elevation beam angles and shapes can be changed to suit particular operational needs.

(d) Parallel rather than serial processing.

(e) Considerable gain in dynamic range over systems employing single receiver channels.

These Martello features are inherent in its design but in common with multi-beam 3D radars in general, there are the advantages that ground clutter is mainly confined to the lowest beam and the effects of jammers are minimized in that not all elevation beams are likely to be affected simultaneously.

THE FUTURE

It is difficult to imagine the advances which will come in the next 50 years of radar. Perhaps Martello will then be seen as one of the milestones along the way, especially if some of its techniques find new applications. Two at least are probable: the use of the L-Band transistor power modules for other purposes such as Air Traffic Control radars, and the beam forming techniques for a variety of defence requirements including passive and multistatic radar sensors.

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