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REVIEW OF SAFEGUARDING OF RADAR UNITS AT AIRFIELDS

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Executive Summary

The Civil Aviation Authority Safety Regulation Group presently uses three Radar Safeguarding Criteria that can be applied by a nonspecialist. Each criterion sets limits for inclined slopes centred on the radar antenna. The primary purpose is to provide protection for the radar beam against physical obstructions. The slopes are extended out to a distance of 4600m. Since the criteria are identified with specific Primary Surveillance Radars and generic Secondary Surveillance Radars, it was necessary to review their applicability to present radars and to analyse whether radar usage problems had been encountered.

The objectives of this study were to:

- Review, assess and revalidate or amend the presently used safeguarding criteria for airfield, or other site, radar installations

- Establish where necessary new criteria for recent artefacts potentially in the visible horizon of the radar, e.g. wind power generators

- Justify and recommend additional quantitative guidelines to support the choice of criteria as a back-up for use by the Safety Regulation Group

The study has researched the history of the Radar Safeguarding Criteria, and investigated performance aspects of modern surveillance radars which influence the criteria. This involved consideration of factors such as ground clutter and reflections, which are likely to influence the radar behaviour at a radar site. Information was obtained from airport authorities, the International Civil Aviation Organisation, the Civil Aviation Authority, the Ministry of Defence and radar manufacturers. The analysis of information gathered and a detailed literature survey has provided practical engineering data for revising the criteria.

The study has also investigated the benefits of improvements in radar signal processing and more complex tracking algorithms, which have appeared in the last decade. The opportunities they offer reduce the effects of adverse phenomena.

It was concluded that the basic format of the present criteria should be retained, and extended to overcome limitations, i.e. written in a more precise form to make them easier to use.

It was further concluded that new criteria would provide solutions to ameliorate many of the radar engineering problems reported by the airport operators. These new criteria are radar-type specific, and will enable radar performance aspects for particular effects to be measured, recorded and evaluated.

Guidelines are proposed to support the new criteria and to provide further interpretation of radar performance measurements for the Safety Regulation Group. In addition, a radar safeguarding procedure is proposed for use by Airfield Authorities, leading to issuing of a Site Approval Certificate. The benefits of this procedure are to formalise the safeguarding assessment into a logical process, and to make the airfield records more accessible to the approving authority, i.e. the Safety Regulation Group.

Table of Contents

Glossary

AGARD	Advisory Group for Aerospace Research and Development
AP	Air Publication
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
ATS	Air Traffic Services
CAA	Civil Aviation Authority
CAP	Civil Aviation Authority Publication
CFAR	Constant False Alarm Rate
cm	Centimetres
CPI	Coherent Processing Interval
dB	decibel
DRA	Defence Research Agency
DRIC	Defence Research Information Centre
EMI	Electromagnetic Interference
FAA	Federal Aviation Authority
ft	feet
GHz	gigahertz
ICAO	International Civil Aviation Organisation
ICV	Interclutter Visibility
IEE	Institute of Electrical Engineers
IEEE	Institute of Electrical and Electronic Engineers
IFF	Identification Friend or Foe
ISCR	Signal to Clutter Ratio Improvement
ISLS	Interrogation Sidelobe Suppression
LGPO	Local Government Planning Officer
LOS	Line of Sight
LVA	Large Vertical Aperture
m	metres
MHz	megahertz
MOD	Ministry of Defence
MIT	Massachusetts Institute of Technology
MTD	Moving Target Detector
MTI	Moving Target Indicator
NAFECS	National Aviation Facilities Experimental Centre (US)
NATO	North Atlantic Treaty Organisation
NATS	National Air Traffic Services
nm	Nautical Miles
NTIS	National Technical Information Service
PAR	Precision Approach Radar
PPI	Plan Position Indicator
PRF	Pulse Repetition Frequency
PSR	Primary Surveillance Radar

RAF	Royal Air Force
RAF SEE	RAF Signals Engineering Establishment
RAM	Radar Absorbing Material
RAMP	Radar Modernisation Programme
RCS	Radar Cross Section
RNAS	Royal Naval Air Service
RSC	Radar Safeguarding Criteria
RSRE	Royal Signals Research Establishment
SCV	Sub-Clutter Visibility
SNR	Signal to Noise Ratio
SRG	Safety Regulation Group
SRG ATSSD	SRG Air Traffic Services Standards Department
SSR	Secondary Surveillance Radar
TV	Television
UHF	Ultra High Frequency
UK	United Kingdom
US	United States
VOR	VHF Omni Ranging
WFG	Wind Farm Generator

1 INTRODUCTION

The Civil Aviation Authority (CAA) Safety Regulation Group (SRG) is responsible for the establishment and control of Radar Safeguarding Criteria (RSC) which enable Air Traffic Control (ATC) radar sites to be protected from the adverse influences of the immediate environment. This environment affects the performance and operation of the radar in a manner which needs to be understood in order to remove, minimise or compensate for any adverse influences.

The study investigates the history and usage of the criteria for modern radars. The study also assesses the effects of new technology, materials and structures, such as Wind Farm Generators (WFG), and of problems in radar data processing. As of June 1995, twenty-four wind farm sites existed in England and Wales, containing a total of 431 generator masts.

This document forms the Final Report for the Safeguarding of Radar Units at Airfields Study, Contract Ref.: 018/SRG/R&AD. The work has been conducted in accordance with the EASAMS Technical Proposal – Ref. 819323 Issue 1.

1.1 Purpose

The principal objectives of this study as stated in the Proposal are to:

- Review, assess and revalidate or amend the presently used safeguarding criteria for airfield, or other site, radar installations

- Establish, where necessary, new criteria for recent artefacts potentially situated in the visible horizon of the radar, e.g. wind power generators

- Justify and recommend additional quantitative guidelines to support the choice of criteria as a back-up for use by the SRG

1.2 Scope

There are many variants of radars serving different purposes in both the military and civil domains. The radars used for air traffic control are en-route and medium-range terminal movement area radars. These are Primary Surveillance Radars (PSRs) which are supported by the associated interrogator Secondary Surveillance Radars (SSRs):

(a) PSR provides aircraft detection and tracking, and is dependent on the detection of the target echo over a wide range, up to the highest used flight levels and with full azimuth coverage; and

(b) SSR provides an interrogation, decoding and angular tracking function over the same volume of space as the PSR with which it is normally associated. As this is an active beacon system, it will theoretically have a much greater operating range than the PSR (as applied to aircraft fitted with SSR transponders).

1.3 Synopsis

1.3.1 *Introduction*

The RSC are issued by the CAA as a first filter to be used by airfield operators in assessing radar siting requirements, and planning permission, for airfield development out to 4600m. In practice, the RSC are used in conjunction with detailed maps provided by the CAA, specific to aerodrome safeguarding criteria. These show runway approach and departure routes and the height to which development can take place within the airport surrounds.

Consideration has also been given to the approach taken at military airfields. The Ministry of Defence (MOD) use slope criteria specific to the characteristics of each radar equipment.

1.3.2 *CAA Documents*

The CAA produces and utilises a number of documents (e.g. Civil Aviation Authority Publications (CAPs)) which contain material relating to safeguarding issues and concerns. These documents can be listed as:

- CAP 168 Licensing of Aerodromes
- Safeguarding Maps
- CAP 581 Air Traffic Services Engineering Requirements
- International Civil Aviation Organisation (ICAO) Manual on the Performance Testing of Air Traffic Control Radar Systems

Each of the documents above has been reviewed and used for reference in this report.

1.3.3 *Airports*

An important part of the study has been the contacts made with airports. These contacts have provided technical feedback on safeguarding factors, and operational comments on the effectiveness of the RSC. In one case an old Decca Radar site installation report from 1964 was received which gave an insight into the history and development of siting methods and procedures still relevant today.

2 BACKGROUND

2.1 History

2.1.1 *Early Radars and Site Criteria*

One of the earliest relevant papers was published in 'Nature' in 1946 on ATC radars [Smith, 1946], and in the same year the Institute of Electrical Engineers (IEE) held the 'Radiolocation Convention' in London; see JIEE, Vol 93, Part IIIA. Unfortunately no paper in the Convention suggests ATC or site criteria were considered, except for one paper on the effect of obstacles on 10 cm propagation.

Evolution of some ATC radar installations in the United States (US) was mentioned in the 1972 Seminar on Operational Problems [NAFECS,1972], at the National Aviation Facilities Experimental Centre (NAFECS), NJ, (now the Federal Aviation Authority (FAA) Experimental Centre). It was indicated that FPS-60 radars, when decommissioned by the United States (US) military, were modified and made available to the FAA in the 1960s. Similarly, in the UK, a military Siemens-Plessey Watchman radar was modified for use on-site at a civil airfield [Green,1995].

2.1.2 *PSRs and SSRs*

The earliest PSRs with Moving Target Indicator (MTI) used by the FAA were developed in a programme at the Massachusetts Institute of Technology (MIT) Lincoln Laboratory [Skolnik,1980]. This laboratory had been set up during the war for radio research. It is possible that the physical principles encompassed in the RSC may have arisen during such a programme, although as stated in Appendix A Section 2, even in 1972 the FAA appear to have lacked guidelines.

Ward [1987] in Canada has also drawn attention to the continuing development of ATC radars since the end of the War as one of the reasons for the Radar Modernisation Programme (RAMP) for Canadian ATC radars that took place in the late 1980s. This programme was supposed to provide an ATC radar system adequate until the year 2000 [McCallum,1987]. A recent US ATC radar, the Airport Surveillance Radar (ASR-9) was claimed to be the first FAA production radar with a complete Moving Target Detector (MTD); it also had a clutter map and adaptive desensitisation for mapped areas where roads were visible.

In a 1980 paper, Cole [1980] at Marconi reiterated the ATC authorities' movement from PSR to SSR dependency for radar-derived data. Shaw [1987] has also discussed the improved performance achieved with new SSRs and states that this replacement programme, together with progressive improvements to radar sites, has enhanced considerably the plot data quality for ATC.

2.1.3 *Summary*

In the UK the radar network was mainly dependent on systems designed and supplied by Marconi, Plessey, Cossor and Decca. It is suggested that the RSC rules probably came from the MOD, since they controlled regulations in the early days [Hartney 1995].

2.2 **Requirements**

2.2.1 *CAP 168 – Licensing of Aerodromes*

In order to operate a licensed airport facility, the operator or owner, must provide a basic set of facilities; built, manufactured and operated to a prescribed set of standards. These standards are listed in the document CAP 168 – Licensing of Aerodromes published by the CAA. Only on demonstrating conformity to these standards, will an airport be licensed by the CAA.

CAP 168 outlines the 'aerodrome' safeguarding requirements in terms of criteria to safeguard declared distances for the take-off and landing of aircraft, the requirements for instrument approaches and the associated obstacle clearance limits, and the siting of both visual and navigation aids. Safeguarding requirements are currently considered to 'cover all situations and equipment' in terms of obstacles and clearance surfaces. The RSC were not included in CAP 168 as a Licensing Requirement, since the aerodrome safeguards were thought to be sufficient.

2.2.2 *CAP 581 – Air Traffic Services Engineering Requirements*

CAA (SRG) has published the document CAP 581 – Air Traffic Engineering Requirements which outlines a set of requirements for ground-based equipment. Where operational approval of equipment is essential, the implications on system operation are also outlined. Part B, 'RAD 02 Radar Sensor Engineering Requirements' covers the requirements for radar sensor performance and siting requirements.

CAP 581 is used as a reference document for approval of equipment for use at airfield sites, and has limited relevance to the RSC.

2.2.3 *ICAO 8071, Volume 4 (Draft)*

Work concerning safeguarding of radars within ICAO has been conducted by various internal working groups and panels including the Radar Panel and the Airport Operations Group. Currently only one document has been found which makes reference to RSC. This is the Manual on the Performance Testing of Air Traffic Control Radar Systems, and is produced by ICAO. It is presently at the Draft stage and will be incorporated as Volume IV of Doc. 8071 Manual on Testing Radio Navigation Aids, to be published during 1996.

2.3 Present Definition

The existing SRG (Aerodrome Standards) RSC are:

Radar Safeguarding Criteria

(a) Radars S 232, ACR 6, AR 1, Type 424, ACR 430:
1:100 slope from elevation of the radar antenna out to 4600 metres radially

(b) Radars S 264A, AR 5:
1:200 slope from the elevation of the radar antenna out to 4600 metres radially.

(c) Secondary Radar (SSR):
1:200 slope from the elevation of the centre of the antenna out to 4600 metres radially, with consultation regarding the non-use of certain materials considered to be reflective (i.e. metallised glass, metal cladding, chain link fencing, etc.) on elevations facing the SSR installation.

2.4 Application

The RSC relate to three groupings of radars, whose characteristics serve particular operational needs. These are (in the same order as above):

(a) Medium range radars. Generally these radars operate in the 3 and 10 cm bands (originally X- and S-bands, but may now be designated I- and E/F Bands). Those in the RSC list, except for the AR1, appear not to be in use. The CAA list has, for example, the following radars:

	Frequency band	*Range*
Decca ACR 424	I-band	10–15 nm
Plessey ACR 430	I-band	30 nm
Plessey Watchman	E-band	60–80 nm
Marconi ASR 511	E-band	40 nm

(b) En-route radars. The S264 (50 cm) and AR5 (23 cm) are still in the CAA list. However these are not the latest technology from the point of view of signal processing, and it is understood the 264s are gradually being replaced. Typically these C-band radars and other long range D-band radars have ranges as follows:

	Frequency band	*Range*
Marconi S264 AH	C-band	160 nm
HSA SREM5	D-band	210 nm
Siemens-Plessey AR5	D-band	180–280 nm

(c) SSRs. These are a class apart from the normal radars operating in D-band. No radars are identified in the criteria, just the generic type. This group can be more susceptible to the effects of reflections and bearing errors from multipath and obstructions. Two typical radars with comprehensive decoders and plot extractor signal processing are:

	Elevation pattern roll-off
Cossor Condor Mk II	1.9 dB/degree
Marconi Messenger	> 1.6 dB/degree

2.5 MOD (Military) Site Restrictions

2.5.1 *Introduction*

The MOD is actively controlling safeguarding issues (including military aspects) with respect to military radar and ground radio installations. The MOD have adopted more comprehensive radar safeguarding criteria. Paragraph 2.5.3 details site criteria for all Royal Air Force (RAF) radars. This information is found in the Air Publication, (AP) 100G-03 'Site Restrictions for Ground Radio Installations', a restricted MOD reference dealing with site installations for military radio frequency systems, including PSRs and SSRs used for ATC operations.

The purpose of the MOD document is to specify the minimum site restrictions. These must be applied to guard against either man-made or natural obstacles visible to the antenna. They are also applied to intrusions into the slopes for critical areas, which are defined in AP100G. The site restrictions are set out both in general terms and for a number of specific radar types. However, it is stated that these restrictions may be overridden in the case of special-to-site features, which could not have been foreseen before installation of the system.

The AP also details restrictions to be applied to safeguard the antenna site as a whole. Land beyond RAF site boundaries is protected by site safeguarding procedures through maps provided to Local Government Planning Officers (LGPOs) marking areas of concern. The LGPO is required to notify MOD of Planning Applications. Assessments for site concessions are made by RAF Signals Engineering Establishment (SEE) taking into account ICAO and North Atlantic Treaty Organisation (NATO) Standards. Concession Certificates are held by specialist officers at the site to which they apply. Similarly, public utility power line routes are submitted by the appropriate government department to RAF SEE for clearance.

2.5.2 *Radar Types*

The Radio Installations covered by this AP include the following radar types:

- Precision Approach Radar (PAR)
- Tracking radars
- Surveillance
- SSR

The first two radar types are not used by the CAA, but the last two types are similar to, or exist as, a military version of civil ATC radars. For these Surveillance and SSR radars, even where there is no direct equivalent, such as the well known Marconi Martello surveillance radar, the operating frequencies are the same as civilian ATC radars (for engineering reasons). Another common factor is that the frequencies are also allocated world wide, particularly for Identification Friend or Foe (IFF) beacon interrogators.

2.5.3 *Radar Safeguarding Areas*

For the radars in Sub-section 2.5.2, the safeguarded area centred on the antenna may, in most cases, be defined as three regions; an inner circular area, a middle annular zone and an outer annular zone. A typical example for a PSR may be summarised as the following:

(a) The 'line of slope' 1:100 originates at the circumference of a circle, centred on the antenna, radius 300m which lies in a horizontal plane. Within this inner circular area:

  - No vegetation shall exceed 75 mm height in 300 m circle
  - No obstructions, metal pipes or cable within 300m circle

(b) Within the middle annular zone between 300 and 600 m:

  - No obstruction shall exceed height of the 1:100 slope

- No vegetation shall exceed the 1:100 slope or 75 mm whichever is greater

- No metal pipes or cables

(c) Within the outer annular zone between 600m and 1800m:

- No obstruction or vegetation to exceed the 1:100 slope

For SSRs, the safeguarding area is a slope of 1:250, which is more restrictive than the civil SSR slope of 1:200.

3 LITERATURE SEARCH

Only two generic radar types, PSR and SSR, are protected by the RSC. A brief outline is given below of those aspects relevant to the engineering understanding and use of the radars, which are related to, or may influence, the installation and safeguarding criteria. Where necessary, data that have been found in the literature are included to assist in clarifying, revising or setting the criteria. Further technical details are described in Appendix A. In Appendices B and C some definitions and MTI details are provided.

3.1 CAA Radar Siting Issues And Effect On Safeguarding

3.1.1 *Siting of Primary and Secondary Radars*

The present arrangement of radar sites in the UK is given in the CAA List of Radar Stations [CAA 1994]. This is a list of the types of radar covering the long range, ultra-high frequency (UHF) en-route radars in C-band, up to the J-band airport surveillance radars. This list also covers SSRs in D-band.

The medium-range PSRs use a slope criterion of 1:100 (approx. 0.57 deg), and the en-route (long-range) radars, which operate at a lower frequency, use a 1:200 slope (approx. 0.29 deg). The slope values are very close to the line of sight (LOS) clearance of 0.5 degrees suggested in the literature. A reasonable engineering interpretation of these slope criteria is that they are primarily to clear 'obstructions'; a 'rule-of-thumb' to satisfy practical engineering needs at the time and no less relevant today.

Similar reasoning may be used for the D-band SSRs, which as a group are susceptible to reflection and bearing errors from multipath and reflecting obstructions. The choice of a 1:200 slope may have been selected because of these errors and because the frequency band is similar to that used by en-route radars. The use of modern Large Vertical Aperture (LVA) antennas for almost all the SSRs in the CAA List provides a very fast, lower beam cut-off (see Section 2.4) to minimise multipath and reflection effects. The choice of slope helps to deliver a performance improvement.

The data relevant to this study, concerning the height and type of elevation pattern, have been abstracted into Tables 3-1 and 3-2. In regard to the SSRs, the antennas are normally placed on the PSR antenna to ensure that the rotations are completely synchronised for plot tracking. Such placement also minimises the radar's susceptibility to lobing, by raising the ground intercept point to a greater range.

Table 3-1 Primary Surveillance Radars – Summary extract from CAA List

Supplier	*Band (cm)*	*Type*	*Beamwidth (azimuth)*	*Beamwidth (elevation)*	*Ant Height (feet)*
Marconi	50	S264 /S264A /S264AH	2	10	10 – 23.5
Plessey	23	AR5	1.2	cosec^2	55
Hollandse Signaal Apparaten	23	HSA SREM5	1.05 1.02	pencil cosec^2	51 – 125
Siemens Plessey	23	Routeman	1.04	pencil cosec^2	75
Decca (Siemens Plessey)	10	AR1	1.5	25 – 30	42, 55
Siemens Plessey	10	AR15	1.5	15	28
Siemens Plessey	10	Watchman	1.5	cosec^2	34 – 89
Siemens Plessey	10	AR15/2 AR15/2B AR15/2C	1.5 1.5 1.5	cosec^2 cosec^2 25–30	16,40 28,42 32
Not known	10	EN4000	1.5	cosec^2 25–30	58,117
Marconi	10	ASR511 S511	1.5 1.5	28–30 cosec^2/24–30	42 39–52
Thomson-CSF	10	TA10M	1.5	cosec^2	25
Not known	10	787A	1.5	cosec^2	36

Note: Only 3 of the radars above are in the criteria, i.e. S264A, AR1 and AR5;

Table 3-2 Secondary Surveillance Radars – Summary extract from CAA List

Supplier	*Band*	*Type*	*Ant Type*	*Horizontal*	*Elevation*
Cossor	30	Condor 9600	LVA 9642 and 9642-11	2.45±.25 deg SL –26 dB	–4 dB at 65 deg, –1.9dB /deg at –6deg
Cossor	30	SSR 950	Marconi LVA 1095 or Cossor CRS 370 with screens		
Not known	30	SSR 850	Marconi LVA S1095 or Cossor CRS 379		
Marconi	30	Messenger S470	Marconi LVA S1095	2.4 deg –30 dB	1.6 dB/deg
Thomson-CSF	30	MSSR 970	LVA AS909		

Note: these SSRs may be co-located with the PSRs in Table 3-1.

For most of the radars in Table 3-1 there are a number of conflicts with the criteria, particularly where the radars have been installed for many years. For example, on certain sites 'obstructions' have been built either on the airport, for commercial reasons arising from airport growth, or from external incursions into the radar field-of-regard, or azimuth coverage. Another aspect is the increase in local road traffic over the last decade which has produced a more intrusive aspect into the surrounding clutter map for PSRs.

3.1.2 *Relation to Flight Paths*

In modern systems, raster displays are not driven by the radar video directly, but by the plot extractor. This uses PSR/SSR inputs, and is capable of combining aircraft plots from more than one radar.

Loss of aircraft signal can occur typically through the following:

- Multipath lobing with deep nulls

- Aircraft flying through a beam may pass through a number of multi-path lobes at relatively low angles and can be 'lost' in the nulls.

- Cut-off of the elevation pattern

- High flying aircraft passing over the radar site will be lost because the pattern cuts off at elevation angles between approximately 30–40 degrees and the zenith; the 'cone of silence'.

- Physical obscuration of the main-lobe beam

  Screening of the beam due to a large building or similar object will produce target loss at certain azimuth angles, but this would normally be at low elevation angles, on the radar's 'horizon'.

All these factors are recognised and assessed during installation and testing. Lobing does not appear to be a significant problem; where it does occur it is recognised and noted by the operators.

3.2 **Radar Engineering Design**

3.2.1 *Bearing Error*

This is not covered by the present RSC, but is considered to be essential for radar safeguarding. Data has been found in the literature (see Appendix A Section 3.1) giving engineering guidance on the expected bearing errors under a variety of conditions. It is not possible to state theoretically a given error for a particular site. Therefore it is suggested that the experimentally derived values and simple equations should be used for installation guidance with known obstructions. These values and equations should be used to estimate potentially disruptive effects of subsequent obstructions within the radar LOS.

This guidance estimate and radar sightlines would then need to be related to the operational airways and volumes of space that may contain, for example, aircraft in the holding pattern. If sufficient radar coverage from more than one site is available then, knowing any associated errors, plus the need for redundancy arising from maintenance and failure, errors determined for a new site in a particular direction may be operationally acceptable.

It is surmised that the reason that AP 100G does not allow any metal objects within an inner circle for all the PSRs and SSRs (see Sub-section 2.5.3), is in order to minimise bearing errors. Furthermore for the SSRs, AP100G is specific about structures containing metal in the outer zones also not exceeding the height of a 1:250 slope. For PSRs, an even more restrictive caveat is added, in that no metal structures are allowed in the middle zone.

3.2.2 *Antennas*

The antenna is one of the most important elements in the radar system. Its design and the associated feed mechanisms are crucial to achieving low sidelobe levels and antenna patterns consistent with the surveillance function for the aircraft heights and ranges required.

Significant effort has been placed on design and manufacture of the LVA antennas used for the SSRs in the last decade. These provide a very rapid gain 'roll-off' on the lower elevation pattern surface, see Table 3-2. The effect is to reduce the energy irradiating the ground and therefore to minimise the potential for multipath lobing. Even the PSR antennas have very carefully designed reflectors with double curvature, to reduce to the lowest possible level the vertical sidelobe on the ground side of the beam.

3.2.3 *Near and Far Field*

In general terms, for engineering purposes, the fields associated with an antenna can be divided into regions whose boundaries are related to the approximations in the equations of electromagnetic field theory [Skolnik; Holloway, 1995]. These are generally identified as:

- Radiating near field $< \frac{D^2}{2\lambda}$
- Far-field $> \frac{2D^2}{\lambda}$

The far field boundary is an approximate demarcation where, at greater ranges, the patterns can be considered as fully formed. Table 3-3 shows that for selected antennas in the CAA Radar List [CAA 1994] it is possible to indicate the approximate distances of the near and far- field boundaries.

Table 3-3 Near and Far-Field Boundaries as a Function of the Largest Linear Dimension of the Array.

Antenna		*Max Dimension (D) meters*	*Near Field meters*	*Far-Field meters*
Marconi S264 (replaces S232) (50 cm)		16	256	1024
Marconi SSR LVA S1095 (30cm)		8	107	212
Marconi S120 Detailed mechanical data in archives, design dated 1959.		high and low cover elevation plots provided by Marconi	–	–
Siemens Plessey	AR1 (10cm)	5.05	116	464
	AR5 (23cm)	13.18	790	3158
	Watchman (10cm)	4.7	44	177
	Routeman (23cm)	14.5	956	3823
Marconi Mainstay (23cm)		15	489	1957
Marconi Martello (30 cm)				
	S713 original	6.1 x 10.6	187	749
	S723	12.2 x 7.1	248	992

It is clear from the tabulated values that the distance of 4600m in the RSC used by SRG is not directly related to the near and far field boundaries of in-service radars, except that it is always greater than the range to the far field boundary. One radar company [Hartland,1995] suggested that 4600m may have provided adequate clearance on early airfields.

If an obstacle is within the angular sector of the far-field mainlobe (therefore close to the antenna boresight by definition) the effect is more pronounced than if it were positioned in the side-lobe regions. It is recommended that the far field boundary should be used to determine the likelihood of disturbance in the vicinity of the antenna.

As an example, a paper by Green[1977] looked at the impact on the far-field pattern of near-field obstructions, in this case vertical masts. He showed some data for two similar cases, namely:

- A model with a cylindrical obstruction, metal and dielectric, of 2.3λ diameter at a range of 37λ using an antenna aperture of 61λ.

- Measured data at I-band with a 2λ diameter metal obstacle at 33λ using an antenna aperture of 53λ (this conversion has assumed a frequency of 10 GHz)

Unfortunately the paper does not give the free pattern or quote the sidelobe levels. The model showed a main beam loss of 0.7 dB in gain. The primary effect of this was a significant raising of the peak sidelobe levels. For a metal cylinder, or a solid dielectric cylinder of permittivity 2.0, moved over an angle of ±20 degree, the sidelobe levels were increased to a level of <–25dB from >–35dB. It was not explicitly stated, but it appears that there is negligible effect on the beam boresight for the accuracy considered; the effects for the system investigated were mainlobe gain reduction and increased sidelobe levels. If the radar is measuring beam positions to milliradians, then radomes and their supporting structures can cause disturbances in the near field which give rise to errors of this magnitude.

3.2.4 *Anomalous Signal Propagation*

Anomalous propagation (see Appendix A Section 10) has been encountered at a number of sites. It depends on the occurrence of stable meteorological conditions producing particular variations in the atmospheric refractive index. Clearly there are no safeguarding criteria that can be applied to take account of anomalous propagation.

3.2.5 *Surface Roughness and Lobing*

In practical terms the surface characteristics in the vicinity of the radars are determined by factors other than purely electrical engineering performance. Clearly, if there are azimuth sectors of hundreds of metres radius round the radar antenna (comprising tarmac runways, taxiways and mown grass) then some degree of 'specular' reflection with lobing is probable. Where the sector comprises patches of undulating surface or small obstacles (bushes trees, hedges, overhead pipes or cables, etc.) all comparable to, or a little less than, the wavelength, then the reflection is likely to become a scattering process.

It is suggested that the most appropriate measures are:

(a) To make some estimate of the surface roughness, cf. the way that 'sea state' is used for operation over the sea; and

(b) To request the radar supplier to model the elevation coverage for this degree of roughness or a selection of root-mean-square (rms) height deviations.

Consultation with GEC-Marconi [Heath 1996] indicates such modelling can be done by measurement in three ways:

- A specular reflection pattern

- A rough sea pattern for different sea states, which can roughly approximate terrain of the corresponding height deviation

- A detailed terrain profile along a radius can be modelled and used as the input to the elevation coverage routine

It is understood that over terrain generally the lobing is not at all pronounced for the radars, although heavy rain may modify this to some degree. It is assumed that other manufacturers can provide plots appropriate for their radars.

Most radar sites will have areas of relatively clear and smooth (to the radar) terrain round the radar antenna, particularly if sited on an airport. This type of terrain will normally occur close to the radar, where lobing may then occur more easily at higher elevation angles. In general, at low elevation or grazing angles, the surface reflection will suffer increased levels of scattering, and be less likely to cause significant lobing, the further one goes out from the antenna. As the 'surface' becomes more irregular relative to the wavelength there is even less likelihood of constructive interference producing lobing.

It would seem undesirable to allow surfaces, which comprise very large expanses of flat roof or segmented roof structures, in the path of the radar beam at short range. These types of surface may be seen on warehouses, factories, etc. Clearly if vertical surface structures and smooth terrain cause lobing problems for radars mounted at ground level, then roofs have the potential to be a cause of unwanted lobing where the radar is above the roof on a tower. As guidance the potential effect is only likely where the roof area intercepts a substantial cross-section of the radar beam. It would also require the structure to be very close to the radar tower. No data has been found related to such effects and no specific criterion is proposed, although this situation may also be associated with the prohibition of significant structures at slant ranges below the slope quoted in AP 100G.

3.2.6 *Clutter*

Clutter has always been a practical problem for radars. It can, to a very substantial extent, be eliminated from the modern radar by the inclusion of digital computing technology including clutter maps and the use of Doppler techniques, as outlined in Appendix C for PSRs with MTI/MTD processing .

There was a need in early radars to reduce clutter by raising the antenna maximum gain peak in elevation, but this is no longer so critical to modern radars.

3.2.7 *Range Performance and Tilt*

Most radars have adequate detection range performance for the majority of ATC tasks. Where there is a specific requirement for maximum range detection at low elevation altitudes (or more strictly, low elevation angles of the boresight) then the radar may be placed on high ground. In this circumstance any enhancement arising from lobing can be used operationally to extract the maximum range by tilting the beam downwards.

Practical constraints determine that the antenna is fairly close to the ground for reasons of:

- Aircraft clearance and safety
- Structural strength
- Cost factors

Therefore on most sites, to assist in minimising lobing and to reduce the 'horizon' obstacle problem, a small (say 0.5 deg), upwards tilt may be included at site installation; but each site will be different.

In order to assist in avoiding horizon vertical obstructions and reducing the ground clutter outside the airfield perimeter, one radar manufacturer considers that a normal installation procedure should be to tilt the main lobe (i.e. the one having maximum gain and therefore maximum detection range) slightly above the horizon. In practice, at least one manufacturer provides mechanical wedges to enable adjustments up and down in 0.5 degree steps over a small range. Such a tilt would be a compromise between operational needs, lobing and multipath effects, and clutter signal level reduction.

3.2.8 *Signal Processing*

In a modern radar (see Appendix A Section 7, and Appendix C) the capability to track aircraft and handle data is determined mainly by the computing power, processor and memory boards, types of signal tracking algorithms, etc., that are provided with the system. The equipment architecture is modular and more capabilities can usually be added at additional cost without designing a new radar. For example the Raytheon ASR-23SS PSR is normally supplied to handle 500 aircraft, but 750 aircraft tracks are offered as an improved capability option. The Marconi Mainstay uses modules based on those developed for the Martello system, with Adaptive MTD processing to ensure optimum configuration against fixed and moving clutter; the signal processing algorithms can be changed as required for particular operational needs.

Surveillance radars often operate in conditions of highlevel ground clutter returns, but this is normally stationary, whereas aircraft are moving. This difference allows the signal processing (see Appendix C) to discriminate between the two types of return, where the wanted target in this scenario is the moving object.

This type of Doppler discriminating radar is known as a MTI or pulse Doppler radar [Skolnik,1980]. Variations on the basic techniques are described in the literature, but are only relevant to the needs of safeguarding in terms of the clutter levels that may be processed by the radar.

3.2.9 *Vehicle Traffic Processing*

Typical problems that occur with PSRs are target returns from road traffic (or vessels if the radar is sited overlooking the sea) and from other moving objects such as WFGs [Dowdeswell,1995]. These returns are moving with velocities overlapping those of helicopters and fixed wing aircraft taking off or landing, as described in Appendix A, Section 5. The effect is to generate false targets from the signals produced by the Doppler filters, which leads the track extractor to generate false tracks on the operator's screen.

Modern radars have highly effective MTD capabilities, under software control of digital signal processing algorithms. Site-specific software can be prepared and adjusted at site installation for most problems that occur. These signal processing and plot extraction capabilities for a given site are comprehensive and cater for most types of clutter and target conditions. They are not a panacea for all site-specific problems, and more robust methods may be needed on occasion; such as re-siting the radar, or rejecting the building of a road with significant traffic levels in the radar LOS.

Some clutter suppression functions are available to enable the radar operator to remove specific range/azimuth cells. Plot extraction can be continued across suppressed cells by 'coasting'; i.e. allowing time for the real target to pass across the clutter, so that for example, over up to three antenna rotations, the path can still be predicted [Gammon,1996]. There is a simple relationship between the nature of the wind farm clutter region (dependent on its size, range and clutter level), and whether or not the radar will see the target again on the same track. The signal processing can be more complex than this. For example, in the Marconi S7204 Plot Extractor algorithms are used to combine the PSR and SSR plots into a best fit combination.

Furthermore, where road traffic is a known cause of false targets the road segments can be identified and held in store. Those false tracks initiated in these areas can then be matched and eliminated. There will be cases where aircraft 'cross the road' and this can be recognised and allowed for. The S7204 can also deal with large-scale bird migrations.

3.3 Ground Surface Structures

3.3.1 *Surface Alignment*

Using detailed maps of the airport region, alignment of the radar boresight should not be made within an angular zone of ±4 deg, (preferably ±12deg), of the normal to the centreline of roads. This applies only to straight roads along which there are a significant number of buildings (for more details see Appendix A, Section 4.3). This is likely to have less effect if the radar boresight is above the tops of any buildings.

If the region seen by the radar has a few major, tall buildings then the predominant surface alignment of these should be avoided instead of the road centreline, as described above.

3.3.2 *Wind Farms*

It is worth addressing the possibility that an 'array' of WFG masts could be considered as a linear array of elements having an element and array factor, as described in Appendix A, Section 8. For a given spacing the array pattern will show a sequence of lobes and nulls. The irradiating radar should be positioned in a null not a lobe peak. However, as the mast spacing is likely to be many hundreds of wavelengths there will be a large number of narrow lobes and it may not be practical to attempt to site the radar on a null.

A rough estimate can be made using simplifying assumptions from the RAF SEE report for Royal Naval Air Service (RNAS) Culdrose [Dowdeswell,1995]. The field intensity pattern will be given for an array by [Skolnik 1980],

$$E(\theta) = \frac{\sin\left[N\pi(d/\lambda)\sin\theta\right]}{\sin\left[\pi(d/\lambda)\sin\theta\right]}$$

where N = the number of wind generator masts
d = the mast separation
λ = operating wavelength

The last two parameters must be in consistent units. Assuming a row of 5 masts separated by 200 m then, for the two PSR wavelengths, the 'nulls' correspond to an angular spacing of 0.1 mrad at λ = 10 cm and 0.5 mrad at λ = 50 cm.

The masts at RNAS Culdrose are some 6500m distant from the radar site. For the two suggested radar wavelengths, this implies that the movement of the centre of the antenna aperture would need to be 0.65 m or 3.25 m between nulls. However, it seems unlikely that the masts' axes have been surveyed and constructed to an accuracy of 5–10cm. To make matters worse, there are three rows of WFGs at this site, nor are the rows normal to the radar boresight. Hence it may be impossible to position the radar in such a manner to avoid backscatter at this site.

The possible reduction in backscatter that may occur with circular polarisation [Sengupta & Senior,1979] needs assessment as a 'counter measure' against wind farms. The polarisation of the radar can be switched electronically when the radar is looking at such a clutter target, and revert to linear either side if required.

It is understood that modelling of wind farm effects on signal processing has been performed by GEC-Marconi [Larson & Heath,1995]. This should provide a means of measuring the radar performance.

4 ANALYSIS OF AIRPORT RADAR ENGINEERING PROBLEMS

4.1 Introduction

As a part of the study methodology to investigate the application and use of the existing RSC at airports in the UK, a survey was undertaken from a representative sample of airports. Fourteen airports were contacted initially to assess the following:

- The extent to which the RSC are known
- How the RSC had been applied at each airport and the problems encountered with their application, in safeguarding the installed radar system(s)
- Whether or not additional criteria and guidelines would be useful

The airports contacted as a part of the survey were those where radar safeguarding requirements are under the control of the CAA SRG, with the exception of one airport which is under the control of the National Air Traffic Services (NATS).

It should be noted that the responses from airports are based on the operational aspects of the application of the criteria, i.e. the adverse effects on the operation of the radar caused by a particular radar engineering or site installation problem. Airports in general regard radar engineering aspects as a secondary concern, providing that the installation has received approval from the CAA.

4.2 Summary Of Survey And Analysis

Of the original total of fourteen airports contacted, a sub-set of seven airports were selected for detailed analysis. A summary of the survey findings appears in Table 4-1. In support of the responses received from airports, further analyses were conducted into the application of the RSC using Ordnance Survey, Safeguarding Maps and a vertical obstruction database. These were used to examine the integrity of the 1/100 and 1/200 slopes defined within the existing criteria, and to examine the nature of the environment around the radar installation out to a distance of 4600 m, as shown in Figure 4-1. The radar-engineering problems encountered are considered in terms of the cause of the problem and the effect that is produced, as detected through the operation of the radar system.

Table 4-1 Summary of Survey Findings

Airport	*Criteria Known*	*Criteria Applied*	*Radar Passed*	*Radar Engineering Problems Experienced*	*Radar Engineering Problem*				*Radar Effects on other Systems (EMI)*	*Radar Type*	*PSR(P) SSR(S)*	*Extend Existing or Apply new criteria*
					Clutter	*Vehicle Reflections*	*Building Obscuration*	*Masts & WFG Obscuration / Clutter*				
A	Yes	Yes	Yes	n/a	–	–	–	–	–	264/R	P	n/a
B	Yes	Yes	Yes	No	–	–	–	–	Yes	W	P	n/a
C	Yes	Yes	No (P)	Yes	Yes	Yes	Yes	–	Yes	AR15	P	Ext/New
D	Yes	Yes	No	Yes	Yes	–	Yes	Masts	Yes	424	P	(N)
E	Yes	Yes	Yes	Yes	Yes	Yes	–	–	–	W	P	Ext/New
F	Yes	Yes	Yes	Yes	–	–	Yes	–	–	AR15	P	(N)
G	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	511	P	Ext/New
	Yes	Yes	n/a*	Yes	–	Yes	Yes	Yes	Yes	264	P	n/a *
	Yes	Yes	No (P)	Yes	–	Yes	Yes	Yes	Yes	424	P	New
	Yes	Yes	No (P)	Yes	–	Yes	Yes	Yes	Yes	470	P	Ext/New

Key:
(P) – partial pass of existing criteria
R – Routeman radar
W – Watchman radar
P – PSR
S – SSR
Ext/New – use extended / new RSC
(N) – new criteria (partial application)
* – radar being decommissioned – 1996
n/a – information not available
EMI – Electromagnetic interference

Of these seven airports, each airport company both knew and had applied the RSC to the installed radar equipment. A total of six airports indicated that the radar installations passed the criteria; however, in three of these instances the installed system only achieved a 'partial pass'. The definition of a 'partial pass' being that the criteria are met, but only along the orientation of the primary (or main) runway.

The airport survey showed that suitable values of the slopes and range of applicability of the radars could be derived from a more detailed empirical survey of the causes of the radar problems encountered, i.e. from a statistical sample of airfields. For example, it is established that intrusions into the defined slopes within the 4600m range have caused radar problems at some sites. What has not been established, from the small sample of airfields available in this study, is the maximum range at which intrusions still cause significant problems (as a function of radar type). It is not considered appropriate to use different values of slopes and range until such further evidence is available.

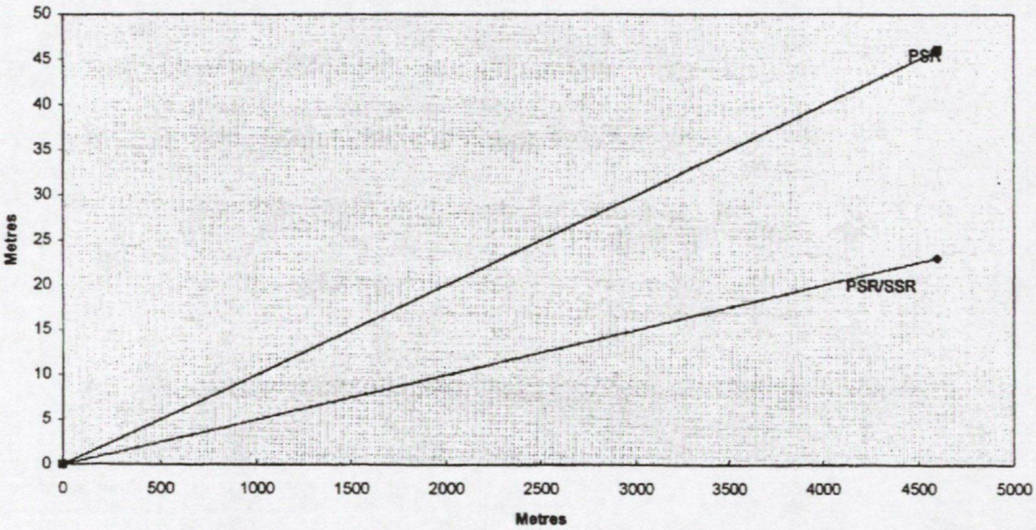

Figure 4-1 Slope/Encroachment Zones

The slopes in Figure 4-1 were used only as a guideline, since it was assumed that in applying the existing criteria at each airport the slopes originated from the centre of the radar antenna.

Two airports indicated that the installed radar system passed the RSC and reported that no radar-engineering based operational problems had been identified. One of these airports indicated that the radar systems from which it received radar data were not located on the airfield, but were two and a half miles away at a 'Technical Site'.

Five airports indicated that the installed radars passed or partially passed the criteria, but reported that radar-engineering problems had been, or are being experienced. Such instances imply that the RSC may need to be extended or engineering guidelines issued to cover such situations, and the recommended changes are stated in Chapter 6.

The radar site engineering problems (see Sub-section 3.1.2) reported as having operational effects on the radar can be categorised as:

- Clutter
- Vehicle Reflections
- Building Obscuration

These problems were identified as being caused by radar clutter suppression limitations, atmospheric conditions, vehicle traffic movement within the radar beam, and the masking/obscuration effect of tall buildings and urban developments within the line-of-sight of the radar out to a distance of 4600m, the limit to which the RSC are applied.

4.3 Clutter

The analysis of airport responses has indicated that four airports experience radar engineering problems caused by the effects of radar signal clutter. These clutter effects can be associated with:

- Antenna height and tilt
- Anomalous signal propagation
- Signal processing capabilities

The causes and effects of the clutter problems experienced at airports are outlined below.

4.3.1 *Antenna Height*

One airport reported that ground clutter out to a range of 1.25nm is experienced due to the fact that the radar antenna is not located high enough up from the ground to suit the particular engineering requirements and characteristics of the installed radar.

This clutter problem is not covered by the RSC. Analysis of the problem suggests that guidance should be provided for reduction of the clutter, provided that returns from aircraft in the airspace at the runway threshold are not suppressed. Recommendations for guidelines on the clutter map function and use of clutter suppression techniques are described in Chapter 6.

4.3.2 *Anomalous Signal Propagation*

Two airports reported that distant clutter out to a range of 25–40 nm from anomalous propagation was experienced under certain meteorological conditions (i.e. a stable atmosphere with temperature inversion). (see Sub-section 3.2.4)

Another airport highlighted clutter problems, based on the following factors:

- Urban Clutter at 1000/1200 m
- Hospital Buildings at 2000/2300 m

These buildings and developments do not however encroach into the 1/100 slope at the ranges specified from the site of the radar, however, signal clutter is experienced under certain atmospheric conditions from these obstructions. Anomalous propagation conditions are not, and cannot be, covered by the RSC. An analysis of the problem is described in Sub-section 3.2.4. No specific RSC changes are recommended for such environmental effects. However, recommendations for guidelines on clutter suppression for new radar sites are provided in Chapter 6.

4.3.3 *Signal Processing*

One airport reported that intermittent clutter breakthrough is experienced with one of the radar systems installed. This is caused by the installed MTI filter processing system accepting fast moving vehicle traffic (with speeds similar to aircraft) as false aircraft targets at ranges up to 40 nm. The processing system's ability to filter aircraft from vehicle traffic returns is exacerbated in dense traffic conditions (see Sub-sections 3.2.8 and 3.2.9).

The intermittent clutter problem is not covered by the RSC. An analysis of the problem leads to the conclusion that MTI signal processing for road traffic needs to be evaluated by the radar manufacturer. The evaluation should consider particular levels of traffic and movements at and around the particular radar site. A recommendation for guidance on road traffic at new radar sites is provided in Chapter 6.

4.4 **Vehicle Traffic Reflections**

Analysis of the airport responses has highlighted that three airports experience radar engineering problems caused by reflections. These arise from fixed or moving surfaces or targets. Radar engineering aspects of reflections are discussed in Sub-sections 3.2.6, 3.2.9 and Appendix A Section 5.

The airports have indicated that vehicle traffic reflections cause operational difficulties to the installed radars. Analysis of the surrounding environments of the selected airport sites indicates that the visibility of traffic has become significant for three reasons which can be listed as:

- An overall increase in the number of major roads in the vicinity of airports and the progressive increase in the volume of traffic
- Increased speeds of vehicle traffic becoming close to aircraft speeds
- A siting problem where there are similar angular sightlines between the positioning of roads and approach paths

One airport experiences a radar engineering problem of reflections caused by vehicle traffic utilising an elevated section of a nearby motorway. The airport handles a considerable number of light aircraft and helicopter movements, the latter utilising special approach procedures. Although the section of motorway in the line of sight (visible) of the radar is outside the radar safeguarding limit of 4600m, in some instances the doppler returns from aircraft / helicopters and vehicle traffic cannot be separated by Air Traffic Control Officers.

This reflection / clutter problem is not covered by the RSC. The analysis of the problem indicates that roads in a radar's LOS should be assessed for the level of acceptability of clutter. A recommendation for extending the RSC for roads in a radar's LOS is provided in Chapter 6. If the recommendation is implemented, acceptability of the clutter suppression solution could be covered by a Site Concession Certificate.

Another airport also reported similar experiences with reflections from vehicle traffic on a dual carriageway one mile from touchdown. The orientation of the road is such that it runs parallel to the approach path for the runway for two miles, but does not encroach into the defined RSC slope for PSRs. The effect of the reflections is such that the doppler returns for aircraft on approach cannot be distinguished from fast moving traffic on the carriageway, since the approach speed of some aircraft and the speed of the fastest moving traffic are similar.

The analysis for this second airport is the same as for the first airport. In this case, guidance on road traffic provided in Chapter 6 (for potentially rejecting the building of a road) may be relevant.

The responses made by a third airport also highlighted engineering problems associated with reflections from vehicle traffic affecting the ASR511 radar located on top of a 30m tower. Although the installation passes the RSC, doppler returns from vehicle traffic are encountered over a wide range (30–40 nm) through 360 degrees of coverage. An MTI Clutter and False Plot Filter have been installed to assist in the reduction of vehicle reflections causing false target responses from vehicles. This was achieved by a process of matching the extracted plots to roads. However, it was found that the number of roads 'visible' to the radar are such that the ability of the signal processor to filter out all reflections is limited.

The analysis for this third airport is the same as for the first airport. In this case, guidance on road traffic provided in Chapter 6 (for potentially re-siting the radar) may be relevant for new radars.

4.5 Building Obscuration

A total of four airports from the survey indicated that radar operational problems were experienced, caused by building obstruction and obscuration effects (see Sub-sections 3.1.1, 3.1.2, 3.2.5 and Appendix A Section 4.3). Assessed against the RSC, three airports achieved a pass or partial pass, and one airport failed. In all cases some form of aircraft operational procedure has been put in place, however, this is outside the scope of this report.

Note that further analysis of the building intrusions, described below, would be possible within a (larger) statistical sample, in order to determine the maximum range at which intrusions cause significant problems (as a function of radar type).

One airport has an AR15 radar system which is approved for aerodrome approach to a range of 2nm. The installation fails the existing criteria due to building obstructions encroaching the 1/100 slope for PSRs. The obstructions can be listed as:

- Airport/ATC facilities at 650/700m
- Housing development at 700/800m

- Factory/Industrial Estate at 2100m
- Telephone exchange at 1400m
- Bank Computing Centre at 1600m

The criteria are passed at this site along the orientation of the runway i.e. the critical airspace of approach and departure paths is not obscured or obstructed. Since the problems were caused by building intrusions which were identified by the criteria, then the RSC have been successfully applied.

Another airport has a type 424 radar system (modified with an antenna tilt system between –10 and +15 degrees). The installation fails the existing criteria for PSRs (where the 1/100 slope applies) due the encroachment into the defined slope of a hangar (height 32m). When the radar was originally installed in the mid-1960s the installation was tested against the MOD Ground Radio Installation Criteria document – known now as AP100G – and at that time passed those criteria. The hangar is located 300m from the radar installation. This results in a blind angular sector of airspace to the radar of approximately 27 degrees. As the hangar was identified as encroaching the 1:100 slope of the criteria and there was a radar engineering problem, the RSC have been successfully applied in this instance.

A third airport has an AR15 radar installed on the aerodrome. The installation passes the existing RSC slope criteria for PSRs. However, a large building with a metal clad roof located 900m from the installation causes clutter and reflection problems. An analysis of reflection problems is described in Sub-section 3.2.5. No specific RSC changes are proposed. However it is recommended that a guideline for building reflections in Chapter 6 be applied.

This airport also indicated that planning permission had been sought and approved for the installation of a SSR system at the existing site. Installation of such equipment would require that the new antenna be raised on a taller platform, in order for the same building not to encroach into the 1/200 slope for SSRs as currently defined. This demonstrates successful application of the criteria, as described in Sub-section 3.1.1.

A fourth airport indicated that four radar systems were installed on the aerodrome. These radar systems can be listed as:

- ASR511 system (on 30m tower)
- S264 system (being decommissioned in 1996)
- ACR424
- S470

The latter three radars fail the existing criteria for PSRs due to encroachment of buildings and obstructions into the 1/100 slope. The obstructions penetrating the slope can be listed as:

- Airport buildings and associated works at 300–1000m
- Urban development and existing buildings at 1500m (including a church spire)

The ACR424 and S470 radars pass the existing criteria along the orientation of the runway i.e. the critical airspace of approach and departure paths is not obscured. This demonstrates successful application of the criteria, as described in Sub-section 3.1.1.

4.6 Masts And Wind Farms

The survey indicated that none of the airports contacted, currently experienced any radar siting problems related to wind farms and associated clutter. One airport expressed concerns over the potential development of wind farms in the vicinity of the airport. These wind farm sites are inside the unofficial twenty kilometre advisory zone agreed by the CAA (SRG) and local planning authorities, although they are beyond the 4600m range within which the safeguarding of radar installations are presently applied. Therefore, if the wind farms were to be built, the structures would not penetrate the defined slopes (1/100 and 1/200) of the existing criteria. An analysis of radar engineering aspects is provided in Sub-section 3.3.2. Recommendations for new criteria for wind farms are proposed in Chapter 6.

A further airport indicated that a group of three telecommunications masts produced a permanent echo (reflection) at a range of 6 nm from the radar installation. While beyond the limit for the application of safeguarding criteria, the echoes produced are used as a reference point to assess the performance of the radar on a periodic basis. This is an example of constructive use of an adverse effect.

This masts problem is not covered by the RSC, since the masts are outside the maximum range to which the RSC are applied (4600m). The analysis of the problem of such masts is that there may be a potential aircraft bearing error, since the masts are still within detection range for the SSRs. A recommendation for extending the RSC for bearing errors is provided in Chapter 6, based on the radar engineering considerations described in Sub-section 3.2.1.

4.7 Electro-Magnetic Interference (EMI)

A total of four airport responses indicated that due to the siting of the radar installation, and irrespective of passing or failing the RSC, the radar produces breakthrough on electrical / computing equipment both at the airport and within the surrounding environment. The analysis of the effects of EMI falls outside the scope of this report.

5 CONCLUSIONS

5.1 General

This Radar Safeguarding Study has examined:

- The current CAA RSC and Safeguarding Maps
- MOD radar safeguarding for military installations
- The replies from a survey of seven airport companies, which was made to assess the extent of the application and utilisation of the criteria
- The effect of wind farms and road vehicles on radar safeguarding

5.2 Use Of Existing Criteria

The RSC have been used successfully by airport operators for many years. It is concluded that the RSC were produced to protect radars from LOS obstructions to a range of 4600m by means of defined slopes, with a secondary objective of clutter reduction. The RSC provide a criterion for each of the following three radar groups :

- PSRs (using a 1:100 slope)
- PSRs (using a 1:200 slope)
- SSRs (using a 1:200 slope)

The values for the slopes and range of applicability in the RSC appear to be based on radar LOS calculations. However, the airport survey indicates that further research may allow the values to be refined for particular radars. It is not considered appropriate to use different values until such further evidence is available. However, some extensions to the existing criteria and new criteria are proposed in Chapter 6 to ameliorate particular problems not covered by the criteria as they now stand.

The following specific limitations of the RSC have been identified :

(a) Radar groupings are not defined, e.g. PSRs (using a 1:100 slope) are Medium Range 10cm radars;

(b) Radar types within each grouping need to be generalised, since the CAA List of Radars is continuously being updated; and

(c) The purpose of each criterion is not defined.

It is concluded that the basic format of the RSC should be retained and extended to overcome the limitations – (a) to (c) above.

It is concluded that the Safeguarding Maps produced by the CAA should be retained, since the Airport Authorities find them satisfactory as a first pass method of assessing planning permissions/applications.

It is noted that MOD has applied radar-specific safeguarding criteria to its airfields, and the procedures document (AP100G) is updated as new radar types are developed and installed at military installations.

5.3 Radar Problems Reported

From the results of the survey received, as summarised in Table 4-1, safeguarding problems have been encountered mainly for clutter, vehicle traffic or building obscuration. There is also potential concern about the development and building of wind farms in the vicinity of airports.

It is concluded that new criteria are needed to overcome these airport problems, and that these criteria should also take into account other radar engineering aspects, as described in Chapter 3. These new criteria should be based on radar-specific measurements, similar to those used in the AP100G. These additional criteria could be used as a second filter to assess planning permissions that failed the RSC. This would enable refinement of the analysis for safeguarding an individual airfield site.

Problems caused by vehicles are largely outside the control of airports and the CAA. Therefore the radars have been adapted or modernised to minimise the adverse effects. The CAA can object to the construction of roads and bridge structures, if when built they would encroach into protected surfaces as defined in CAP168 and the RSC.

Building construction has the effect of obscuring, partially or wholly, the radar returns from regions of airspace. It is concluded that co-operation during installation siting between airports and the radar manufacturers has mitigated many problems, using radar adjustments and operations procedure changes, e.g. re-routing aircraft approach.

Wind farms are currently affecting RNAS Culdrose and in future may affect other airports. It is concluded that although this mainly causes interference with helicopter and small aircraft radar returns, it could have serious consequences if a target is lost. RAF SEE have recently conducted a short investigation and have produced a research report (see Sub-section 3.3.2).

5.4 Radar Siting Factors

The increasing urbanisation and commercial infrastructure in and around airports since the 1960s has made the impact of man-made obstructions and signal clutter increasingly significant. The radar signal clutter accompanying this urbanisation can be reduced by signal processing improvements. It is concluded that the effect of obstructions should be evaluated in terms of how it degrades operational information used by controllers for ensuring a safe flight regime.

Calculations of obstacle effects are theoretically complex. If obstacles (size, say <1/10 beamwidth) are in the near field, where the plane wavefront, far-field pattern is being formed by phase interactions, then the obstacle disturbance produces reflection and obstruction of the wavefronts. The effect is to reduce the antenna main-lobe gain and increase the general side-lobe levels over the whole of the pattern. It is concluded that obstacle disturbance should be assessed by measuring the effects on the performance of the radars.

6 RECOMMENDATIONS

A number of specific conclusions have been reached during the work carried out for the Radar Safeguarding Criteria (RSC) Study. The associated recommendations are presented below.

6.1 Revised Existing Criteria

The RSC should now refer to the radar types as given by the CAA list [1994]; the radar wavelength designation is used from the list. Each criteria has been amended to provide a clear interpretation, with a stated purpose, so that this is kept in mind when the criteria are being used.

(a) Medium Range Radars (10cm) in the CAA List of Radars. The slope of 1:100 should start from ground level at the base of the antenna tower and be extended to a circle of radius of 4600m. This will minimise the obscuration of the radar LOS;

(b) En-Route Radars (23 and 50 cm) in the CAA List of Radars. The slope of 1:200 should start from ground level at the base of the antenna tower and be extended to a circle of radius of 4600m. This will minimise the obscuration of the radar LOS; and

(c) SSR (30 cm) in the CAA List of Radars. The slope of 1:200 should start from ground level at the base of the antenna tower and be extended to a circle of radius of 4600m. This will minimise the obscuration of the radar LOS. Consultation is required regarding the non-use of certain materials considered to be reflective (i.e. metallised glass, metal cladding, wire mesh type fencing, etc.) on elevations facing SSR installations. At sites with in-service SSRs, it is recommended that, when a reflective obstacle is proposed in any angular sector, further investigation is conducted to ensure that the SSR will have the signal processing required to suppress the false returns.

6.2 New Radar Safeguarding Criteria

It is recommended that the following additional criteria be applied to measure adverse radar effects and errors. The data should be passed to the SRG Air Traffic Services Standards Department (ATSSD) for assessment by operational specialists.

(a) Potential aircraft bearing errors for the SSR should be assessed from horizon obstacles within the LOS to the radar, using the data in Figs A-1 and A-2 (see Sub-section 3.3.2 and Appendix A Section 3.1). This will avoid generating bearing errors and thereby associated position errors of the target aircraft;

(b) Alignment of the radar boresight should not be made within an angular zone of ±4 deg, (preferably ±12deg), of the normal to the centreline of roads. This applies only to straight roads along which there is a significant number of buildings with large 'flat' elevations (see Sub-section 3.3.1 and Appendix A Section 4.3). This will minimise strong specular reflections;

(c) The far-field zone boundary should be calculated as shown in Sub-section 3.2.3; if obstacles are present within or close to this zone, then SRG should draw the attention of the appropriate ATSSD operational specialists to the potential disturbance on a target bearing measurement close to the obstacle bearing on the azimuth scan;

(d) Elevation coverage plots, as shown in Appendix D, should be obtained from the radar manufacturer if lobing or multipath is expected to be possible in a given angular azimuth sector because of smooth terrain (see Sub-section 3.2.5, Appendix A Sections 4.2 and 6). This will allow investigation into potential loss of aircraft radar returns;

(e) For a new radar, the site should be assessed with the radar manufacturer. The radar will be provided with a clutter map function to deal with fixed and moving clutter such as buildings and road traffic. Older radars usually have a reduced clutter map capability. This will allow targets to be seen which would otherwise be 'lost' to the radar tracking algorithms;

(f) For wind farms it is expected that, for modern PSRs, the complexity of signal processing and interaction with each unique wind farm site make it virtually impossible to suggest general criteria (see Sub-section 3.3.2). The following alternatives are recommended:

(i) If the wind farm is being proposed by a third party, then the governing legislation for consideration of the application should require that party to include with their proposal a modelling assessment of radar signal processing performance (based on data previously agreed by the CAA); or

(ii) SRG should obtain the modelling capability for themselves, although this would require ensuring the models are kept up to date and reflect accurately the installed radars. In EASAMS opinion this is best done by the radar manufacturer although such models may not be retained for old radars.

(g) For roads in LOS to the PSR, the speed and frequency of traffic must be considered. All traffic will produce doppler clutter which is undesirable. Modern signal processors can suppress such clutter in association with clutter maps, but the radar degradation will be dependent on the degree to which traffic is visible to the radar. The proposed radar site performance should be assessed with the radar manufacturer as in (e) and (f) above; and

(h) For wind farms in LOS to SSRs it is not expected that the same effects as for PSRs will occur. The site will induce bearing errors as found for 'single' obstructions given in 6.2(a) above. The bearing errors may be estimated outside the edges of the wind farm site using the curves of Figures A-1 and A-2 (see Sub-section 3.2.1 and Appendix A Section 3.1).

6.3 Siting Assessment

(a) It is recommended that each radar site assessment carried out by the CAA SRG should have an associated Site Certificate, with a Site Concession Approval where appropriate. The assessment should use these revised criteria and take into account ICAO Standards (see Sub-section 2.2.3), with the help of the Guidelines in Section 6.4 for interpretation; and

(b) It is recommended that a Radar Safeguarding Procedure, an example of which is shown in Appendix E, be developed to include assessment of sites against CAP 168, etc. The procedure would include production of an agreed set of siting documents for review by the CAA.

6.4 Supporting Guidelines

The following guidelines are recommended when considering any existing or new-site radar installation. It is expected that they will be used as a basis for consideration in the preparation and issuing of a Site Approval Certificate or Site Concession Certificate. The guidelines are:

(a) In view of the difficulty in locating information on site problems, it is strongly recommended that 'RSC – Clearance Certificates' with supporting assessment documents should be provided now at the airport site as a licensing requirement, as is required for RAF stations (see Sub-section 2.5.1 and AP 100G);

(b) If the radar is placed on a tower, then for the slope criteria as now defined, penetration of the slope surface by an obstruction may be allowed under restricted circumstances. The slope criteria are used to ensure minimal obstruction and scattering of the radar beam. The following points should be observed in considering such a penetration:

   (i) Does it penetrate the slope originating at the ground, but not a second parallel slope starting at the centre of the antenna (the original form of the criterion);

   (ii) Does it penetrate the second parallel slope starting at the centre of the antenna;

   (iii) Does it contain metal sufficient in quantity and disposition to disturb the LOS of the beam passing through or close to the obstruction, such that there is a reasonable chance of the target bearing being subject to unacceptable disturbance, or that the beam is subject to reflection of a specular nature such that the target bearing is measured incorrectly (see Sub-section 3.2.3); and

   (iv) Is the penetration in a sector where long range detection is required from the radar, i.e. where the LOS is close to the horizon.

(c) If the antenna assembly and turning gear is placed on the ground or a small foundation, the slope surface may be penetrated by an obstruction, but the restrictions as stated under (ii), (iii) and (iv) above are more critical;

(d) Road Traffic can be detected by modern radars using highly-effective moving target detection capabilities, under software control of digital signal processing algorithms. Site-specific software can be prepared and adjusted at site installation for many problems that occur. These signal processing and plot extraction capabilities for a given site are comprehensive and cater for most types of clutter and target conditions. They are not a panacea for all site specific problems and more robust methods may be needed on occasion, such as re-siting the radar (which may have other effects), and either screening or rejecting the building of a road with significant traffic levels in the radar LOS (see Sub-section 3.2.9 and Appendix C);

(e) Building reflections as described in 6.2(b) above can be minimised by signal processing in modern PSRs and SSRs. This criterion should be interpreted with the cost benefit in mind of whether:

   (i) The signal processing can cope with the level of reflected signal clutter;

   (ii) The road can be realigned; or

   (iii) The radar site can be repositioned.

(f) If the radar does not have a clutter map function (see Sub-section 6.2 (e) above) then it is recommended that consideration should be given to either operator training, modification to flight paths, or investigation of a radar upgrade; and

(g) The clutter suppression facility in modern radars is likely to have adaptive threshold control such that the clutter in each resolution cell can be suppressed independently in the signal processor. The effect will be to suppress the clutter by raising the threshold, but the result may be to lose small targets. Targets may have their track predicted across such 'cells', but the performance may not be acceptable for some azimuth sectors and should be drawn to the attention of the appropriate SRG ATSSD operational specialists.

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Appendix A Review of Literature

A.1 GENERAL

Database searches for a number of relevant topics have been made on the National Technical Information Service (NTIS) and other databases. Searches were also made on the monthly indexes to the MOD DRIC Abstracts, and the proceedings of radar conferences. In addition, visits to the IEE and CAA libraries were made to identify ATC radar aspects relevant to radar site safeguarding references.

The areas covered were:

- Radar reflections from buildings
- Wind turbines
- Airport surveillance radars
- Site installations

A.2 HISTORY OF ATC RADAR TOPICS

One of the earliest papers on ATC radars was published in 'Nature' in 1946 [Smith,1946], and in the same year the IEE held the 'Radiolocation Convention' in London, (see JIEE, Vol 93, Part IIIA). Unfortunately, no paper in the Convention suggests ATC or site criteria were considered, except for one paper on the effect of obstacles on 10 cm propagation. In the 'Nature' paper it is of interest to note that numerous references were made to reflections and to clearing the site of obstructions.

Clearly one area that has changed most crucially for ATC radars is the improvement in system design, signal processing and display technology. This has, for example, seen the water acoustic delay line (that was held at constant temperature) in early basic MTI radars become a solid-state logic, computer device with high reliability, stability and operating frequencies. This improvement has allowed processing architectures to be designed and manufactured giving enhanced performance in clutter suppression. Skolnik [1970] has pointed out that MTI theory and concepts were initiated during the war and early 1950s, but the availability of hardware and signal processing technology held back the introduction of MTI (in full measure) by some 20 years.

Evolution of some ATC radar installations in the US was mentioned in the 1972 Seminar on Operational Problems [NAFECS,1972]. This reported that FPS-60 radars, when decommissioned by the US military, were modified and made available to the FAA in the 1960s. Similarly in the UK, a military Siemens-Plessey Watchman radar has been modified for civil use. Ward [1987] has also drawn attention to the continuing development in ATC radars since the end of the War as one of the reasons for the Radar Modernisation Programme (RAMP) for Canadian ATC radars that took place in the late 1980s. This programme was intended to develop an ATC radar system which would remain operational until the year 2000.

The US ATC radars, ASR-9 and ASDE-3, were discussed in two papers in the Proceedings of the IEEE 'Special Issue on Radar', dated February 1985, together with a paper on digital technology. The ASR-9 was claimed to be the first FAA production radar with a complete MTD; it also has a clutter map and adaptive desensitisation for mapped areas where roads are visible.

In a 1980 paper, Cole [1980] at Marconi reiterated the ATC authorities' plan for movement from PSR to SSR for radar-derived data. Shaw [1987] has also discussed the improved performance achieved with new SSRs, and he stated that this replacement programme, together with progressive improvements to radar sites, has enhanced considerably the plot data quality.

MTI performance (see Appendix C) is strongly related to the clutter minimisation requirements inherent in the radar safeguarding. The pressure of increased aircraft density in controlled airspace is forcing an evaluation of MTI radar system techniques; e.g. Kamal [1992] has proposed a cylindrical phased-array radar as one method to provide improved target handling capacity.

A.3 RADAR OBSCURATION AND OBSTRUCTION

Physical blockage of the radar signal on the line of sight between the antenna and the target is unavoidable in certain circumstances. To overcome a blockage, either the radar system has to be repositioned, or operational procedures developed to allow the use of the radar (despite the loss of target return over some 'solid' angle of the radar's scan). From the 1960s, radar suppliers have been measuring the horizon obstructions as part of the site assessment process [Cottel,1995].

For example, Spingler [NAFECS, 1973] reported on the obstruction and reflection effects of remote transmitter towers on the southern horizon at Chicago's O'Hare Airport. These towers were 40ft high and surmounted by 8ft square platforms. They were reported as causing signal loss and reflection of SSR signals, even though the towers extended only about 1 degree above the radar horizon.

Smith [1972] described methods for selecting unobstructed sites for weather radars. He suggested picking the site to provide a close-in radar horizon with an elevation of about 0.5 degrees, to mask long-range ground clutter. For example, the Institute of Atmospheric Sciences radar site has a horizon varying between 0.4. and 0.8 degrees with little ground clutter beyond 10 miles. Radar coverage is then restricted to a height of some 10,000ft above ground at 100 miles range when curvature and refraction are taken into account. Smith suggested that there is little advantage in placing the radar on a tower, since for a 100ft tower, the distance to the optical radar horizon increases from the 'ground level' horizon by only about 14 miles, while this area will contain strong clutter impairing the short-range performance. To minimise the ground multipath effect, Smith advised that the beam could be tilted upwards by the 3 dB beamwidth.

A.3.1 Bearing Error

Spiridon [1975] provided a number of graphs and equations for SSR azimuth bearing errors for different obstacles, which he obtained from antenna theory and also from analysis of trials measurements using a 22l wide, flat SSR antenna. His study arose as a result of tracking errors noticed when radar-aircraft sightlines pass close to horizon obstacles.

Macey at the CAA [1992] provided further measurements taken at the Clee Hill site, as shown in the combined graph of Figure A-1. These measurements were obtained as a result of reconstituting an aircraft track from outputs of 6 SSRs, while the Clee Hill SSR scanned past a large meteorological radar tower some 320λ distant. The parameters of operational interest were the azimuth error and the disturbance in terms of angular width.

Shaw at the Royal Signals Research Establishment (RSRE) [1987] stated the 'normal' and 'exceptional' azimuth measurement errors are of greater importance in ATC surveillance than range error. In particular, the 'exceptional' errors have a wider spread and are often highly correlated, and this can mislead a data tracking system into assuming an aircraft is manoeuvring. The data tracking problem is usually caused by site conditions (most likely at certain azimuths), although the effects can also depend on aircraft elevation. It should be noted that the use of monopulse and LVAs has reduced azimuth measurement errors (over the earlier technology), as shown in Table A-1.

Table A-1 Typical Azimuth Error Deviations (deg)

Processing	*Hogtrough Ant*	*LVA*
Sliding Window	0.18	0.10
Monopulse	0.09	0.05 0.03, [Stevens 1987]

The MOD AP100G radar safeguarding criteria state that obstacles should occupy only certain maximum allowable angular zones (as seen by the radar). For example, the criteria for one radar type states that no obstacle structure is to exceed 0.25 degree of azimuth, and it should be ensured that the structures distribution does not exceed 0.5 degree in any of the azimuth thirty-six 10 degree sectors. The AP100G criteria also define the allowed angular extent of metal in the obstacle.

A.4 Radar Scattering and Reflection

Ground and sea clutter is described in many books and papers, and since the war many programmes have been set up to make measurements. Radar engineering aspects of ATC radars for both types of clutter are presented in the following paragraphs. Radars looking over the sea will tend to suffer fewer clutter problems than inland sites when the sea is smooth. This is because surfaces that are smooth tend to reflect the radar signal in accordance with geometric optics; rough surfaces tend to return the radar signal in all directions.

A.4.1 *Polarisation*

Sherwood and Ginzton [1955] reported that measurements at 3 GHz, close to grazing incidence, may produce specular reflection for horizontal polarisation, and scattering for vertical polarisation. Their measurements were based on a dry, slightly rolling terrain of grass (4–18inches high). This may account for the AP100G requirement that grass should be cut to 3 inches height, if (for operational reasons) it is likely that military radars need to switch polarisations with minimum effect from ground reflections.

A.4.2 *Ground*

Rigden [1973] reported clutter measurements taken at DRA, Portsdown, using a high resolution pulse radar at 5.75 GHz looking over the countryside (and sea areas). These data are some of the most appropriate for ATC surveillance radars, because the experiment covered woods, fields, buildings, villages, small towns and point reflectors such as pylons. The data show for the amplitude:

- 65% of clutter exceeds 0.1 m^2
- 18% of clutter exceeds 1 m^2
- <1% of clutter exceeds 10 m^2

Similarly for the spatial distribution for:

- >0.1 m^2 clutter lengths of 2 m to >330 m, and separated by <30 m up to 112 m
- >1 m^2 clutter lengths < 30 m
- >10 m^2 clutter lengths < 6 m, and separated by 135 m to 675 m

Rigden suggested that the results show the degree to which high resolution radar will facilitate the tracking of targets through surface clutter. Note that the dominant scatters, i.e. >10 m^2, were found to be correlated with pylons and buildings.

There seems to be no firm rule given in the radar literature to determine the effect on the elevation coverage of ATC radars used at low grazing angles. The equations available make certain assumptions about surfaces to give an indication of the effects which will be seen. The majority of radars in the UK urban/ semi-urban environments are unlikely to show significant lobing patterns. (However, in restricted azimuthal zones, the ground may be sufficiently flat and clear of obstructions along the radius to allow interference fringes to form.)

A.4.3 *Obstruction Surfaces*

Ranade and Noerpel [1988] used a database of 2,500 buildings in San Francisco to compile the density distribution of surface orientations. The results suggested that radar sight lines should not be within ±4 deg, or better still ±12 deg, of the normal to a road. These angular zones corresponded to 90% and 99% of the reflecting surfaces for the San Francisco database.

Skolnik [1980] stated that buildings, towers, pylons and similar structures give more intense echo signals than ordinary ground clutter. These signals are typically produced by flat reflecting surfaces and 'corner reflectors'. Bramley and Cherry [1973] made measurements by flying a 9.4 GHz transmitter near to buildings, and measuring the direct and scattered signals. Seven different large buildings were selected, having a wide variety of surfaces (brick, tiles, pebble-dash and concrete panels). All the buildings, except one, had metal-framed windows. In non-specular zones, the scattered energy was about 30 dB less than the direct signal. Specular reflection was given by all buildings except one, which comprised a brick surface with many metal frame windows and metal balconies. In all the tests, vertical polarisation gave the strongest scattering, which was a few decibels greater than for the horizontal polarisation.

From mathematical arguments, Bramley and Cherry deduced that the main azimuthal scattering contribution arises from flat surfaces with horizontal dimensions greater than λ, together with corner reflectors (when present). Two effects are of interest for the ATC radars, namely:

- Specular reflection giving rise to false target azimuth zones
- Backscatter causing high levels of clutter

Natchipolsky [NAFECS, 1973] reported that the major problem for SSR systems is azimuthal reflections, since ground clutter does not exist. However, exact predictions of the severity of the radar effects are not possible, because the 'objects' causing the problem will vary and they are not ideal reflectors.

The two operational problems for these reflections for the SSR systems are:

- Static building reflection
- Temporary aircraft reflection

Partial solutions to these problems are software to search for spurious code, and 'reflection maps' held in the processor. Brook-Footitt [1973] reported that a B-747 tail fin represents an almost perfect reflector of size 912 square wavelengths. Such phantom targets add to the processing load of the radar tracker. This implies that aircraft stand locations and orientations need to be considered when siting a radar. A patented method with additional directional Yagi arrays is advocated in the US to reduce the problems arising from the Improved 3-Pulse Interrogation Sidelobe Suppression (ISLS). This method is listed in the ICAO Recommendations. Brook-Footitt described trials designed to address the Heathrow Airport site problems, making reference to the multi-storey car park and control-tower complex of structures.

Similarly Cole [1980] described a Marconi patent for SSRs, which aimed to substantially reduce static reflections from sites, using transponders. In trials over a range of 50 nm without transponder protection, the generation of false replies was between 12–22%. After incorporating the new system, the false replies were almost eliminated out to about 25nm, and reduced to less than 10% out to 50nm.

A.4.4 *Radar Absorbing Material (RAM)*

RAM is available in solid sheet, flexible material or even as paint from specialist manufacturers. Up to 20 to 30 dB of signal attenuation can be achieved depending on various factors, e.g. frequency band, bandwidth, angle of incidence, degree of weather-proofing required.

Materials for lower frequency PSRs and SSR bands are thick and therefore heavy. RAM made of such material is obtrusive, and requires constant vigilance from a maintenance point of view (in order to prevent rain penetration or material degradation). As it has no structural strength, the obstacle, e.g. a building, may need reinforcing to take the weight of the material. This is normally achieved using adhesives, since bolting is not allowed.

Fulghum [1991] reported that spray-on RAM has been used to reduce radar and microwave reflections from buildings and towers. It can also be used for airport structures such as fences and landing lights. However, it is assumed that it is effective for the higher microwave bands, which are not those used for PSRs and SSRs.

Sengupta and Senior [1978] estimated the RAM required to reduce the wind generator blade section. They concluded that the weight penalty for 6 dB reduction would be intolerable at $\lambda = 30$ cm.

A.5 Elevation Coverage

The need for a special antenna elevation coverage pattern was recognised many years ago for targets approaching at constant altitude relative to the ground surveillance radar. The cross-section and velocity of some road vehicles can be similar to helicopters and aircraft (particularly aircraft coming in down the glide slope).

Airfields that have been contacted in this study report a wide range of road traffic 'interference'. For one airfield, an elevated motorway causes interference, and for another, rush hour traffic is clearly visible on the radar from the main A-road – which is aligned with the runway.

One proposal reported in Skolnik [1980] is to use a secondary feed for the reflector-type PSR antenna. The primary feed is always used for transmitting and receiving, but for short range use, if the road traffic is highly-intrusive, then the secondary feed is used. This secondary feed is switched electronically to provide a beam optimised for higher elevation angles. This technique also assists in the elimination of bird clutter. In fact, most radars now provide this electronic beam switching. Ward [1987] reported that the secondary feed can be adaptively-switched, in order to prevent receiver saturation from strong stationary clutter. This can be used in conjunction with time-varying gain associated with the clutter level stored in the 'clutter map'.

A.6 Multipath Phenomena

A.6.1 *General*

Many studies have made on the multipath effect related to military surveillance and weapon-tracking radar systems. Barton [1973] and Skolnik [1980] have provided good reviews. The ATC radar situation is different in that it relates to management and control of aircraft flying over a wide range of heights, generally on steady courses.

The reflection of both the PSR and SSR signals from the terrain around the radar has been noted for the lobing produced in the elevation pattern. The effect is prevalent at the lower radar frequencies, since airfield sites are relatively smooth at these frequencies. Barton [1973,1977] drew attention to the limitations in the analysis of characterising the 'rough-surface'. The situation is exacerbated by the presence of vegetation, which when dense and moist could virtually eliminate reflections for elevations above 1 or 2 degrees.

The practical effect of such reflection is to cause a periodic variation in the received signal strength. The variation can be from 'hardly noticeable' to nulls causing total loss of signal in the receiver. Placing the antenna as high as possible minimises the effect operationally by spreading the ground-irradiated region over a larger area. This diminishes the coherent reflection in practical installations, so that it becomes more diffuse. The equation for the nulls and peaks [Skolnik,1980] indicates that they become more numerous and closer together with height; therefore the impact on the radar performance is reduced.

It was recognised over 20 years ago that the principal SSR source of azimuthal errors arose from the effects of multipath propagation [Ullyatt,1973]. The reflection situation is more complex for SSRs. Wyndham & Shaw [1983], Scofield & Simcox [1977] reported that the SSR code garble that occurred at the Clee Hill radar site was associated with ground reflections. It was found that the garble could be virtually eliminated by using an experimental receiver with adaptive threshold.

A.6.2 *Fences*

A number of authors have reported the use of metallic fences either on an arc or circumscribing the radar site (the first known reference appears in the work of Hey and Parsons [1955]). These fences can serve three purposes, namely:

- Reduce ground reflection
- Reduce fixed or moving clutter
- Provide public protection against high effective radiated powers

Simple techniques have been employed in the past to minimise vertical lobing interference over smooth ground by the use of wire fences, either close to the radar, or located at some moderate distance. In one example, it was proposed to install a 20 ft fence at a distance of 286 ft, and inclined at 16.5 deg towards the radar. The fence is only required over the sectors causing a reflection problem. The top edge is normally at, or below, the bottom of the antenna assembly. The fence slopes towards the antenna by an angle, which returns the majority of the reflected signal at the Brewster angle for the terrain type [Spingler/NAFECS/1973].

The use of fences was investigated in the UK and subsequently found to be beneficial at the Clee Hill radar site in reducing the ground reflected wave by about 15 dB, and reducing the SSR standard deviation to about 0.05 degree [Wyndham,Shaw,1983].

As an alternative to wire fences, evergreen tree foliage has also been recommended, or low mounds of earth with the correct slope for maximum absorption (the effectiveness of trees in removing lobing multipath was noted at the site of the SSR for Whitehouse, Florida).

A.6.3 *Site Survey*

McDevitt and Spalding [1987] recommended that essentially the prerequisite to radar installation should be the site survey and map data analysis. The antenna height is normally chosen so as to avoid positioning a null at an operationally-significant angle; this is particularly critical along the approach path to the airfield. A computer program can be used to assess the lobing under different surface conditions. They reported on the improved performance in reduction of lobing with LVA antennas. The suggested optimum antenna tilt for the LVA was to place the S channel –4dB point at 0 degree elevation. Further site-specific adjustments to the tilt, or the signal processor time varying gain can minimise problems in particular range-azimuth cells.

An example of such a survey was the site installation performed by Decca Radar Ltd [Cottel,1995].

A.7 Signal Processing

The major improvement in radar performance over the last twenty years or more has been due to the increasing availability of computer processing technology, at lower costs. This has permitted substantial improvements to be made to clutter reduction techniques, particularly by the use of clutter maps. The effects of clutter change for many reasons, e.g. the seasons. As noted in Section 6.3 of this appendix, McDevitt and Spalding [1987] reported that modern SSRs can be adjusted to give the required performance in specific range-azimuth cells.

Gertz [1987] described the surveillance processing function available with the new Mode-S SSR, and the new algorithms being tested at Washington National Airport in 1987. He showed an example from one data set plotted, the reply correlator had eliminated false or reflected targets from the ATC operator's display comprising 12.8% of the total targets.

Lensu and Savuori [1992] has proposed a fast, adaptive-clutter canceller for installations where the search radar has parameters not conducive to updating with MTD.

A.8 Vehicles and Wind Farms

It is noted that there is a large amount of literature on detection of moving targets for military purposes. This was originally to describe the many types of operational scenario for land, air and sea targets. However, such literature is primarily describing signal processing, and is of little direct interest to site installation and layout problems.

The more recent 'moving target' phenomenon, e.g. the wind generator farm (for public electricity supply), is not so well documented. However, there are some reports on the increasing urbanisation and the associated road vehicles in the vicinity of airports, see Schrader and Gregers-Hansen [Skolnik,1990].

Wind farms have been brought to industry's attention because of television picture disturbance, and also the potential to interfere with microwave links for communications. Some structures are given in Table A-2.

Mahony [1995] reviewed the mapping technology (or GIS), and identified potential sites meeting certain criteria on the Isle of Man. In her site assessments, she recognised and used a number of environmental criteria and Department of Environment recommendations, including the airport height restrictions. The impact of helicopter blade rotation on airborne doppler radar was analysed by Moaveni and Vazifehdoost [1981], and similarly Martin and Mulgrew [1992] looked at the returns from turbo-prop aircraft blades.

Table A-2 Wind Generator Structures in the Literature

Source	*Mast Height*	*Blade Diameter*	*Generator*	*Remarks*
van Kats	22m(72ft)	Two blades 25m/ 82ft, enclosed angle 170 degree.	10.6m x 2.75m 35ft x 9ft	Carbon fibre blades, tapered 1.9m to 0.3 over 12.5m, steel boom at root and internal elec. wires
van Kats	45m at Medemblik	Not known	Not known	Estimated backscatter s = 24 dBm^2 ca 640 MHz
Ousbäck	at Näsudden			Reinforced concrete tower, metal rotor
Sengupta & Senior	at Plum Brook, 30m/100ft	Two blades 37.5m/125ft		
Dowdeswell	At Goonhilly, 14 towers	Three blades		tower spacing 200m, row spacing 300m

A.8.1 *Single Generator*

In one of Sengupta and Senior's earlier reports [1978] consideration was given to effects on aircraft VHF Omni Ranging (VOR) receivers. Stationary windmill blades were found to produce greater bearing indicator errors. It was stated that FAA standard guidelines (FAA Report 6700.11) could be used for siting of WFGs near to such VOR stations. Some measurements given in their reports are shown in Table A-3.

Table A-3 Radar Cross Section for various Blades

Blade	*s (dB rel to 10" sphere)*	*s (m^2)*	*Equiv Scattering Area X 10^3 (m^2)*	*Scattering Efficiency*
MOD-O Al sheet over girder frame, like a/c wing; 58.5 ft long	14.6	1.47	8.44	0.67
MOD-O(FG) fibre glass	7.7	0.30	3.81	0.282
MOD-OA composite fibre glass laminate; 60 ft long.	6.5	0.277	3.32	0.244
MOD-OA with minimal lightning strips	7.2	0.267	3.6	0.265
Metal MOD-OA		1.28	7.88	.587

Note: Further information on the characteristics of single generators is available, if required.

A.8.2 *Multiple Generators*

The RAF SEE report [Dowdeswell,1995] is the only report found which addresses the interaction of WFGs and airport surveillance. Although it described only a short-duration trial, comprehensive measurements were made to estimate the following factors :

- Magnitude and nature of interference
- RCS of turbine and blades
- Doppler shift
- Effect on aircraft detection

The PSR used was the Siemens-Plessey Watchman which viewed fourteen WFG masts at 3.6 nm distance; the radar boresight elevation lay between 0.27 and 0.42 deg to the rotor centres. Each WFG was resolvable on the Plan Position Indicator (PPI) display. In general, the 14 targets were decorrelated from scan-to-scan, but there was at least one target seen on each scan.

The interference phenomenon was characterised by strong periodic responses. The range-cell resolution did not permit isolation of aircraft target returns between the individual generator clutter returns. Unfortunately, no unclassified RCS figures have been found for helicopters. However, the shape of the Sea King, and similar size commercial helicopters, indicates that the side on view will produce a large specular flash. The tracks shown in the report indicate the helicopter was 'seen' most of the time at positions near to the ends of the fuselage.

Detection of targets having a velocity-component radial to the radar, is the expected signal for doppler radars Other radars have appropriately-designed detection circuits and signal processing. WFGs can potentially be a radar processing problem if the generator blades are in the main radar lobe. However, if the signal return from sidelobes is competing with the primary return it is not necessarily an unwanted type of signal in some circumstances, e.g. the doppler return from the aircraft turbine first compressor disc is discussed by Pellegrini et al. [1992], and can be used to correlate with the aircraft position to help the ATC operator identify the aircraft type.

A.8.3 *Summary*

It seems clear from the available data, and the theoretical outlines in Knott [Skolnik,1990] of radar cross-section, that:

(a) A single generator tower will have a strong forward scatter lobe and a relatively lower level backscatter region. As the wind speed and direction varies there will be specular returns directed towards the radar, again of a variable nature – with rotation, blade twist and blade feathering;

(b) Multiple towers will provide a more complex return. Some simple estimates of the effects may be possible, based on the basic equations for bistatic radar cross-section, and ignoring multipath, for two particular cases:

(i) A single line of towers along a radial from the radar; or

(ii) A single line of towers tangential to the radius from the radar.

(c) These towers might also be considered as wide-spaced linear arrays, producing an echo with a (sinx/x) form at distances much greater than the 'array length'. While they are not representative of all sites, it may give an order of magnitude of the cross-section and the direction of maximum response.

A.9 Rotating Targets

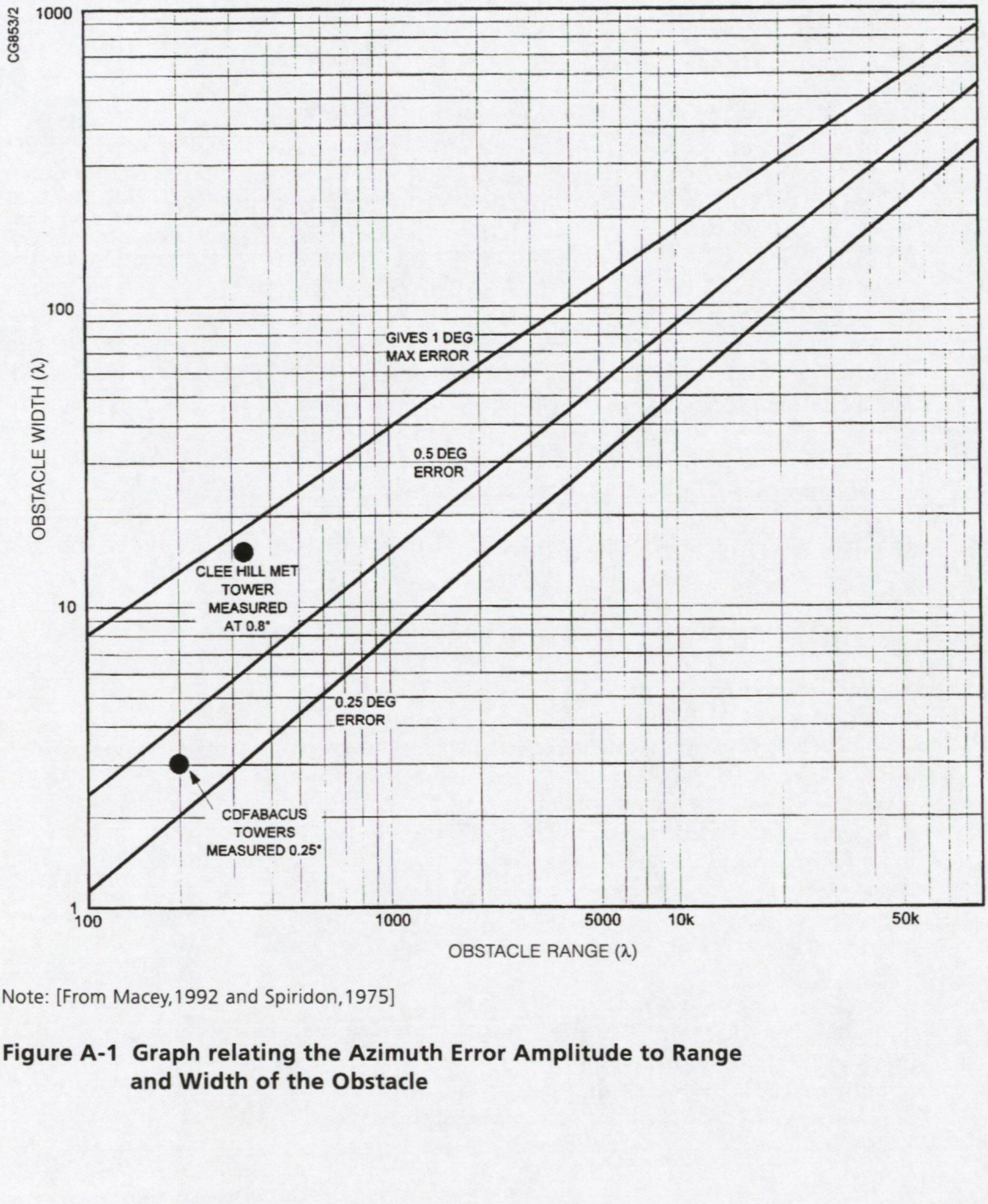
The reflection of radar signals from rotating propellers has been investigated for many years as part of signature analysis of military airborne targets. Martin and Mulgrew [1992] performed a theoretical analysis to show that the time-varying signal reflected from propellers has the properties that:

- The frequency separation of the generated sidebands is directly proportional to the number of blades and rotation frequency
- The bandwidth of each sideband is determined by the propeller rotation frequency
- The blade pitch produces amplitude modulation of the return

A.10 Anomalous Propagation

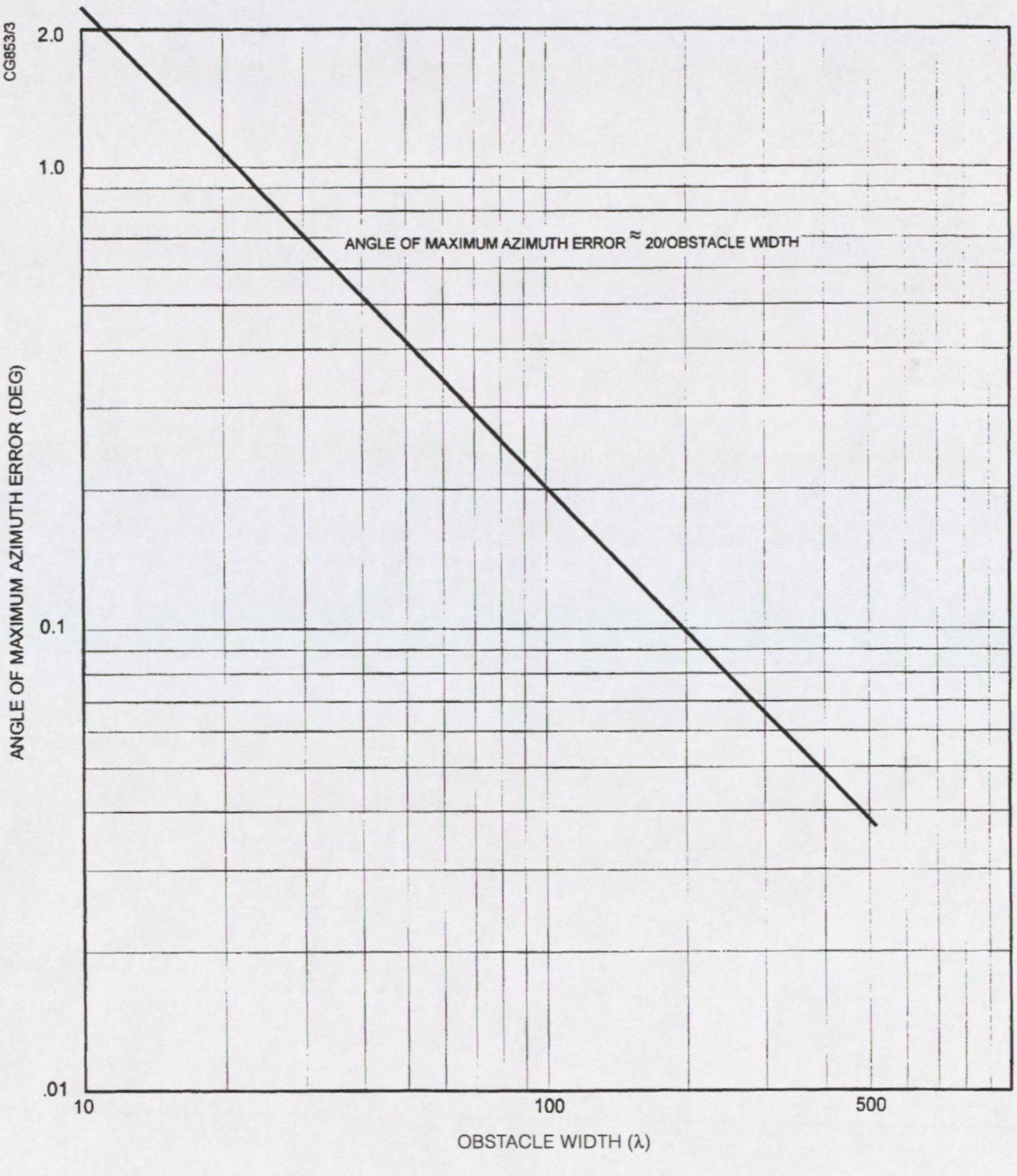
Stable meteorological conditions over a given period form atmospheric ducts. These ducts can lead to the effect of long-range transmission. Such transmissions are received by radars as signals from targets outside the normal range of the PSR or SSR. For surface-based radars, ducting is limited to low angles of elevation. This has the effect of extending the surface coverage over that expected from the refraction induced in plane wave propagation over a smooth earth. Under anomalous propagation, an 'apparent' target is seen in the operating range. However, in reality, it is a multiple of the apparent distance away from the radar site.

One of the airports has mentioned this as a well-known phenomena, although it is unpredictable. However, the effect has been recognised on PPI displays at certain times of the year, and therefore can be discounted by the operator. McDevitt and Spalding [1983] reported that the reflecting surfaces can be included in the permanent-reflector file (if not recognised at the initial site installation trials).



Note: [From Macey,1992 and Spiridon,1975]

Figure A-1 Graph relating the Azimuth Error Amplitude to Range and Width of the Obstacle



Note: The curve is based on plotted points for 6 obstacle ranges from 2000λ to 32000λ.
[From Spiridon 1975]

Figure A-2 Angle at Off-The-Centre of Obstacle where Peak Azimuth Errors occur vs Obstacle Width (λ)

Appendix B Definitions

Radar Cross Section (RCS)	Also known as echo area or effective area, s, for discrete targets. The projected area of a metal sphere, large compared with the wavelength, which would return the identical echo signal as the target. A detailed discussion will be found in Knott [Skolnik,1990] and others. Full discussions will be found in various texts. For the purpose of this Study the RCS s is the monostatic case, i.e. the transmitter and receiver use the same antenna. Formal exact analysis of practical target shapes is virtually impossible except for certain geometrically symmetrical bodies, e.g. a sphere.
Interclutter visibility (ICV)	The ability of some radars to separate or resolve strong clutter regions, between which targets may be detected, is called interclutter visibility. The clutter in the separating areas is lower, and therefore the target stands out more easily. The dB ratio of the clutter in the two regions is indicative of the achievable improvement.
Blind Speed	An MTI/MTD radar has zero response to the target's radial component of velocity, including stationary targets at integer multiples of the Pulse Repetition Frequency (PRF). These are the blind speeds given by $V_B = kx0.29x \frac{fr}{F}$ Where k = ±0, 1, 2, 3, ... F = transmitter frequency, GHz At 1300 MHz and 400HZ PRF these are ±89, ±178, ... knots
Improvement factor, I.	This is defined for an MTI system as the Signal to Noise Ratio (SNR) at the output of the clutter filter, divided by the SNR at the input of the clutter filter, and averaged uniformly over all target radial velocities of interest.
Signal-to-Clutter Ratio Improvement, ISCR	In an MTD system, each doppler filter will have a different improvement factor against the same target clutter. By common usage, this factor is the ratio at each target doppler frequency obtained at the output of the doppler filter bank to the signal-to-clutter ratio at the input of the filter bank.
Subclutter Visibility (SCV)	This is a measure of the radar's ability to detect moving targets signals superimposed on clutter signals. It is the ratio by which the target echo power may be weaker than the coincident clutter power, and still be detected with specified detection and false alarm probabilities. (See further description in Barton and Shrader,1969)
Differential Cross Section	This is the radar ground return described by s0 rather than by the (total) radar cross section, s, above. The return from the ground varies with the geometric radar parameters. The definition provides a coefficient independent of these parameters.

Appendix C MTI Radar

C.1 DESCRIPTION

A simple MTI radar uses the doppler shift given to signals reflected from all targets with a radial component to their motion. If the target is stationary no shift occurs. The ability of the radar to recognise the doppler shift requires a highly stable reference oscillator in the radar. The phase reference, provided by the oscillator, is used by a phase detector to detect the returned signal phase. The phase is stored between pulses and compared; if a change occurs because the target has moved then a signal is detected.

In modern PSRs, this basic MTI process becomes a more complex digital processing system located after the phase detector. It is preceded by superheterodyne operation producing an intermediate frequency input to the phase detector. This is termed a Moving Target Detector (MTD) radar. The bipolar video will be converted to a digital word, followed by parallel doppler filters, followed by Constant False Alarm Rate (CFAR) processing, plus the inclusion of high resolution clutter maps to suppress point clutter.

The MTD radar transmits a pulse group of N pulses at constant PRF for a period called the 'coherent processing interval' (CPI). Anomalous propagation conditions may require one or two additional pulses. The returns from one CPI are processed, then the radar may change PRF and/or radio frequency and transmit a further CPI of N pulses.

The result of this causes successive doppler responses to appear at different frequencies enabling blind speeds to be eliminated. It provides greater coherent signal integration in each filter. It also maximises clutter attenuation of different doppler frequencies over a larger range of doppler frequencies than achievable with a single, simple MTI filter radar, i.e. suppresses land and weather clutter significantly. Each doppler filter output may be further processed through a range-azimuth cell averaging filter. This has the effect of further suppressing extended range clutter not completely eliminated in the earlier filter.

Modern computer techniques are heavily used in these radars to provide clutter maps after doppler filtering to suppress residual unwanted returns to below the receiver noise level. The performance of the radar depends on highly stable phase coherent oscillators, and also the dynamic range of the signal processor.

Note that the above is a highly-summarised description of modern surveillance radars to be found in radar books, e.g. Skolnik [1990]. Skolnik describes the complexity of the various methods for implementing designs for adaptive MTI filters.

C.2 CLUTTER MAPS

The following features have been incorporated in MTI radars to reduce the clutter:

- Sensitivity time control
- Improved radar resolution
- Reduced antenna gain close to the horizon

However, in many MTI radars the clutter-to-noise ratio will exceed improvement factors associated with the above methods. The clutter residues, after the MTI canceller, require further suppression to avoid PPI display saturation, or excessive false alarm rate.

Suppression of clutter residues is relatively easy for spatially homogeneous clutter, e.g. rain, but not for general land clutter, which must be suppressed using other techniques. Land clutter, such as buildings and towers, is fixed, since it always appears at the same range and bearing. While it was known for many years that a suitable memory could store this information and therefore remove it from the signal during processing, it is only with the aid of solid-state memory ICs and the development of techniques in the early 1980s that this has become really effective.

The map is usually organised as a range-azimuth cell representing target space comprising 8 or 16 bits of memory. The cell 'dimensions' are a compromise between:

- Required memory for system
- Cut-off velocity
- Its transient response
- Loss insensitivity

The minimum size will be the normal, radar-system, resolution cell.

Appendix D Examination of Lobing

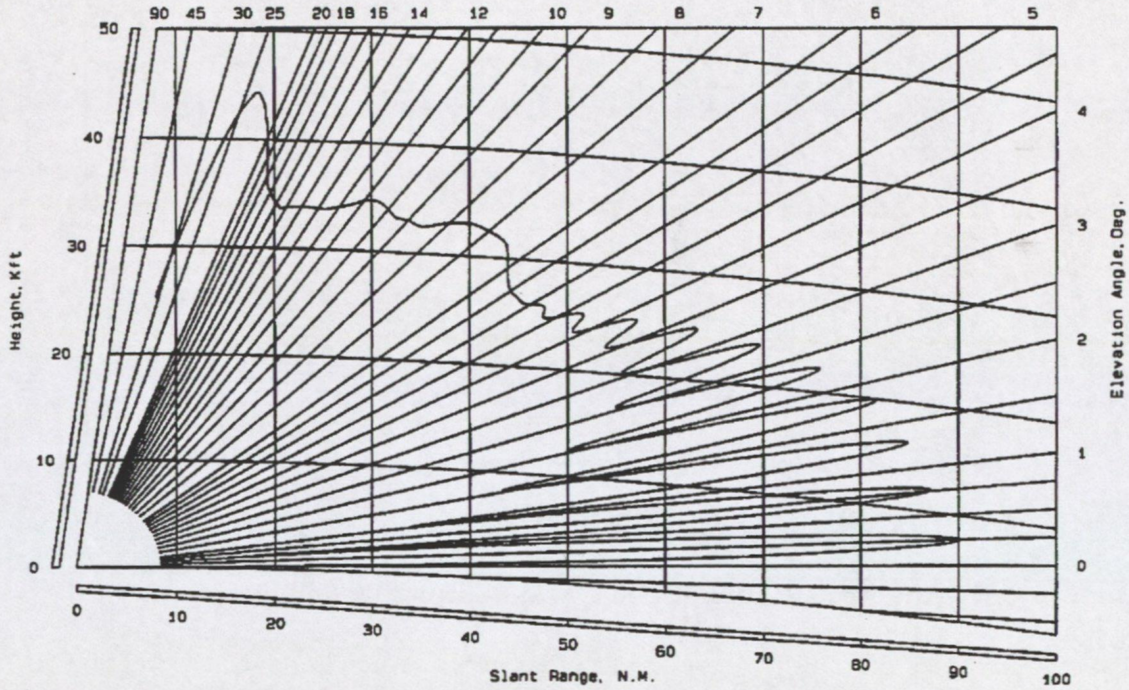


Figure D-1 S511 Antenna Height 20 Feet, with Multipath (Sea State 2)

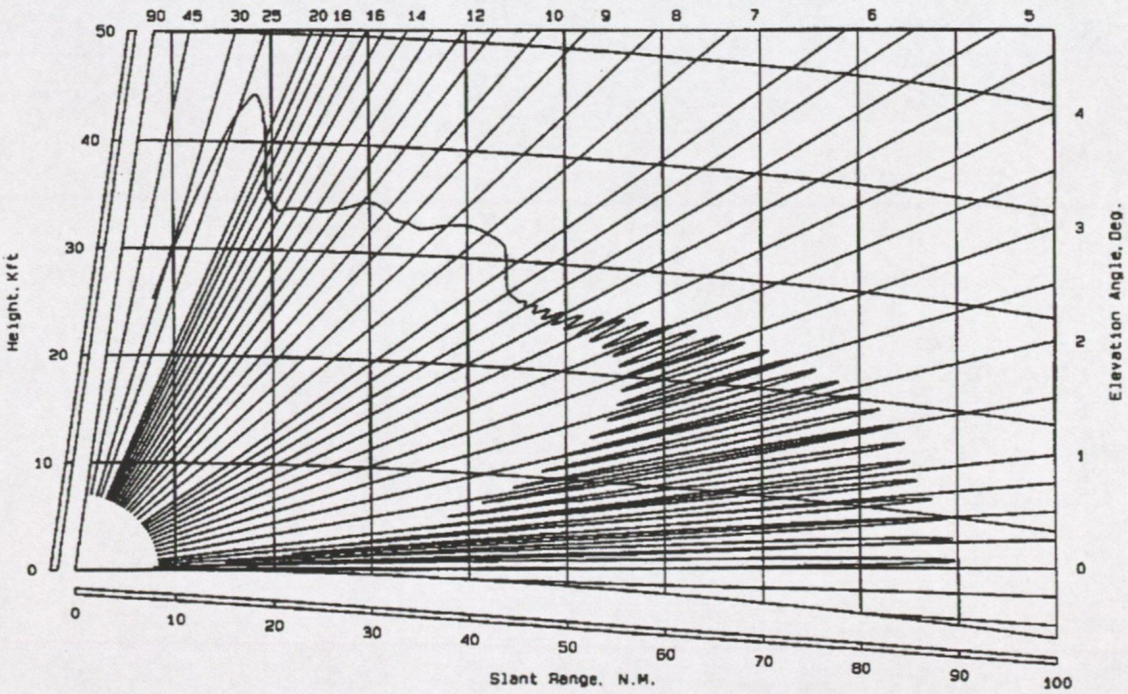


Figure D-2 S511 Antenna Height 50 Feet, with Multipath (Sea State 2)

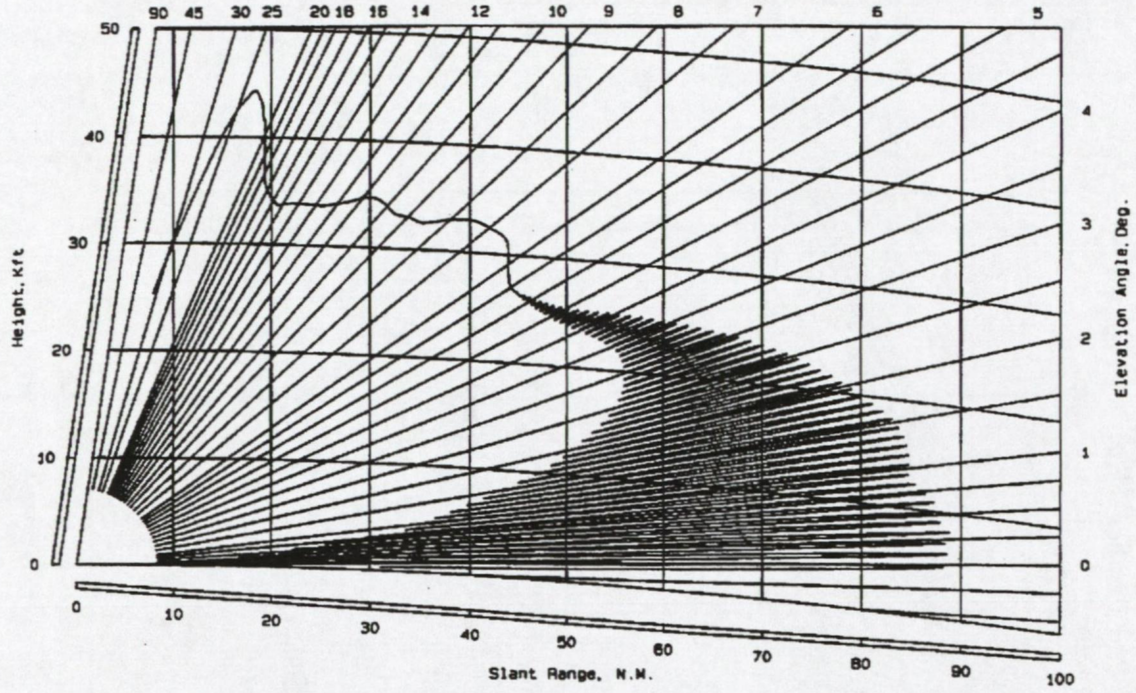


Figure D-3 S511 Antenna Height 100 Feet, with Multipath (Sea State 2)

The above examples of lobing at three S511 radar antenna heights over a reflecting surface equivalent to sea state 2 were provided courtesy of Dr. D J Acath, Marconi Radar Systems Division.

Appendix E Radar Safeguarding Methodology

E.1 RADAR SAFEGUARDING PROCEDURE

It is recommended that the following procedure in Figures E-1 to E-3 could be further developed and used as an interim safeguarding methodology for use by Airport Authorities. Such a methodology could be later incorporated into a handbook.

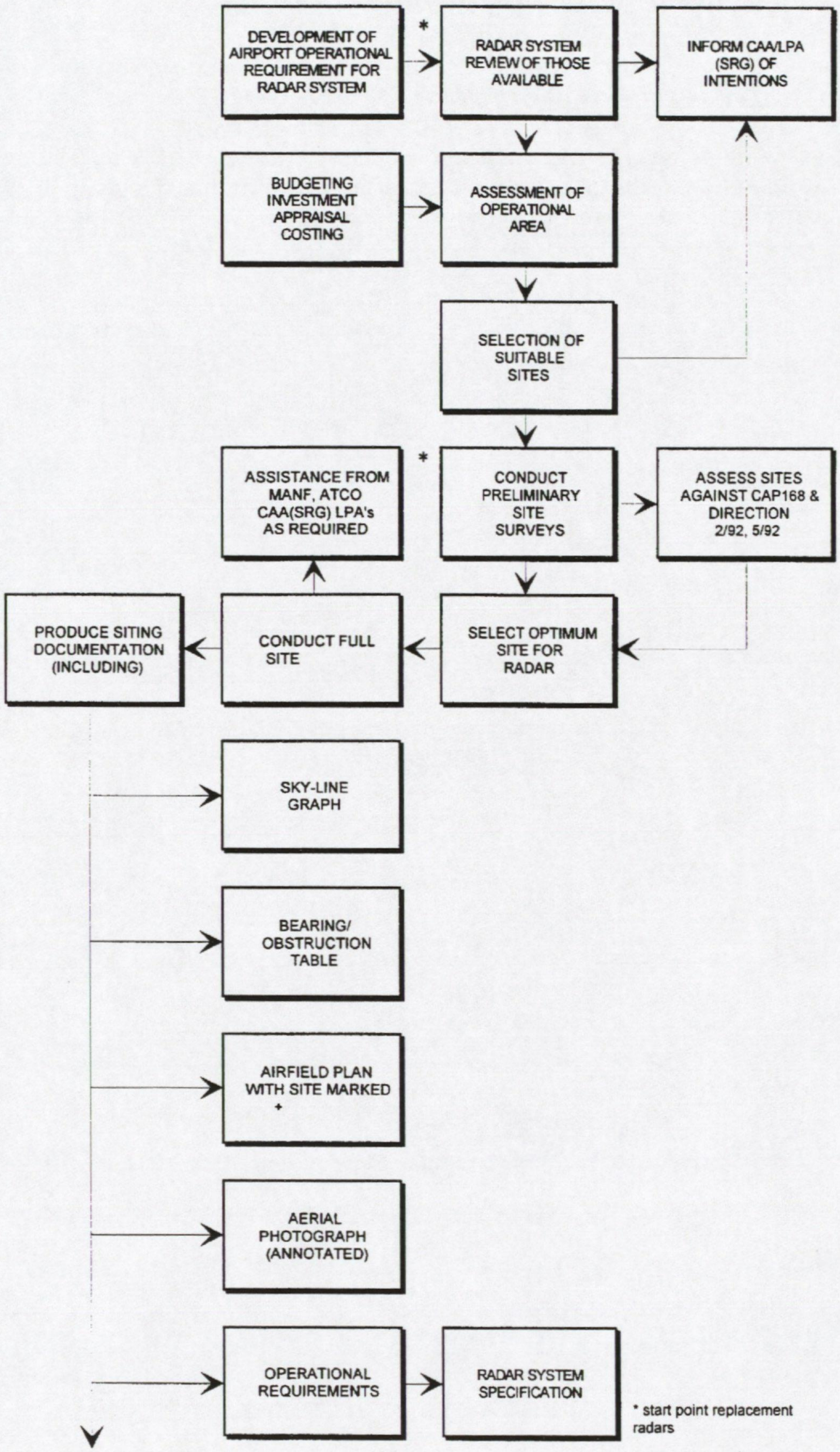


Figure E-1 Radar Safeguarding Procedure

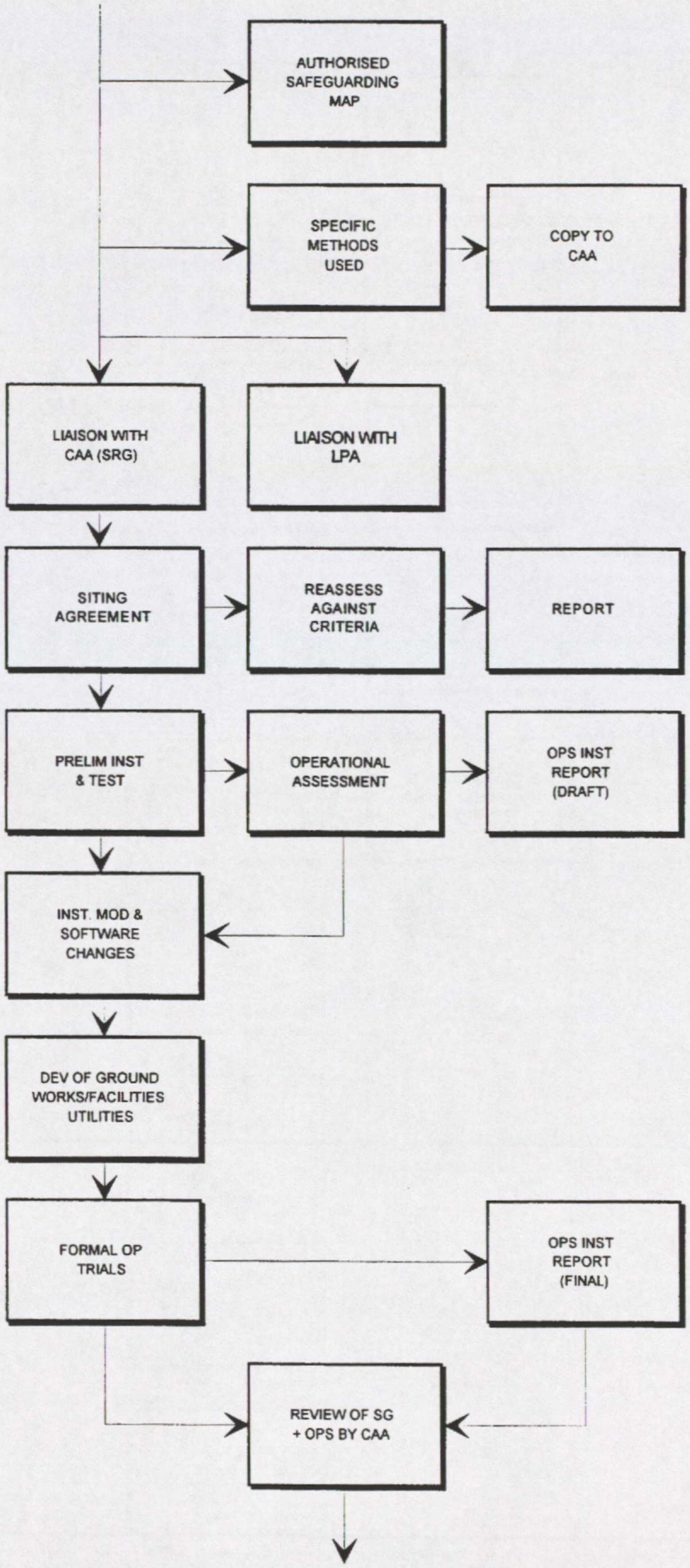


Figure E-2 Radar Safeguarding Procedure

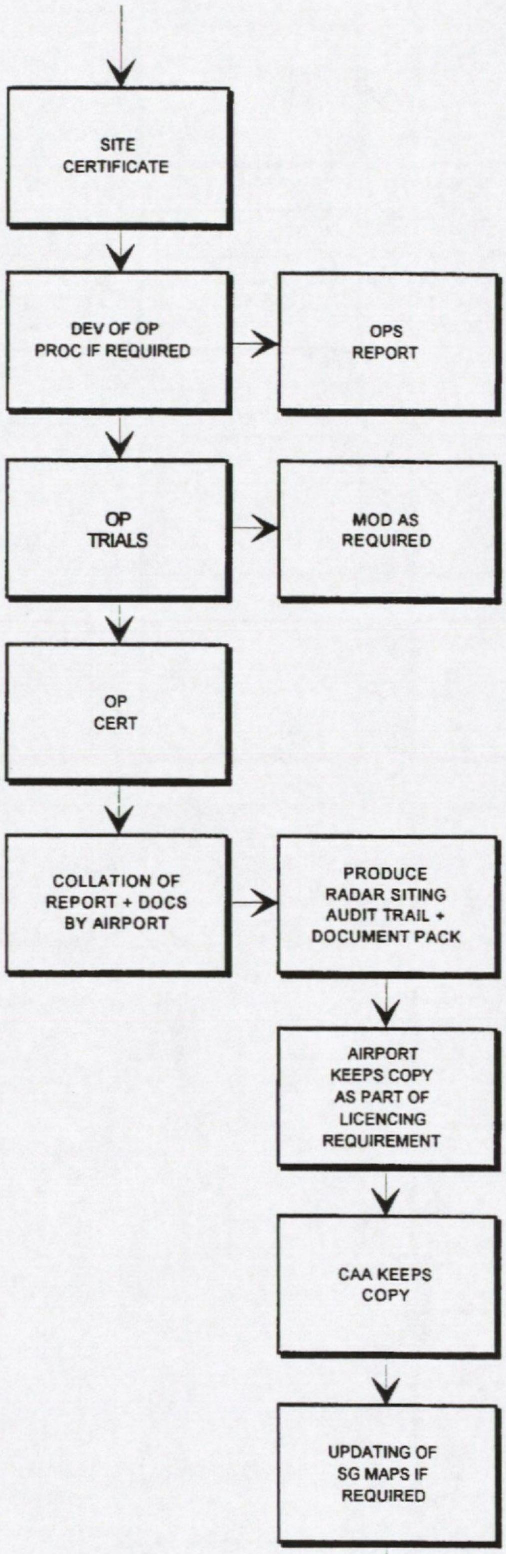


Figure E-3 Radar Safeguarding Procedure