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Contents

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Page No	Radar Systems I
1	'Adaptive radar in remote sensing using space, frequency and polarization processing' Dr D T Gjessing and J Hjeltnstad <i>Royal Norwegian Council for Scientific and Industrial Research, Norway</i>
7	'Intrapulse polarization agile radar' Dr M N Cohen and E S Sjöberg <i>Georgia Institute of Technology, USA</i>
12	'On search strategies of phased array radars' W Fleskes <i>Forschungsinstitut für Funk und Mathematik, FGAN, Federal Republic of Germany</i>
15	'Design and performance considerations in modern phased array radar' E R Billam <i>Admiralty Surface Weapons Establishment, UK</i>
20	'A new generation airborne synthetic aperture radar (SAR) system' Dr J R Bennett and R A Deane <i>MacDonald, Dettwiler and Associates Ltd, Canada</i>
	Radar Systems II
24	'Results from a new dual band, dual purpose radar for sea surface and aircraft search' P D L Williams <i>Racal-Decca Ltd, UK</i>
30	'The Dolphin naval surveillance radar' Dr J Blogh <i>Plessey Radar Ltd, UK</i>
36	'AN/APS-134(V) maritime surveillance radar' J M Smith <i>Texas Instruments Inc, USA</i>
509	'Modular survivable radar for battlefield surveillance applications' Dr E L Hofmeister, W E Szczepanski, R F Oot, Dr D C Dalpe and Dr M E Davis <i>General Electric Co, USA</i>
41	'A British AEW radar system' Dr J Clarke <i>Royal Signals and Radar Establishment, UK</i> Dr J King <i>Marconi Avionics Ltd, UK</i>
	Sequential Detection and MTI
46	'Sacrifices in radar clutter suppression due to compromises in implementation of digital doppler filters' J W Taylor Jr <i>Westinghouse Electric Corporation, USA</i>
51	'A comparison between noncoherent and coherent MTIs' Dr F F Kretschmer Jr, Mrs F C Lin and B L Lewis <i>Naval Research Laboratory, USA</i>
56	'Study of weather clutter rejection with moving target detection (MTD) processor' Bao Zheng, Peng Xueyu and Zhang Shouhong <i>Northwest Telecommunication Engineering Institute, People's Republic of China</i>
61	'Reliable single scan target acquisition using multiple correlated observations' Dr R A Dana <i>Mission Research Corporation, USA</i> D Moraitis <i>Hughes Aircraft Co, USA</i>
66	'A simplified sequential detection scheme' M C Jackson <i>Marconi Research Centre, UK</i>



Contents

Page No	
	Adaptive Processing Techniques
71	'False alarm control in automated radar surveillance systems' Dr W G Bath, Ms L A Biddison, S F Haase and E C Wetzlar <i>Johns Hopkins University, USA</i>
76	'Performance evaluation of some adaptive polarization techniques' Professor D Giuli and Dr M Gherardelli <i>University of Florence, Italy</i> Professor E Dalle Mese <i>University of Pisa, Italy</i>
82	'Impact of extremely high speed logic technology on radar performance' Dr E K Reedy and R B Efurd <i>Georgia Institute of Technology, USA</i> M N Yoder <i>Office of Naval Research, US Navy, USA</i>
87	'Superresolution using an active antenna array' U Nickel <i>Forschungsinstitut für Funk und Mathematik, FGAN, Federal Republic of Germany</i>
92	'A fast beamforming algorithm for large arrays' Dr E K L Hung and Dr R M Turner <i>Department of Communications, Canada</i>
	HF/VHF Radar
97	'HF sky-wave backscatter radar for over-the-horizon detection' G R Nelson and Dr G H Millman <i>General Electric Co, USA</i>
101	'HF ground-wave radar for sea-state and swell measurement; theoretical studies, experiments and proposals' Professor E D R Shearman, Dr L R Wyatt, G D Burrows, M D Moorhead and D J Bagwell <i>University of Birmingham, UK</i> Dr W A Sandham <i>Formerly with University of Birmingham, now with British National Oil Corporation, UK</i>
107	'Experimental studies of the performance of an MF/HF ground-wave radar on a coastal site of irregular contour' Professor E D R Shearman, Dr D C Cooper, Dr K Kumar, D J Bagwell and M D Moorhead <i>University of Birmingham, UK</i>
110	'Propagation effects on a VHF radar' F Christophe and Dr P Golé <i>Office National d'Etudes et de Recherches Aérospatiales, France</i>
	Radar Systems III
115	'A barrier radar concept' J Marshall, C Ball and I Weissman <i>Riverside Research Institute, USA</i>
120	'Search and target acquisition radar for short range air defence systems. A new threat environment—a new solution' Dr J O Winnberg <i>Telefonaktiebolaget L M Ericsson, Sweden</i>
125*	'CW multi-tone radar ranging using DFT techniques' L C Boinar, Dr W J Steinway, S A Faulkner and Ms L L Harkness <i>Georgia Institute of Technology, USA</i>
130	'A fixed-beam multilateration radar system for weapon impact scoring' Dr S Gaskell <i>RCA Corporation, USA</i> M Finch <i>Ministry of Defence, UK</i>
134	'Instrumentation and analysis of airborne pulse-doppler radar trials' Dr J Clarke, E B Cowley and I W Scroop <i>Royal Signals and Radar Establishment, UK</i> Dr K Clifton and Dr J King <i>Marconi Avionics Ltd, UK</i>

* The text of this contribution was not available at the time of publication.

Contents

Page No	
	Coherent Radar Processing
138	'Optimum pulse doppler search radar processing and practical approximations' V G Hansen <i>Raytheon Co, USA</i>
144	'Resolution of ambiguous radar measurements using a floating bin correlator' E R Addison and Dr E L Frost <i>Westinghouse Electric Corporation, USA</i>
149	'Optimising the integration aperture for a high PRF CW surveillance radar' R A Hall <i>Marconi Avionics Ltd, UK</i>
154	'Performance comparison of MTI and coherent doppler processors' Dr D C Schleher <i>Eaton Corporation, USA</i>
159	'A spatially-variant autofocus technique for synthetic-aperture radar' Dr M R Vant <i>Department of Communications, Canada</i>
	Multi-Site Radar Operation
164	'Problems of data processing in multiradar and multisensor defense systems' Dr H Ebert <i>AEG-Telefunken, Federal Republic of Germany</i>
169	'Association of multisite radar data in the presence of large navigation and sensor alignment errors' Dr W G Bath <i>Johns Hopkins University, USA</i>
174	'Active array receiver studies for bistatic/multistatic radar' Dr J G Schoenenberger <i>Formerly with University College London, now with Racal-Decca Ltd, UK</i> Professor J R Forrest <i>University College London, UK</i> Dr C Pell <i>Royal Signals and Radar Establishment, UK</i>
179	'Coherent multi-static radar: stochastic signal theory and performance evaluation' Dr A Wernersson <i>National Defence Research Institute, Sweden</i>
183	'Multistatic tracking and comparison with netted monostatic systems' Dr A Farina <i>Selenia SpA, Italy</i>
	Radar Clutter: Sea
188	'Bistatic sea clutter return near grazing incidence' Dr G W Ewell and S P Zehner <i>Georgia Institute of Technology, USA</i>
193	'Sea clutter statistics' Dr J Maaløe <i>Technical University of Denmark, Denmark</i>
198	'Amplitude and temporal statistics of sea spike clutter' I D Olin <i>Naval Research Laboratory, USA</i>
203	'A radar sea clutter model and its application to performance assessment' K D Ward <i>Royal Signals and Radar Establishment, UK</i>

Contents

	Air Traffic Control I: Secondary Radar
208	'Monopulse secondary surveillance radar—principles and performance of a new generation SSR system' M C Stevens <i>Cossor Electronics Ltd, UK</i>
215	'Decoding-degarbling in monopulse secondary surveillance radar' Professor G Marchetti and Professor L Verrazzani <i>University of Pisa, Italy</i>
220	'Evaluation of angular discrimination of monopulse SSR replies in garble condition' Dr G Benelli and Dr M Fossi <i>University of Florence, Italy</i> Dr S Chirici <i>Whitehead Motofides, Italy</i>
225	'Integral SSR antenna having independently optimized sum and difference beams' P T Muto <i>Electronic Navigation Research Institute, Ministry of Transport, Japan</i> T Izutani, S Itoh, H Yokoyama and H Takano <i>Nippon Electric Co, Japan</i>
230	'Secondary radar performance prediction' B E Willis <i>Ministry of Defence, UK</i> B Pugh and S Strong <i>British Aerospace PLC, UK</i>
	Simulation and Data Processing
235	'Generic tracking radar simulator' Dr W K McRitchie, P I Pulsifer and G A Wardle <i>Defence Research Establishment Ottawa, Canada</i>
240	'Simulation of radar returns from land using a digital technique' Dr J R Morgan, P E Sherlock and D J Hill <i>Ferranti Computer Systems Ltd, UK</i>
245	'Radar electromagnetic environment simulation' J F Michaels <i>Republic Electronics Inc, USA</i>
250	'An equipment for simulating airborne radar video' T Snowball, T R Berry and A M Pardoe <i>Royal Signals and Radar Establishment, UK</i>
254	'The automatic track while scan system used within the searchwater airborne maritime surveillance radar' M Symons <i>Thorn EMI Electronics Ltd, UK</i>
259	'Automatic integration of data from dissimilar sensors' W I Citrin, R W Proue and J W Thomas <i>Johns Hopkins University, USA</i>
	Target Recognition
262	'Recognition of targets by radar' Dr N F Ezquerro and Ms L L Harkness <i>Georgia Institute of Technology, USA</i>
266	'Digital signal processing of scattering data from nonlinear targets' J Y Hong and Professor E J Powers <i>University of Texas at Austin, USA</i>
271	'Radar spectroscopy' Dr P J Moser <i>Naval Research Laboratory, USA</i> Professor H Uberall <i>Catholic University of America, USA</i>
274	'Classification of ships using an incoherent marine radar' Dr J Maaløe <i>Technical University of Denmark, Denmark</i>

Contents

Page No	Low Probability of Intercept Radar and Passive Operation
278	'The impact of waveform bandwidth upon tactical radar design' C H Gager <i>Mitre Corporation, USA</i>
283	'Radar assisted passive DF tracking' Dr R S Farrow <i>Admiralty Surface Weapons Establishment, UK</i>
288	'A filtering technique of passive radar in hyperbolic coordinate system' Hungcun Chang, Zhuoying Wang and Yiyen Feng <i>Tsinghua University, People's Republic of China</i>
291	'Deghosting in an automatic triangulation system' Dr G van Keuk <i>Forschungsinstitut für Funk und Mathematik, FGAN, Federal Republic of Germany</i>
	Air Traffic Control II
296	'The multiradar tracking in the ATC system of the Rome FIR' Dr G Barale, Dr G Fraschetti and Dr S Pardini <i>Selenia SpA, Italy</i>
301	'Methods for radar data extraction and filtering in a fully automatic ATC radar station' Dr E Giaccari <i>Selenia SpA, Italy</i>
306	'Presentation and processing of radar video map information' Dr R J G Edwards <i>Ministry of Transport, New Zealand</i>
311	'ASMI-18X an airport surface surveillance radar' J D Holcroft and S J Martin <i>Racal-MESL Radar Ltd, UK</i>
316	'Detection of hazardous meteorological and clear-air phenomena with an air traffic control radar' D L Offi, W Lewis and T Lee <i>Federal Aviation Administration Technical Center, USA</i>
	Signal Processing
321	'Matched filtering using surface-acoustic-wave convolvers' Dr D P Morgan, D R Selviah, D H Warne and Dr J J Purcell <i>Plessey Research (Caswell) Ltd, UK</i>
326	'A fiber optic pulse compression device for high resolution radars' Dr E O Rausch, R B Efurd and M A Corbin <i>Georgia Institute of Technology, USA</i>
331	'New polyphase pulse compression waveforms and implementation techniques' B L Lewis and Dr F F Kretschmer Jr <i>Naval Research Laboratory, USA</i>
336	'A digital high-speed correlator for incoherent-scatter radar experiments' Dr H J Alker <i>Electronics Research Laboratory, University of Trondheim, Norway</i>
341	'A retrospective detection algorithm for extraction of weak targets in clutter and interference environments' R J Prengaman, R E Thurber and Dr W G Bath <i>Johns Hopkins University, USA</i>
346	'A Kalman approach to improve angular resolution in search radars' Professor E Dalle Mese and Dr G De Fina <i>University of Pisa, Italy</i> Dr V Sacco <i>Segnalamento Marittimo ed Aereo SpA, Italy</i>

Contents

Page No	Antennas: Low Sidelobe Antennas
351	'Reduced cost low sidelobe reflector antenna systems' Dr N Williams and Dr D J Browning <i>ERA Technology Ltd, UK</i> P Varnish <i>Admiralty Surface Weapons Establishment, UK</i>
355	'On the performance degradation of a low sidelobe phased array due to correlated and uncorrelated errors' Dr J K Hsiao <i>Naval Research Laboratory, USA</i>
360	'Minimisation of sidelobes from a planar array of uniform elements' G J Halford and W J McCullagh <i>Admiralty Surface Weapons Establishment, UK</i>
365	'The in-situ calibration of a reciprocal space-fed phased array antenna' Dr E K L Hung, N R Fines and Dr R M Turner <i>Department of Communications, Canada</i>
	Radar Returns from Weather and Land
370	'Multiple-parameter-radar techniques and applications for precipitation measurements: a review' S M Cherry, M P M Hall and J W F Goddard <i>Rutherford Appleton Laboratory, UK</i>
375	'The Federal Aviation Administration weather radar research and development program' D E Johnson <i>Federal Aviation Administration, USA</i>
380	'Land clutter study: low grazing angles (backscattering)' Dr J W Henn and D H Pictor <i>British Aerospace PLC, UK</i> Dr A Webb <i>Royal Signals and Radar Establishment, UK</i>
385	'Millimeter wave land clutter model' N C Currie and S P Zehner <i>Georgia Institute of Technology, USA</i>
	Antennas: Beam Forming and Steering
390	'Beamforming for a multi-beam radar' J M Chambers <i>Plessey Radar Ltd, Plessey Co Ltd, UK</i> R Passmore and J Ladbrooke <i>Plessey Electronic Systems Research Ltd, Plessey Co Ltd, UK</i>
394	'An X-band microstrip phased-array antenna with electronic polarization control' Dr C H Hamilton <i>AEG-Telefunken, Federal Republic of Germany</i>
399	'Results from an experimental receiving array antenna with digital beamforming' Dr U Petri <i>AEG-Telefunken, Federal Republic of Germany</i>
403	'Beam forming with phased array antennas' W Sander <i>Forschungsinstitut für Funk und Mathematik, FGAN, Federal Republic of Germany</i>
408	'Optical fibre networks for signal distribution and control in phased array radars' Professor J R Forrest, F P Richards and Dr A A Salles <i>University College London, UK</i> P Varnish <i>Admiralty Surface Weapons Establishment, UK</i>

Contents

Page No	
	Novel Applications of Radar
413	'Portable FMCW radar for locating buried pipes' Dr A D Olver, Dr L G Cuthbert, Dr M Nicolaides and Dr A G Carr <i>Queen Mary College, University of London, UK</i>
419	'A novel method of suppressing clutter in very short range radars' Dr A Al-Attar, D J Daniels and H F Scott <i>British Gas, Engineering Research Station, UK</i>
424	'Cable radar for intruder detection' A C C Wong and P K Blair <i>Standard Telecommunication Laboratories Ltd, UK</i>
429	'Coupling mechanism for guided radar' Dr P W Chen <i>ESL Inc, USA</i> Dr G O Young <i>TRW Inc, USA</i> Dr R K Harman <i>Formerly with Computing Devices Co, now with Senstar Corporation, Canada</i>
	Radar Tracking Systems
434	'A new family of Selenia tracking radars; system solutions and experimental results' Dr T Bucciarelli, Dr U Carletti and Dr M D'Avanzo <i>Selenia SpA, Italy</i> Professor G Picardi <i>Selenia SpA and also University of Rome, Italy</i>
439	'An X-band array signal processing radar for tracking targets at low elevation angles' A Pearson, Dr P Barton and W D Waddoup <i>Standard Telecommunication Laboratories Ltd, UK</i> R J Sherwell <i>Admiralty Surface Weapons Establishment, UK</i>
444	'Tracking radar electronic counter-countermeasures against inverse gain jammers' S L Johnston <i>International Radar Directory, USA</i>
	Poster Displays — Radar Systems
448	'A new broadband array processor' K M Ahmed and Dr R J Evans <i>University of Newcastle, Australia</i>
453	'Estimation of ship's manoeuvres with a navigation radar' Professor G F Lind <i>Lund Institute of Technology, University of Lund, Sweden</i>
458	'Measuring target position with a phased-array radar system' G A van der Spek <i>Physics Laboratory TNO, Netherlands</i>
464	'Automatic detectors for frequency-agile radar' Dr G V Trunk and P K Hughes II <i>Naval Research Laboratory, USA</i>
469	'A novel 35 GHz 3-D radar for flight assistance' G M Ritter <i>Siemens AG, Federal Republic of Germany</i>

Contents

Page No	Poster Displays — Signal Processing
473	'Suboptimum clutter suppression for airborne phased array radars' Dr R Klemm <i>Forschungsinstitut für Funk und Mathematik, FGAN, Federal Republic of Germany</i>
477	'Ambiguity functions of complementary series' Squadron Leader J A Cloke <i>Royal Air Force, Ministry of Defence, UK</i>
482	'MTI-filtering for multiple time around clutter suppression in coherent on receive radars' S Carlsson <i>Royal Institute of Technology, Sweden</i>
486	'The Gram-Schmidt sidelobe canceller' Dr T Bucciarelli, Dr M Esposito, Dr A Farina and Dr G Losquadro <i>Selenia SpA, Italy</i>
491	'Ground clutter suppression using a coherent clutter map' Dr J S Bird <i>Department of Communications, Canada</i>
496	'An experimental adaptive radar MTI filter' Y H Gong <i>Chengdu Radio Engineering Institute, People's Republic of China</i> J E Cooling <i>University of Technology, Loughborough, UK</i>
501	'The use of a multi-level quantiser in plot extraction' P N G Knowles <i>Plessey Electronic Systems Research Ltd, UK</i>
505	'Improved coherent-on-receive radar processing with dynamic transversal filters' R L Trapp <i>Johns Hopkins University, USA</i>

List of Authors

	Page No		Page No		Page No
Addison, E R	144	Fleskes, W	12	Morgan, J R	240
Ahmed, K M	448	Forrest, J R	174, 408	Moser, P J	271
Al-Attar, A	419	Fossi, M	220	Muto, P T	225
Alker, H J	336	Fraschetti, G	296		
		Frost, E L	144	Nelson, G R	97
Bagwell, D J	101, 107			Nickel, U	87
Ball, C	115	Gager, C H	278	Nicolaides, M	413
Bao Zheng	56	Gaskell, S	130		
Barale, G	296	Gherardelli, M	76	Offi, D L	316
Barton, P	439	Giaccari, E	301	Olin, I D	198
Bath, W G	71, 169, 341	Giuli, D	76	Olver, A D	413
Benelli, G	220	Gjessing, D T	1	Oot, R F	509
Bennett, J R	20	Goddard, J W F	370		
Berry, T R	250	Gol�, P	110	Pardini, S	296
Biddison, L A	71	Gong, Y H	496	Pardoe, A M	250
Billam, E R	15			Passmore, R	390
Bird, J S	491	Haase, S F	71	Pearson, A	439
Blair, P K	424	Halford, G J	360	Pell, C	174
Blogh, J	30	Hall, M P M	370	Peng Xueyu	56
Browning, D J	351	Hall, R A	149	Petri, U	399
Bucciarelli, T	434, 486	Hamilton, C H	394	Picardi, G	434
Burrows, G D	101	Hansen, V G	138	Pictor, D H	380
		Harkness, L L	262	Powers, E J	266
Carletti, U	434	Harman, R K	429	Prengaman, R J	341
Carlsson, S	482	Henn, J W	380	Proue, R W	259
Carr, A G	413	Hill, D J	240	Pugh, B	230
Chambers, J M	390	Hjelmstad, J	1	Pulsifer, P I	235
Chen, P W	429	Hofmeister, E L	509	Purcell, J J	321
Cherry, S M	370	Holcroft, J D	311		
Chirici, S	220	Hong, J Y	266	Rausch, E O	326
Christophe, F	110	Hsiao, J K	355	Reedy, E K	82
Citrin, W I	259	Hughes II, P K	464	Richards, F P	408
Clarke, J	41, 134	Hung, E K L	92, 365	Ritter, G M	469
Clifton, K	134	Hungcun Chang	288		
Cloke, J A	477			Sacco, V	346
Cohen, M N	7	Itoh, S	225	Salles, A A	408
Cooling, J E	496	Izutani, T	225	Sander, W	403
Cooper, D C	107			Sandham, W A	101
Corbin, M A	326	Jackson, M C	66	Schleher, D C	154
Cowley, E B	134	Johnson, D E	375	Schoenenberger, J G	174
Currie, N C	385	Johnston, S L	444	Scott, H F	419
Cuthbert, L G	413			Scroop, I W	134
		King, J	41, 134	Selviah, D R	321
Dalle Mese, E	76, 346	Klemm, R	473	Shearman, E D R	101, 107
Dalpe, D C	509	Knowles, P N G	501	Sherlock, P E	240
Dana, R A	61	Kretschmer Jr, F F	51, 331	Sherwell, R J	439
Daniels, D J	419	Kumar, K	107	Sjoberg, E S	7
D'Avenzo, M	434			Smith, J M	36
Davis, M E	509	Ladbrooke, J	390	Snowball, T	250
Deane, R A	20	Lee, T	316	Stevens, M C	208
De Fina, G	346	Lewis, B L	51, 331	Strong, S	230
		Lewis, W	316	Symons, M	254
Ebert, H	164	Lin, F C	51	Szczepanski, W E	509
Edwards, R J G	306	Lind, G F	453		
Efurd, R B	82, 326	Losquadro, G	486	Takano, H	225
Esposito, M	486			Taylor Jr, J W	46
Evans, R J	448	Maal�, J	193, 274	Thomas, J W	259
Ewell, G W	188	Marchetti, G	215	Thurber, R E	341
Ezquerria, N F	262	Marshall, J	115	Trapp, R L	505
		Martin, S J	311	Trunk, G V	464
Farina, A	183, 486	McCullagh, W J	360	Turner, R M	92, 365
Farrow, R S	283	McRitchie, W K	235		
Finch, M	130	Michaels, J F	245	Uberall, H	271
Fines, N R	365	Millman, G H	97		
		Moorhead, M D	101, 107	van der Spek, G A	458
		Moraitis, D	61	van Keuk, G	291
		Morgan, D P	321		

List of Authors

	Page No		Page No		Page No
Vant, MR	159	Weissman, I	115	Yiyen Feng	288
Varnish, P	351, 408	Wernersson, A	179	Yoder, MN	82
Verrazzani, L	215	Wetzlar, EC	71	Yokoyama, H	225
		Williams, N	351	Young, GO	429
Waddoup, WD	439	Williams, PDL	24		
Ward, KD	203	Willis, BE	230	Zehner, SP	188, 385
Wardle, GA	235	Winnberg, JO	120	Zhang Shouhong	56
Warne, DH	321	Wong, ACC	424	Zhuoying Wang	288
Webb, A	380	Wyatt, LR	101		

ADAPTIVE RADAR IN REMOTE SENSING USING SPACE, FREQUENCY AND POLARIZATION PROCESSING

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1 INTRODUCTION

The radar scientist is facing a challenging and inspiring future, one of matching new technological achievements to important applications in the field of remote detection and identification.

This contribution is dedicated to the following concept: Most of the existing detection/identification systems do not make optimum use of all the a priori information on the object of interest that one generally is in possession of. Knowing something about the geometrical shape of the object on which our attention is focused (distribution of scattering centers and motion pattern), an optimum illumination and detection system which adapts itself to this target against a terrestrial background through an adverse propagation medium can be designed.

We are thus faced with the consideration of three filter functions: the transmission medium between the observation platform and the target, the terrestrial background against which the target is viewed, and the target itself. The more detailed information we require about the particular target per unit time, the more widebanded must our radar illuminator be.

In this brief contribution we shall concentrate on the multifrequency radar system. As we shall see, this system lends itself directly to simple computer control in a manner which is very familiar to the computer scientist.

Having structured the illumination in the time domain for optimum coupling to the target, it remains to shape the phasefront in space so as to obtain maximum coupling to the particular reflecting structure of interest by making use of a matrix antenna (two-dimensional broadside array).

Finally, we can manipulate the polarization properties of our transmit/receive system so as to investigate the polarization characteristics (the symmetry properties) of the target.

In this brief presentation we shall lean heavily on earlier contributions from the authors' laboratory (1,2,3,4,5), highlight these and describe a multi-frequency polarimetric radar system which presently is being developed by the authors. We shall present results from simple mathematical models and offer some preliminary experimental verifications.

2 BASIC PHYSICAL CONCEPTS: FORMULATION OF THE PROBLEM

As introduced above, we shall be considering four signature domains:

- a) By measuring the correlation properties $R(\Delta F)$ in the frequency domain of the waves scattered back from the illuminated area (target against background) we obtain information about the longitudinal distribution of the scatterers. Specifically it can be shown (1,2,3,4,5) that if we describe the distribution in range (longitudinally) of the scatterers by the delay function $f(z)$ which has dimension field-strength and is the square root of the scattering cross-section $\sigma(z)$, then the correlation function in the frequency domain $R(\Delta F)$ is the Fourier transform of $f(z)$. A measure of $R(\Delta F)$ is obtained, as we know, by multiplying the scattered field-strength of frequency F by the complex conjugate of the field-strength at frequency $F+\Delta F$.

Thus we have

$$E(F) E^*(F+\Delta F) \sim R(\Delta F) \sim \text{FT}\{R(\Delta z)\} \quad (2.1)$$

Note that if the target is illuminated with two frequencies spaced ΔF apart, then irregularities in the target with scale size $\Delta z = c/(2\Delta F)$ contribute to the scattered field.

- b) By measuring the spatial correlation properties of the field scattered back from the target in a plane normal to the direction of propagation, i.e. transversely, we obtain information about the transverse distribution of the scatterers. If then the x and y directions are orthogonal to the direction of propagation z (direction from radar to target), then we measure the field-strength at the points x and $x+\Delta x$ in exactly the same way as above where we were dealing with different frequencies.

It can here readily be shown (page 18 of reference 2) that

$$E(x) E^*(x+\Delta x) \sim R(\Delta x) \sim \text{FT}\{\sigma(x/R)\} \quad (2.2)$$

where $\sigma(x)$ is the transverse distribution of the scatterers over the scattering body in the x direction and R is the distance to the target. This, of course, is the same as saying that the spatial auto-correlation of the transverse field-strength is the Fourier transform of the angular power spectrum of the scattered wave (angle of arrival spectrum).

- c) By measuring the temporal distribution of the scattered field (the power spectrum) information about the motion pattern of the target is obtained through the well-known Doppler relationship

$$f = \frac{1}{2\pi} \mathbf{k} \cdot \mathbf{v} \quad (2.3)$$

where f is the Doppler frequency, \hat{K} is the vector difference $\hat{K}_i - \hat{K}_s$ between the wavenumber \hat{K}_i of the illuminating (incident) wave and \hat{K}_s the wavenumber of the scattered wave. V is the velocity of the scattering element.

Thus if we are dealing with a target (such as the sea surface) composed of many scattering centers or facets which have different velocity, we obtain information about the velocity distribution of scale size Δz by illuminating the target with two frequencies with frequency difference $\Delta F = c/(2\Delta z)$ and by measuring the temporal variation (power spectrum) of the quantity

$$W(\omega) \sim V(F, t) V^*(F + \Delta F, t) \quad (2.4)$$

Note that the velocity of the scattering element of scale size Δz is obtained from equation (2.3) by noting that it is the wavenumber $\Delta K = 2\pi/\Delta z$ of the difference frequency ΔF that enters into the Doppler equation in this case.

Hence the Doppler frequency is given by

$$f = \frac{2\Delta F}{c} \cos \phi$$

For details the reader is referred to ref (5), page 15.

- d) By measuring the distribution of the scattering centers (the $\sigma(z)$, $\sigma(x)$ and $\sigma(y)$ functions) for each element of the scattering matrix, we obtain information about the symmetry characteristics of the target.

Figure 2.1 finally sums up the basic concepts of the general adaptive (inverse scattering) radar system, whereas figure 2.2 shows the radar signature (correlation function in the frequency domain) of some idealized scattering objects. Note that the spatial correlation function is obtained by changing the abscissa of figure 2.2 from ΔF to $R/\Delta x$.

Before we proceed to give experimental verifications of the simple mathematical models based on first principle physics, let us consider the basics of polarimetry in relation to a multi-frequency radar system. Single frequency pulsed polarimetric radars have recently received considerable attention (6-9); in this very space limited presentation, we shall confine ourselves to introducing the basic concepts involved in an experimental investigation which is in progress at the authors' laboratory aiming at increasing the target identification potential of our multi-frequency radar system. Note that the present radar (see figure 3.1) makes use of six correlated computer controlled frequency synthesizers which will give 15 different frequency spacings (can couple to 15 different target scales). The radar has two transmitters and two receivers with polarization control so as to enable us to determine the frequency covariance function

$$R(\Delta F) \sim V(F) V^*(F + \Delta F)$$

simultaneously for 15 frequency separations and for the three polarization combinations

(horizontal/horizontal (S_{11}), horizontal/vertical (S_{12}) and vertical/vertical (S_{22})). The radar can also operate with adaptive polarization basis, that is, the radar optimizes its detection and identification capability by transmitting the optimal elliptic polarization.

After having completed the preliminary tests with this system, the program will be expanded to include six spaced receivers so as to allow us to determine the spatial correlation properties of scattered field with 15 spatial separations.

In order to introduce this concept, figure 2.3 is presented. Here we have "modelled" a target in the form of an airplane making use of seven isotropic and polarization invariant scattering centers. Note that the scattering matrix elements merely are represented by their moduli. The actual system, however, measures their relative phase thus allowing detailed analysis of the target's symmetry properties within each time/space resolution in an arbitrary polarization basis.

Figure 2.3 refers to the longitudinal case where the target is viewed head on with 15 coherent frequency spacings. The idealized delay function is shown and the corresponding frequency covariance function $R(\Delta F)$.

In exactly the same way, the spatial correlation of the scattered field can be calculated, giving a $R/\Delta x$ abscissa rather than a ΔF abscissa.

Having introduced the multi-domain adaptive radar designed primarily for environmental surveillance applications, we shall present a somewhat more general target configuration and give the $R(\Delta F)$ signatures for the three pertinent polarization configurations.

Figure 2.4 shows the simplified air plane target viewed head on with our 15 frequency spacings and three polarization combinations. Note that as in figure 2.3 the target has seven scattering centers. However, as a means of illustrating the polarization issue, we have selected four different classes of scattering in figure 2.4 with the following notations:

- scatterers for horizontal/horizontal S_{11}
- | scatterers for vertical/vertical S_{22}
- | odd-bounce scatterers
- < even-bounce scatterers

Note that to the extent that the target has polarization sensitive scattering centers, we can draw conclusions regarding detailed aircraft dimensions, not merely overall length as in the case of the simplest scheme illustrated in figure 2.2.

3 A BRIEF DESCRIPTION OF THE RADAR SYSTEM

The adaptive polarimetric multi-frequency radar system shown in figure 3.1 is made from a conventional 960 channel microwave communications link. The system structure is, as indicated in the figure, very simple. The six frequencies in the 50 - 90 MHz band delivered

from a common crystal oscillator are up-converted to the 6 GHz band giving a total output power of 200 mW (33 mW per frequency) to the transmitting antenna. Two different antennas were used for the various applications: a horn antenna with an aperture of 30 x 30 cm and a paraboloid with diameter 1.20 m.

The receiving antenna was positioned adjacent to the transmitter (110 dB isolation). Transmitting and receiving antennas are identical. The backscattered signal is down-converted to the IF band (50 - 90 MHz) by means of a 6 GHz source. This source is x-tal-controlled and common to both the up- and down converters. Upon amplification and filtering, the six separate VHF receiver frequencies are mixed with the corresponding six frequencies from the transmitting synthesizers. The resulting 6 voltages giving 15 different frequency pairs are then multiplied and the products (the 15 covariances $V(F,t) V^*(F+\Delta F,t)$ resulting) are subjected to 15 sets of Fast Fourier Transform filters, thus producing 15 power spectra (Doppler spectra).

The essence of these processes is illustrated in figure 4.1.

4 EXPERIMENTAL VERIFICATIONS

The multi-frequency radar system was used for three different investigations:

- Measurement of directional ocean wave spectra (wave intensity, velocity and direction)
- Investigation of ship signatures against a sea background
- Classification of air targets (F-16 aircraft)

A brief highlighting of the results of these investigations will now be given.

4.1 Directional ocean wave spectra

Illuminating the sea surface from a cliff 50 m above the sea, the ocean wave spectra (wave intensity and wave velocity) was determined for various azimuth directions and for 15 different ocean wavelengths in the interval from some 5 m (coupled to $\Delta F = 27$ MHz) to 150 m (corresponding to $\Delta F = 1$ MHz). For each frequency separation ΔF the power spectrum of the frequency covariance function $V(F,t) V^*(F+\Delta F,t)$ was computed.

Examples of such power spectra (Doppler spectra) are shown in the upper part of figure 4.1. In the lower part of the figure two curves are plotted: The curve marked with crosses gives the wave intensity (wave height) spectrum for ocean wavelengths ranging from 18 to 150 m. The curve marked with points gives the Doppler shift as a function of ocean wavelength obtained from the power spectra shown in the upper part of the figure. Note that the theoretical Doppler shift (phase velocity of gravity waves given by:

$$v = \sqrt{\frac{gL}{2\pi}} \quad \text{where } L \text{ is the ocean wavelength}$$

(ref 4)) is also shown. The systematic shift of the experimental points towards higher velocity is probably due to tidal currents on which the wave motion is superimposed. We obtain one such set of spectra for each azimuth direction of the antenna system.

4.2 Radar signature of a ship against a sea clutter background

Let us focus our attention on ship targets obtained experimentally. Figure 4.2 shows the time-record of the frequency covariance function $V(F,t) V^*(F+\Delta F,t)$. To illustrate the essential features, three values of ΔF (out of the total ensemble of 15 frequencies) have been selected. We see that when the radar beam illuminates the sea surface only, the time-record shows an irregular structure. When the ship enters the radar beam, a Doppler signature which is proportional to the frequency separation ΔF is clearly shown.

Before we change the subject from sea surface targets to aircraft, let us present another two sets of experimental results on ship signatures against a sea clutter background. With reference to figure 4.2 above, figure 4.3 shows the Doppler shift for the various frequency separations caused by the ship and by the sea surface, respectively. Note that the ship gives a linear (non-dispersive) relationship between frequency separation and Doppler shift whereas the sea surface gives results which are in reasonably good agreement with the theoretical relationship for deep water gravity waves.

Finally, figure 4.4 shows the normalized correlation as a function of frequency separation for a particular cargoship and also for the sea surface background. Note that the sea surface signature is expanded by a factor 10³ relative to the signature of the ship. Note also that there is a remarkably good agreement between experimental results and the theoretical ones if the assumption is made that the scatterers are distributed evenly over the scattering body 37.5 m long.

4.3 Radar signature of a rigid airplane

Finally, we shall present a very brief highlighting of the radar signature investigations which were carried out for various types of air targets. In this brief presentation we shall focus our attention on a particular rigid aircraft, namely the F-16 fighter airplane. Tests were also performed on airplanes of comparable size, but different structure. These produced drastically different signatures both as regards the Doppler spectrum (flutter and vibrations superimposed on a translatory motion) and as regards the frequency covariance function. Figure 4.5 shows the signature for the F-16 airplane. Note that by-and-large the agreement with theory when the assumption is made that the scatterers are distributed in a Gaussian manner is reasonably good. There is clear evidence, however, of a small number of scattering centers which dominate over the Gaussian distribution. For details the reader is referred to ref (3).

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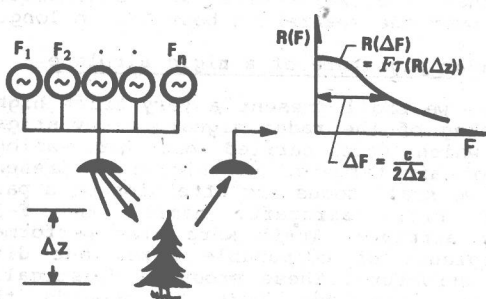
The multi-frequency radar is based on a 960 channel radio relay link generously provided by Mr Standahl of A/S Elektrisk Bureau, Division NERA.

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A SEVERAL CORRELATED FREQUENCIES



B SPACED ANTENNAS

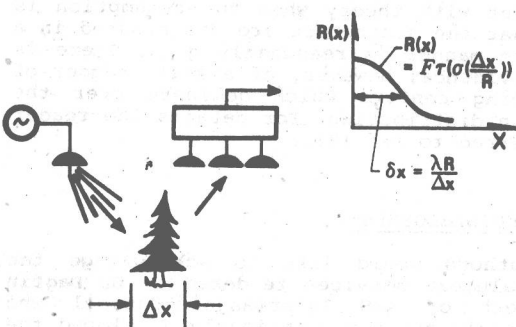


Figure 2.1 The basic concepts of the general adaptive (inverse scattering) radar system

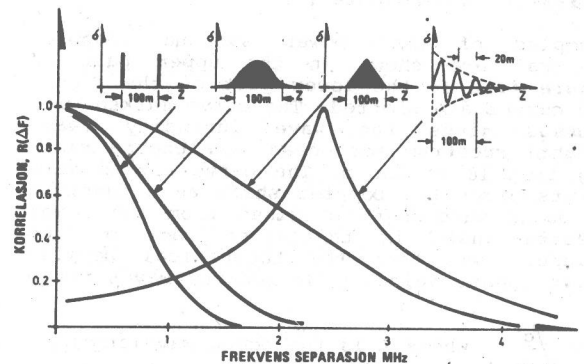


Figure 2.2 The radar signature (correlation function) of some simple scattering objects