Bistatic and Multistatic Radar

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Abstract: *Bistatic radar systems have been studied and built since the earliest days of radar. They have the advantages that the receivers are passive, and hence undetectable. The receiving systems are also potentially simple and cheap. Bistatic radar may have a counter-stealth capability, since target shaping to reduce monostatic RCS will in general not reduce the bistatic RCS. In spite of those advantages, rather few bistatic radar systems have got past the 'technology demonstrator' phase. It has also been remarked that activity in bistatic radar tends to vary on a period of approximately fifteen years, and that currently we are at a peak of that cycle; there is particular current interest in passive coherent location (PCL) techniques, using broadcast and communications signals as 'illuminators of opportunity'.*

Keywords: bistatic radar, multistatic radar, passive coherent location.

1. Introduction

Bistatic radar systems have been studied and built since the earliest days of radar. As an early example, the Germans used the British Chain Home radars as illuminators for their *Klein Heidelberg* bistatic system. Bistatic radars have some obvious advantages. The receiving systems are passive, and hence undetectable. The receiving systems are also potentially simple and cheap. Bistatic radar may also have a counter-stealth capability, since target shaping to reduce target monostatic RCS will in general not reduce the bistatic RCS. Furthermore, bistatic radar systems can utilize VHF and UHF broadcast and communications signals as 'illuminators of opportunity', at which frequencies target stealth treatment is likely to be less effective.

Bistatic systems have some disadvantages. The geometry is more complicated than that of monostatic systems. It is necessary to provide some form of synchronization between transmitter and receiver, in respect of transmitter azimuth angle, instant of pulse transmission, and (for coherent processing) transmit signal phase. Receivers which use transmitters which scan in azimuth will probably have to utilize 'pulse chasing' processing.

Over the years a number of bistatic radar systems have been built and evaluated. However, rather few have progressed beyond the 'technology demonstrator' phase. Willis [33] has remarked that interest in bistatic radar tends to vary on a period of approximately fifteen years, and that currently we are at a peak of that cycle.

The purpose of this paper is therefore to present a review of the properties and current developments in bistatic and multistatic radar, with particular emphasis on passive coherent location using broadcast or communications transmissions.

2. Properties of Bistatic Radar

2.1. Bistatic radar geometry

The properties of bistatic radar have b een described in detail by Willis [31, 32] and by Dunsmore [6]. Jackson [17] has analyzed the geometry of bistatic radar systems, and his notation has been widely adopted.

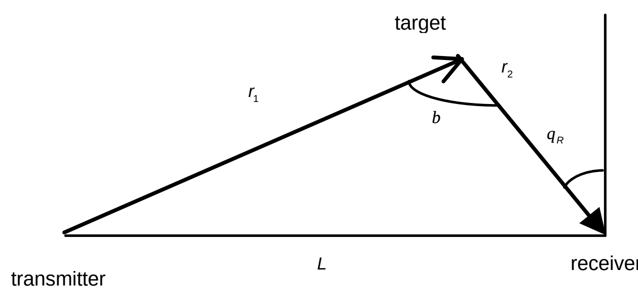


Figure 1. Bistatic radar geometry.

From this:

$$r_2 = \frac{\left(r_1 + r_2\right)^2 - L^2}{2\left(r_1 + r_2 + L\sin q_R\right)} \quad (1)$$

Contours of constant bistatic range are ellipses, with transmitter and receiver as the two foci.

The bistatic radar equation is derived in the same way as the monostatic radar equation:

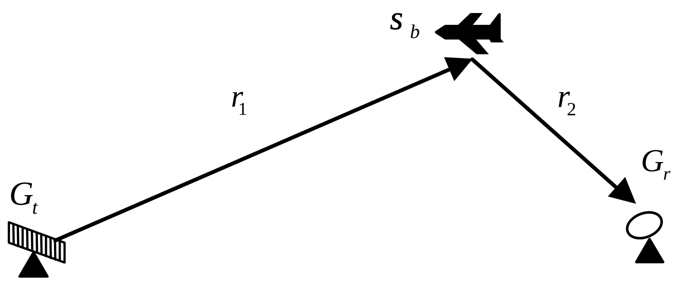
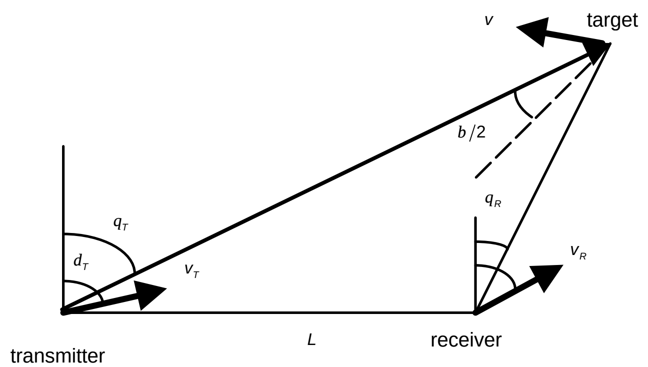


Figure 2. Bistatic radar equation.

$$\frac{P_r}{P_n} = \frac{P_t G_t G_r \lambda^2 \sigma_b}{(4\pi)^3 r_1^2 r_2^2 k T_0 B F} \qquad (2)$$

The factor $1/(r_1 r_2)$, and hence the signal-to-noise, has a minimum value for $r_1 = r_2$. Thus the signal-to-noise ratio is highest for targets close to the transmitter or close to the receiver.

Doppler shift depends on the motion of target, transmitter and receiver (Figure 3), and in the general case the equations are quite complicated [17, 32].



$$\beta = \theta_T - \theta_R$$

Figure 3. Bistatic Doppler (after Jackson [17]).

In the case when only the target is moving the Doppler shift is given by:

$$f_D = \left(\frac{2V}{\lambda}\right)\cos\delta \cos(\beta/2) \qquad (3)$$

2.2 <u>Bistatic radar cross section</u>

The bistatic RCS of targets has been studied extensively [7], though relatively little has been published in the open literature. Early work [4, 18] resulted in the bistatic equivalence theorem, which states that the bistatic RCS σ_b is equal to the monostatic RCS at the bisector of the bistatic angle β, reduced in frequency by the factor cos (β/2), given (i) sufficiently smooth targets, (ii) no shadowing, and (iii) persistence of retroreflectors. These assumptions are unlikely to be universally valid, particularly for stealthy targets, so the results should be used with care.

2.3 <u>Forward scatter</u>

A limiting case of the bistatic geometry occurs when the target lies on the transmitter-receiver baseline. Whilst this means that range information cannot be obtained, the geometry does give rise to a substantial enhancement in scattering, even for stealthy targets, due to the forward scatter phenomenon. This may be understood by reference to Babinet's principle, which shows that a perfectly absorbing target will generate the same forward scatter as a target shaped hole in a perfectly conducting screen. The forward scatter RCS is approximately $\sigma_b = 4\pi A^2/\lambda^2$, where A is the target projected area, and the angular width θ_B of the scattering will be of the order of λ/d radians, where d is the target linear dimension. Figure 4 shows how these vary with frequency, for a target of the size of a typical aircraft, and shows that frequencies around VHF / UHF are likely to be optimum for exploiting forward scatter.

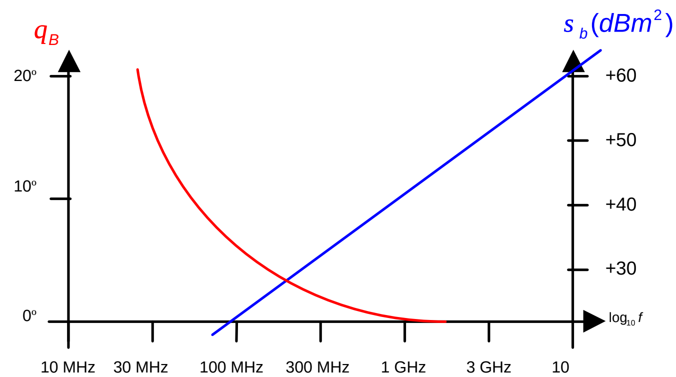


Fig. 4. Variation of forward scatter RCS and angular width of response (d = 10m, A = 10m²).

2.4 <u>Bistatic clutter</u>

Bistatic clutter is subject to greater variability than the monostatic case, because there are more variables associated with the geometry [31]. The clutter RCS σ_c is the product of the bistatic backscatter coefficient σ_b^0 and the clutter resolution cell area A_c. Both σ_b^0 and A_c are geometry dependent, with the maximum value of σ_b^0 occurring at specular angles. There is relatively little experimental data available, and little work has been done in developing models for bistatic clutter.

There is some reason to suppose that bistatic sea clutter may be less ‘spiky’ than equivalent monostatic sea clutter, and hence that bistatic geometries may be more favourable for detection of small targets – but this remains to be investigated.

There is thus much scope for new work on bistatic clutter; to gather data, to analyze the results, and to develop bistatic clutter models.

2.5 The Ambiguity Function for Bistatic Radar

Woodward’s ambiguity function is a classic way of analyzing and presenting the performance of a radar waveform, and has been universally used and taught, presenting the resolution and ambiguity performance as a function of the two parameters delay (range) and velocity (Doppler).

$$\left|\chi(\tau,\nu)\right|^2 = \left|\int u(x)\,u^*(x+\tau)\exp(-j2\pi\nu x)\,dx\right|^2 \qquad (4)$$

With a bistatic or multistatic radar the situation is more complicated. Tsao et.al. [29] have looked at this, and shown that the relationship between Doppler shift and target velocity, and between delay and range, are highly non-linear, and hence that the shape of the ambiguity function is a strong function of geometry as well as waveform properties. They propose that the ambiguity function for bistatic radar should instead be written:

$$\left|\chi\left(R_{R_H}, R_{R_a}, v_H, v_a, \theta_R, L\right)\right|^2$$

$$= \left|\int_{-\infty}^{\infty} \tilde{f}\left(t-\tau_a\left(R_{R_a},\theta_R,L\right)\right)\tilde{f}^*\left(t-\tau_H\left(R_{R_H},\theta_R,L\right)\right) \exp\left[-j\left(\omega_{D_H}\left(R_{R_H},V_H,\theta_R,L\right)-\omega_{D_a}\left(R_{R_a},V_a,\theta_R,L\right)\right)t\right]dt\right|^2 \qquad (5)$$

We can take this further, and attempt to calculate and plot the ambiguity functions for bistatic and multistatic radars, although there does not seem to be the same elegant way of plotting the function as is the case with monostatic radars.

3. Passive Coherent Location

The use of broadcast or communications signals as ‘illuminators of opportunity’ has become known as ‘passive coherent location’ (PCL) or ‘hitchhiking’, and there has been particular interest in this aspect of bistatic radar in recent years.

The properties of transmissions for these purposes can be assessed in terms of (i) power density at the target, (ii) spatial and temporal coverage, and (iii) waveform. The power density Φ (in W/m^2) at the target is evaluated from:

$$\Phi = \frac{P_t G_t}{4\pi r^2} \qquad (6)$$

The spatial and temporal coverage will depend on the location of the transmitter, its radiation pattern, and (for example) whether it is stationary or moving and whether it operates for 24 hours per day or not. In some cases the vertical plane radiation pattern of TV or radio transmissions is deliberately shaped so as to avoid wasting power above the horizontal.

The coverage achieved by VHF FM radio and TV transmissions is substantial. This is because such systems have to be designed to cope with non line-of-sight propagation and very inefficient antenna and receiver systems. Cellphone base stations are also potentially useful as PCL illuminators [34, 36]; whilst these are of rather lower power, there are many of them, especially in urban areas. Satellite-borne illuminators, such as DBS TV [12], satellite communications and navigation [2, 19] and spaceborne radar [13, 23, 35] are also of interest.

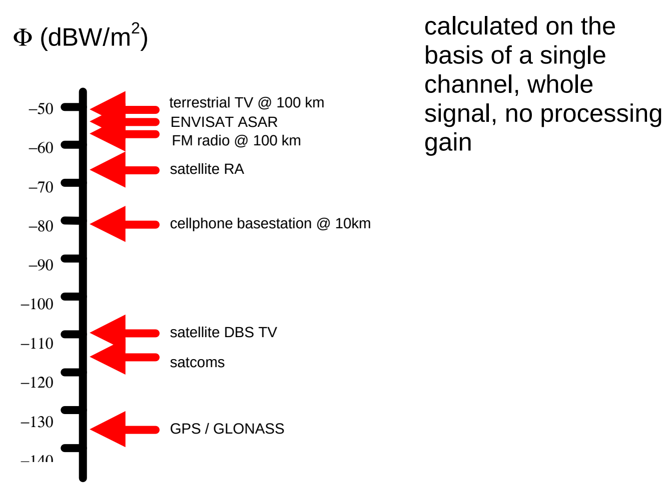


Fig. 5. Power density Φ for various PCL illuminators.

The waveform parameters of interest are the frequency, bandwidth, ambiguity function, and stability. In some cases it may be appropriate only to use a portion of the available signal (for example, to avoid ambiguities associated with the line and frame repetition rate of analogue TV modulation). In such cases the transmit power value used in equation (4) should be appropriate.

Figure 5 shows the values of Φ for various PCL illuminators, under various assumptions. These are calculated on the basis of a single channel, the whole signal bandwidth, and no processing gain.

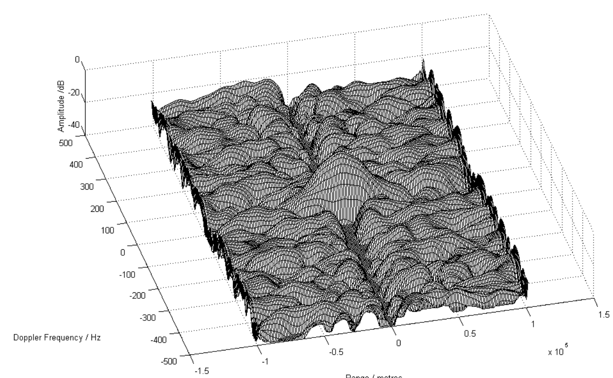
The detection performance can then be estimated from:

$$\left(r_2\right)_{\max} = \left(\frac{\Phi \sigma_b \lambda^2 G_p}{\left(4\pi\right)^2 \left(S/N\right)_{\min} k T_0 B F} \right)^{1/2} \quad (7)$$

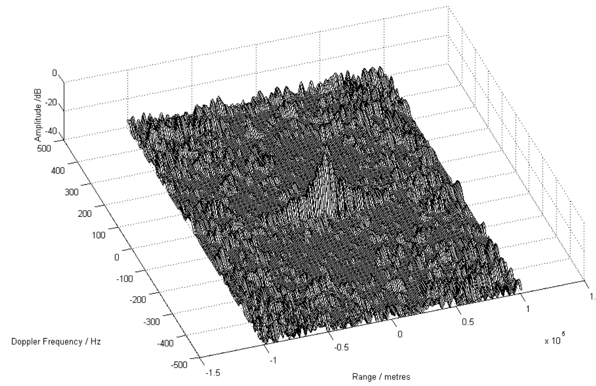
where G_p is the processing gain, which is the product of the waveform bandwidth and the integration dwell time. The integration dwell time in turn depends on the waveform coherence and the target dynamics. As a rule of thumb, the maximum integration dwell time is given by:

$$T_{\max} = \left(\frac{\lambda}{A_R} \right)^{1/2} \quad (8)$$

where A_R is the radial component of target acceleration. From these equations the coverage can be predicted in terms of Ovals of Cassini around transmitter and receiver.



(a)



(b)

Fig. 6. Typical ambiguity functions: (a) BBC Radio 4 transmission (93.5 MHz) and (b) digital audio broadcast transmission (222.4 MHz).

The waveform properties of a variety of PCL illuminators (VHF FM radio, analogue and digital TV, digital audio broadcast (DAB) and GSM at 900 and 1800 MHz) have been assessed by digitizing off-air waveforms and calculating and plotting their ambiguity functions [14]. The receiving system was based on a HP8565A spectrum analyzer, digitizing the 21.4 MHz IF output by means of an Echotek ECDR-214-PCI digitizer card mounted in a PC. The system has the advantage of great flexibility, since the centre frequency and bandwidth of the receiver can be set by the controls of the spectrum analyzer. The rather high noise figure of the spectrum analyzer is not a disadvantage, since all of the signals are of high power and propagation is line-of-sight.

Figure 6 shows typical ambiguity functions derived using this system of (a) BBC Radio 4 at 93.5 MHz, for which the programme content is speech (an announcer reading the news), and (b) a digital audio broadcast (DAB) signal at 222.4 MHz. Both show range resolution appropriate to their instantaneous modulation bandwidths (9.1 and 78.6 kHz respectively), though the difference in the sidelobe structure is very evident, showing that the digital modulation format is far superior because the signal is more noise-like.

Table 1 summarizes the measured ambiguity function performance of the various signals captured.

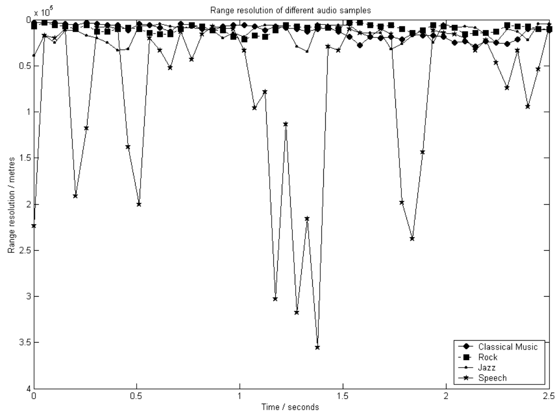


Fig. 7. Variation in range resolution against time for four types of VHF FM radio modulation.

It is also important to know how these properties vary with time, as variations in the form of the ambiguity function will determine the radio system performance. Fig. 7 shows variation in range resolution of four VHF FM radio transmissions, calculated from the −3 dB width of the zero Doppler cut through the ambiguity function, over a 2.5 second interval.

It is evident that for the three types of music the range resolution varies by a factor of two or three, but for the speech modulation the range resolution is badly degraded during pauses between words, by a factor of ten or more.

Furthermore, when we also take into account the dependence of the ambiguity function on geometry (equation 5), it can be seen that there is scope for adaptively choosing the signals from a variety of transmitters in a multistatic PCL system, selecting those for which the geometry and instantaneous modulation are favourable.

signal	frequency (MHz)	range resolution (km)	effective bandwidth (kHz)	peak range sidelobe level (dB)	peak Doppler sidelobe level (dB)
FM radio: speech (BBC Radio 4)	93.5	16.5	9.1	−19.1	−46.5
FM radio: classical music	100.6	5.8	25.9	−23.9	−32.5
FM radio: rock music (XFM)	104.9	6.55	22.9	−12.0	−26.0
FM radio: reggae (Choice FM)	107.1	1.8	83.5	−27.0	−39.5
DAB	219.4	1.54	97.1	−11.7	−38.0
Analogue TV: chrominance sub-carrier	491.55	9.61	15.6	−0.2	−9.1
Digital TV (DVB-T)	505.0	1.72	87.1	−18.5	−34.6
GSM 900	944.6	1.8	83.3	−9.3	−46.7
GSM 1800	1833.6	2.62	57.2	−6.9	−43.8

Table 1. Properties of ambiguity functions of various types of broadcast and communications signals.

4. Examples of Systems

4.1 Amateur radio forward scatter experiments

An interesting early example of PCL was given by a radio amateur, the Rev. Dr P.W. Sollom, who had noticed a fluttering effect on VHF amateur signals due to the interference between direct signals and Doppler-shifted echoes from aircraft [24]. The same effect may easily be observed with VHF FM radio and VHF or UHF TV, and works best when the direct signal and scattered signal are of comparable amplitude.

He devised an elegant set of experiments using a VHF TV signal located in northern France as illuminator, and built a two-Yagi interferometer, such that a moving target would pass through the interferometer grating lobes, allowing the target motion to be estimated from the amplitude modulation.

4.2. Non-co-operative radar illuminators

The first work on bistatic radar at University College London was undertaken in the late 1970s. Schoenenberger and Forrest designed and built a system using a UHF Air Traffic Control radar at Heathrow airport as illuminator, and investigated particularly the problems of synchronization between receiver and transmitter [28]. Figure 8 shows a typical PPI display from this system. A real-time co-ordinate correction scheme was also developed for this system.

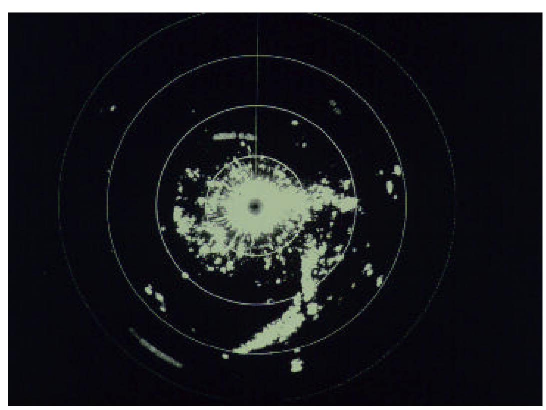


Fig. 8. PPI display from UCL bistatic radar system.

Further developments included a digital beamforming array [9] for pulse chasing experiments (Fig. 9) and a coherent MTI system using clutter from stable local echoes as a phase reference [10].

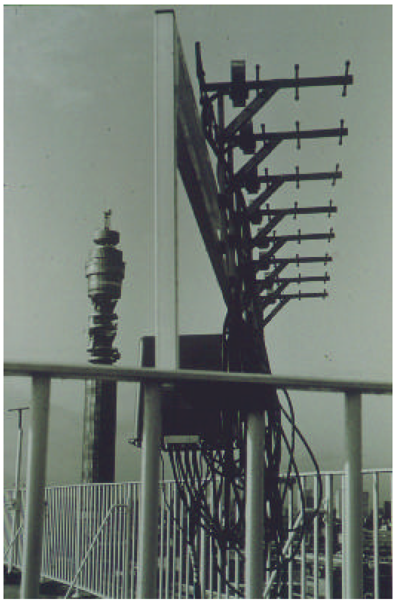


Fig. 9. Digital beamforming array used for pulse chasing experiments with UCL bistatic radar system.

4.3 Television-based bistatic radar

Subsequent work at UCL attempted to use UHF television transmissions as illuminators of opportunity, to detect aircraft targets landing and taking off from Heathrow airport, to the west of London [11]. Figure 10 shows the geometry. The results showed that although the television waveforms are very suitable in terms of power and coverage, the analogue television modulation format suffers from ambiguities at the 64 µs line repetition rate, which correspond to a bistatic range of 9.6 km.

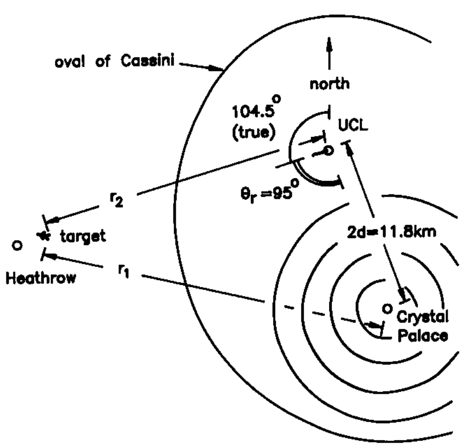


Fig.10. Horizontal-plane geometry of Crystal Palace television transmitter and Heathrow. Indicated Oval of Cassini is the locus $r_1 r_2 = 2 \times 10^8$ m.

4.4 TV-based forward scatter system

Howland [16] developed a UHF forward scatter system based on television transmissions. Because a forward scatter system is not able to provide range information, he adopted a different approach, measuring angle of arrival (from a two-element interferometer) and Doppler shift of the vision carrier of the television signal. Target tracking was done by an extended Kalman filter algorithm.

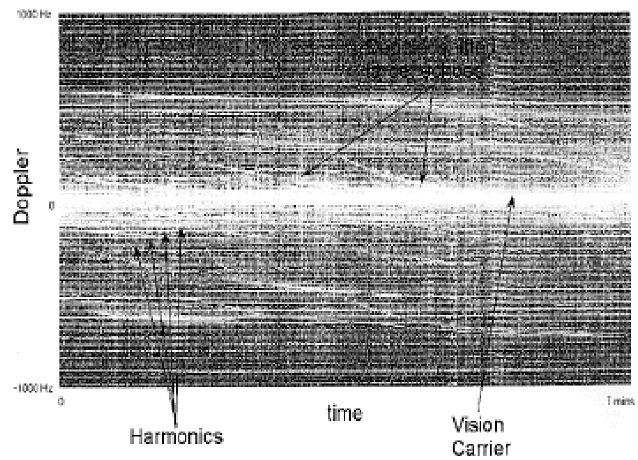


Fig. 11. Example power spectrum against time, around TV vision carrier (after Howland [16].

He was able to demonstrate tracking of aircraft targets at ranges well in excess of 100 km (Fig. 12).

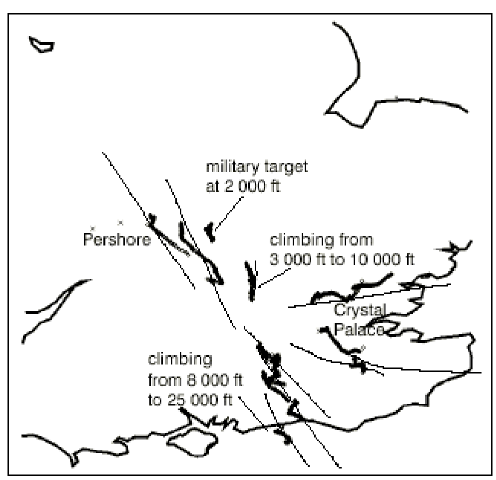


Fig. 12. Track estimates formed on 21 February 1997 between 14:00 and 14:07, compared with secondary radar tracks for the same aircraft (after Howland [16]).

4.5. <u>The Manastash Ridge Radar</u>

The Manastash Ridge Radar is a rather remarkable system conceived and built by John Sahr of the University of Washington, Seattle, for studies of the ionosphere. It uses a single VHF radio transmitter as illuminator, and a receiver separated from the transmitter by a large mountain range (Mt. Rainier). The receiving system is based on a standard digitizer card and PC, and is extremely simple and cheap (~ $15k). Synchronization is achieved by GPS, giving uncertainties of 100 ns in timing (= 15 m in range) and 0.01 Hz in Doppler (= 1 cm/s in velocity). The system provides quasi-real-time imagery, out to ranges in excess of 1,000 km, on their website [36]. Although the purpose of the system is for ionospheric studies, it also routinely detects aircraft targets at ranges up to ~ 100 km.

Such a system demonstrates vividly that high performance can be achieved from simple and inexpensive PCL systems.

4.6. <u>Silent Sentry</u>

Silent Sentry is a PCL system developed by the Lockheed Martin company, based on multiple VHF FM radio and television transmissions. In its present version (SSIII) it has demonstrated tracking of aircraft and space targets at impressive ranges. It is advertised as being applicable to:

- air surveillance and tracking in areas of limited coverage – a 'gap filler;
- capable of tracking low flying, non-cooperative, slow moving targets;
- continuous total volume surveillance of air breathing and ballistic objects;
- low acquisition and operations cost, unattended remotely managed.

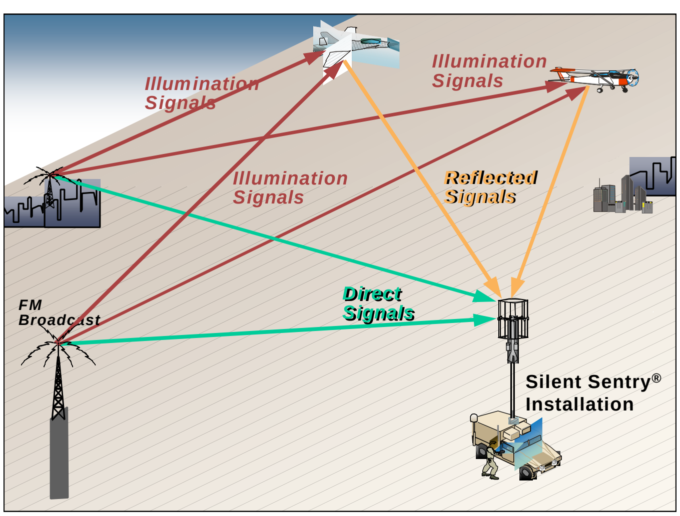


Fig. 13. Principle of operation of Silent Sentry (figure courtesy of Lockheed Martin).

5. Conclusions

This paper has attempted to present a review of bistatic radar systems, with particular emphasis on Passive Coherent Location (PCL) techniques. The introduction indicated that the question of whether the present interest is just another peak in the cycle will be addressed. There are several reasons why the answer to this is 'no', and that there is reason to believe that practical bistatic radar systems may now be developed and used.

Firstly, there is ever greater spectral congestion. Military operations are likely to be carried out close to centres of population, where there are numerous broadcast and communications signals. For most purposes this spectral congestion is a problem, but for PCL it is a positive advantage. Furthermore, the VHF and UHF frequencies used by high power FM radio and television transmissions are in many senses optimum for PCL.

Secondly, as has already been pointed out, bistatic receivers are potentially simple and cheap.

Thirdly, the advent of GPS solves many of the synchronization and timing problems that have previously limited the performance of bistatic systems.

Fourthly, the inexorable increases in signal processing power mean that many of the signal digitization and processing operations are now feasible in real time. Moore's law predicts that these advances will continue for many years.

Fertile areas for new work are: (i) the use of phased array antennas and antenna signal processing techniques for 'pulse chasing', particularly in the context of multistatic systems, (ii) development of advanced tracking algorithms for multistatic geometries, and (iii) experimental programmes to gather bistatic clutter data, and to develop bistatic clutter models.

6. Acknowledgements

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7. References

[1] Baniak, J., Baker, G., Cunningham A.M. and Martin, L., 'Silent Sentry passive surveillance', *Aviation Week and Space Technology*, 7 June 1999.

[2] Cherniakov, M., Nezlin, D. and Kubik, K., 'Air target detection via bistatic radar based on LEOS communication signals', *IEE Proc. Radar Sonar and Navigation*, Vol. 149, No. 1, pp33-38, February 2002.

[3] Cherniakov, M., 'Space-surface bistatic synthetic aperture radar – prospective and problems', Proc. *RADAR 2002* Conference, Edinburgh; IEE Conf. Publ. No.490, pp22–25, 15–17 October 2002.

[4] Crispin, J.W., Goodrich, R.F. and Siegel, K.M., 'A theoretical method for the calculation of the radar cross sections of aircraft and missiles', University of Michigan report 2591-1-1-M, AF 19(604)-1949, AFCRC-TN-59-774, 1959.

[5] Davies, D. E. N., 'Use of bistatic radar techniques to improve resolution in the vertical plane', *Electronics Letters*., Vol.4, pp170-171, 1968.

[6] Dunsmore, M.R.B., 'Bistatic radars', chapter 11 in *Advanced Radar Techniques and Systems* (G. Galati ed.), Peter Peregrinus, 1993.

[7] Ewell, G.W., 'Bistatic radar cross section measurements', chapter 7 in *Techniques of Radar Reflectivity Measurement*, (N.C. Currie ed.), Artech House, 1989.

[8] Fawcette, J., 'Vulnerable radars seek a safe sanctuary', *Microwave Systems News*, April 1980, pp45-50.

[9] Griffiths, H.D., Forrest, J.R., Williams, A.D. and Pell, C., 'Digital beamforming for bistatic radar receiver'; *Proc. 3rd IEE Intl. Conference on Antennas and Propagation*, Norwich; IEE Conf. Publ. No. 219 Part I, pp80–84, 12–15 April 1983.

[10] Griffiths, H.D. and Carter, S.M., 'Provision of moving target indication in an independent bistatic radar receiver', *The Radio and Electronic Engineer*, Vol.54, No.7/8, pp336-342, July/August 1984.

[11] Griffiths, H. D., and Long, N. R W., 'Television-based bistatic radar', *IEE Proceedings*, Vol. 133, Part F, No.7, December 1986, pp649-657.

[12] Griffiths, H.D., Garnett, A.J., Baker, C.J. and Keaveney, S., 'Bistatic radar using satellite-borne illuminators of opportunity', Proc. *RADAR-92* Conference, Brighton; IEE Conf. Publ. No.365, pp276-279, 12-13 October 1992

[13] Griffiths, H. D., Baker, C. J., Baubert, J., Kitchen, N. and Treagust, M., 'Bistatic radar using spaceborne illuminator of opportunity', Proc. *RADAR 2002* Conference, Edinburgh; IEE Conf. Publ. No.490, pp1–5, 15–17 October 2002.

[14] Griffiths, H.D., Baker, C.J., Ghaleb, H., Ramakrishnan, R. and Willman, E., 'Measurement and analysis of ambiguity functions of off-air signals for passive coherent location', *Electronics Letters*, Vol.39, No.13, pp1005-1007, 26 June 2003.

[15] Horne, A.M. and Yates, G., 'Bistatic synthetic aperture radar', Proc. *RADAR 2002* Conference, Edinburgh; IEE Conf. Publ. No.490, pp22–25, 15–17 October 2002.

[16] Howland, P. E., 'Target tracking using television-based bistatic radar', *IEE Proc. Radar Sonar and Navigation*, Vol. 146, No.3, June 1999, pp166-174.

[17] Jackson, M.C., 'The geometry of bistatic radar systems', *IEE Proc.*, Vol.133, Part F., No.7, pp604-612, December 1986.

[18] Kell, R.E., 'On the derivation of bistatic RCS from monostatic measurements', *Proc. IEEE*, Vol.53, pp983-988, 1965.

[19] Koch, V. and Westphal, R., 'A new approach to a multistatic passive radar sensor for air defense', Proc. IEEE International Radar Conference *RADAR 2000*, Washington DC, IEEE Conf. Publ No.95CH3571-0, pp22-28, 8-11 May 1995..

[20] Martinsek, D. and Goldstein, R., 'Bistatic radar experiment', Proc. *EUSAR '98*, European Conference on Synthetic Aperture Radar, Berlin, Germany, pp31-34, 1998.

[21] Ogrodnik, R.F., 'Broad area surveillance exploiting ambient signals via coherent techniques', Proc. IEEE International Conference on Multisensor Fusion and Integration, pp421-429, 1004.

[22] Ogrodnik, R.F., 'Bistatic laptop radar: an affordable, silent radar alternative', Proc. IEEE National Radar Conference, Ann Arbor, MI, pp369-373, 1996.

[23] Ogrodnik, R.F., Wolf, W.E., Schneible, R., McNamara, J., Clancy, J. and Tomlinson, P.G., 'Bistatic variants of space-based radar', Proc. IEEE Aerospace Conference, Vol.2, pp159-169, 1997.

[24] Sollom, P.W., 'A little flutter on VHF', *RSGB Bulletin*, November 1966, pp709-728; December 1966, pp794-824.

[25] Pell, C. and Hanle, E. (eds), Special Issue of IEE Proceedings Part F. on Bistatic Radar, *IEE Proc.*, Vol.133, Pt.F., No.7, December 1986.

[26] Ringer, M.A. and Frazer, G.J., 'Waveform analysis of transmissions of opportunity for passive radar', Proc. *ISSPA'99*, Brisbane, pp511-514, 22-25 August 1999.

[27] Sahr, J.D. and Lind, F.D., 'The Manastash Ridge radar: a passive bistatic radar for upper atmospheric radio science', *Radio Science*, Vol.32, No.6, pp2345-2358, 1977.

[28] Schoenenberger, J.G. and Forrest, J.R., 'Principles of independent receivers for use with co-operative radar transmitters', *The Radio and Electronic Engineer*, Vol.52, No.2, pp93-101, February 1982.

[29] Tsao, T., Slamani, M., Varshney, P., Weiner, D., Schwarzlander, H. and Borek, S. 'Ambiguity function for bistatic radar'; *IEEE Trans. Aerospace and Electronic Systems*, Vol.AES-33, pp1041-1051,1997.

[30] Whelan, D. A., 'DISCOVERER II program summary',

Proc. IEEE International Radar Conference RADAR 2000, Washington DC, 7-12 May 2000, pp7-8.
[31] Willis, N.J., 'Bistatic radar', chapter 25 in *Radar Handbook* (second edition), (M.I. Skolnik ed.), McGraw-Hill, pp25.18-25.24, 1990.
[32] Willis, N.J., *Bistatic Radar*, Artech House, 1991.
[33] Willis, N.J., *Bistatic radars and their third resurgence: passive coherent location*, IEEE Radar Conference, Long Beach, USA, 24 April 2002.
[34] http://www.roke.co.uk/sensors/stealth/celldar.asp
[35] http://envisat.esa.int
[36] http://www.sitefinder.radio.gov.uk
[37] http://rrsl.ee.washington.edu/Data