Bistatics: Introduction and Historical Background

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ABSTRACT

This tutorial provides an introduction to bistatic radar systems. A brief account of the history of bistatic radar is given, with particular emphasis on some recently-unearthed material on the German Klein Heidelberg system from WW2, and also showing that post-WW2 interest in bistatic radar has varied cyclically. Present interest is very high, because many of the problems that previously prevented practical systems from being realized are now soluble. Next, some of the fundamental properties of bistatic radars are described, including the bistatic geometry, bistatic Doppler shift and pulse chasing, the radar equation for bistatic radar, and a number of physical phenomena that may enhance the bistatic radar cross section of targets. Brief mention is made of the subject of bistatic radar clutter. Finally, the nature of the bistatic ambiguity function is explained, showing how this is a function both of the nature of the waveform and of the bistatic geometry, and that the range and Doppler resolution degrade to zero when the target crosses the transmit-receive baseline.

1. INTRODUCTION

A *bistatic radar* is a radar that uses two antennas at separate locations, one for transmission and one for reception. Usually the transmitter and receiver accompany the antennas at these locations. A variation of the bistatic radar is the *multistatic radar*, which uses multiple antennas at separate locations, one antenna for transmission and multiple antennas each at a different location for reception, or vice versa. Again, transmitters or receivers can accompany the antennas. Multistatic radars can use *multilateration* for target state estimates (i.e., target position, often velocity and sometimes acceleration). Multilateration combines range and/or Doppler data from multiple transmitter/receiver pairs having overlapping spatial coverage to estimate the target state without using range-dependent angle data.

Bistatic radars can operate with their own *dedicated transmitters*, which are specially designed for bistatic operation, or with *transmitters of opportunity*, which are designed for other purposes but found suitable for bistatic operation. When the transmitter of opportunity is from a monostatic radar, the bistatic radar is often called a *hitchhiker*. When the transmitter of opportunity is from a broadcast station or communications link, i.e. sources other than a radar, the bistatic radar has been called many things including *passive radar*, *passive coherent location*, *parasitic radar*, and *piggyback radar*. In recent years the term *passive bistatic radar* (*PBR*) has become widely adopted, with *piggyback radar* used for planetary exploration in recognition of their independent development. Finally, transmitters of opportunity in military scenarios can be designated either *cooperative* or *noncooperative*, where cooperative denotes an allied or friendly transmitter and noncooperative denotes a hostile or neutral transmitter. PBR operations are more restricted when using the latter.

These notes begin by providing a short description of the history of bistatic radar, placing particular emphasis on some recently-unearthed material on the German Klein Heidelberg system from WW2. They then give a summary of the essential features and properties of bistatic and multistatic radars, to serve as a introduction to the other lectures in this series.

2. HISTORICAL BACKGROUND

2.1 CHAIN HOME and Klein Heidelberg

Several of the very earliest radar systems developed in various countries in the late 1920s and 1930s were of the CW wave-interference fence type, detecting targets crossing the baseline between transmitter and receiver via the beat between the direct signal and the Doppler-shifted target echo. Such a system simply provides an indication of the presence of the target and does not measure range. The Daventry Experiment on 26 February 1935, in which Watson Watt and Wilkins demonstrated detection of a Heyford bomber at a range of 8 miles, and hence convinced the Air Ministry to provide the support and funding that ultimately led to the development of CHAIN HOME, was one such example. Other examples in other countries were used for air defence alerting and cueing, prior to and during WW2.

CHAIN HOME operated in four different bands in the frequency range 20 – 30 MHz, and used separate transmit and receive antennas. According to some definitions it might be considered to be bistatic, but since the transmit and receive antennas were only a few hundred metres apart (Figure 1) the important features of the system were monostatic.

It has been known for some years [6, 19, 23] that German radar engineers developed a system called *Klein Heidelberg Parasit* (KH) in WW2, making use of transmissions from the CHAIN HOME (CH) radar network as the radar illumination source. However, more recent work has uncovered the fact that there were actually six KH installations, and that their performance was very respectable. This scheme had a number of obvious attractions: firstly it was completely covert (electromagnetically, and to some extent visually), so the British were unaware of it until they learned of its existence from intelligence intercepts and from interrogation of a captured German radar operator [1]; secondly, it was very difficult to jam, since conventional jamming would also have affected the operation of the CH network. Chaff (WINDOW) of length appropriate to the frequencies of the German Early Warning radars (FREYA, WASSERMANN, MAMMUT and JAGDSCHLOSS) would not be effective against KH, and Chaff of length appropriate to KH would also have affected the operation of CH. Thirdly, the KH receiving systems would have been relatively cheap and simple, since they avoided the cost and complication of a dedicated transmitter, and they made use of the antenna towers and bunkers of conventional WASSERMANN radars – all of which amount to a very positive set of attributes.

2.2 The Klein Heidelberg System

There were six KH stations (*Stellungen*) on the coast of France, Belgium and the Netherlands (Figures 2, 3). Reference [1] also states that there was a seventh on the Dutch coast at Limmen, but this was in fact the receiver of an ELEFANT radar whose antenna was physically very similar to that of KH. The KH antenna consisted of an eight-element array of horizontally-polarised dipoles, mounted on the back of a WASSERMANN-S tower, with a small, separate auxiliary antenna to receive the direct signal from the CH transmitter. The receive antenna was rotatable, allowing the direction of arrival of the target echoes to be determined. The receiver and operators were housed in the bunker of the WASSERMANN-S (Figure 4).

The illumination from the CH transmitters was of a broad-beam floodlight form, which was an important factor, since otherwise some form of synchronisation to the transmit beam direction would have been necessary. Trenkle [23, p103] describes the means by which the echoes were displayed and the targets located. The KH receiver would provide (i) the measured target range ($r_1+r_2 - L$) from the difference in propagation delay between the direct pulse and the target echo, which would locate the target on an ellipse with the transmitter and the receiver as the two foci, and (ii) the angle of arrival. The intersection between the angle of arrival vector and the ellipse would unambiguously give the target location. My translation of the relevant sentence from Trenkle's book is:

> *The scale divisions on the A-scope display were calibrated from 0-40, which corresponded to the numbers of the ellipses, and a map with its own set of registered ellipses was provided for each CH transmitter, corresponding to that particular bistatic geometry.*

Figure 5 attempts to depict how this would have worked.

For targets close to the transmit-receive baseline the range resolution would have been very poor (see Section 6 below), but this effect could be mitigated by appropriate selection of CH transmitter (of which there would have been several to choose). Also, Willis makes the distinction between KH performance against targets close to forward scatter (i.e. over the English Channel/North Sea), and those in quasi-monostatic geometry with small bistatic angles (i.e. further into the Netherlands and Germany). The former geometry would give good detection but poor range information, so would be useful as a surveillance alert, whilst the latter would give full surveillance capability. Note also that in forward scatter the relatively low frequency of CH would give quite broad angular scatter from a typical bomber target, though not substantial enhancement of RCS (see Figure 9).

2.3 Discussion

It is interesting to consider what prompted the development of KH, how well it actually worked, and to what extent it was significant, though it is not necessarily easy to give definitive answers to these questions.

German radar scientists would no doubt have been well aware of the attractions of such a system listed earlier, but by the time that KH was introduced (mid- to late-1944) German air defence was starting to rely less on conventional early warning radar (which was increasingly subject to countermeasures of various kinds) and more on the interception of the transmissions such as H2S, IFF and indeed the jamming itself from the Allied bombers. KH was known from captured documents to have been under development in November 1942 [1], so it seems most unlikely that the deployment of MANDREL jamming (in December 1942) was the direct reason for the development of KH. It might, though, have been the German development of Düppel in early 1940 [2, p296] (independently of the development of Chaff in the UK) which was kept highly secret on the orders of Goering, but could have prompted the development of a radar system that might have been immune to such a countermeasure.

There are several pieces of evidence that show that the detection ranges achieved by KH were substantial. Trenkle quotes a range (against typical air targets) '… mostly greater than 200 km, and on one occasion 398 km' [23]. The interrogation of a captured German radar operator from Vaudricourt (*Stellung* SKORPION) indicates that: '… the maximum range claimed each day was usually about 450 km' [1].

As to its significance, there seems little doubt that Klein Heidelberg was the first operational bistatic radar system, and that it demonstrated that such systems were indeed feasible. But in my opinion the German scientists could never have considered it as more than an adjunct to existing conventional methods because it depended fundamentally on the availability of CH transmissions, which were under the control of the enemy.

Reference [1] also considered the issue of countermeasures against KH. One countermeasure would be to put two CH stations on the same frequency and to 'jitter' their pulses. A second, and nicer approach would be to use repeater jammers such as MOONSHINE [3] to generate false targets to provide the enemy with false plots. These conclusions seem just as valid today.

2.4 Historical Background: Post WW2

Although the British carried out trials of their own to evaluate the concept of KH [21], I have not so far been able to find definitive information on their findings. It may be that since the original documents were highly classified they have been more difficult to unearth, but from the distribution lists it is evident that at least some of them were made available to US scientists.

With the advent of pulsed operation and the duplexer in the late 1930s the monostatic radar, with its single-site operational advantage, became the configuration of choice and virtually all bistatic radar work ended after World War II. Since then interest in bistatic and multistatic radars has varied cyclically with a period of approximately fifteen years, so there have been periodic resurgences when a specific bistatic application was found attractive or when the concept was simply rediscovered. That observation was made in 1991 [27], which documented two such resurgences.

The first started in the 1950s, when (a) tactical semiactive homing missiles, (b) bistatic fences for air defense and ballistic missile launch warning, and (c) multistatic radars for test range instrumentation and satellite tracking were developed and deployed. Both the tactical missiles and satellite trackers remain operational.

The second resurgence started in the late 1960s when data link transmitters on satellites and ground-based receivers were used for moon and planetary surface measurements in 10 missions over a span of 40 years. That work is ongoing, now including ground-based transmitters and receivers on satellites. A multistatic radar hitchhiker, called the *Multistatic Measurement System*, was deployed on a ballistic missile test range to improve the measurement accuracy of reentry vehicles. It was finally retired after significant improvements were made to the monostatic radars. In contrast, other bistatic radar concepts were developed and tested, but not deployed, to counter the new, antiradiation missile and emitter locator threats. The bistatic fence was redeveloped and tested to protect high-value ground targets, but not deployed.

The third resurgence began in the early 1990s, and has included a great deal of work on Passive Bistatic Radar (PBR) systems using broadcast, communications or radionavigation signals as illumination sources. The relentless increase in digital processing power predicted by Moore's Law, and the advent of GPS, means that many of the problems of processing, timing and synchronisation that previously made practical systems so difficult are now much easier to solve. In addition, the increasing use of UAVs means that bistatic or multistatic solutions, particularly for synthetic aperture imaging, are attractive. Finally, the potential advantage of bistatic and multistatic systems against low-signature targets is now being explored.

The next sections go on to explain the properties and advantages of bistatic and multistatic radars in more detail.

3. BISTATIC AND MULTISTATIC RADAR

Some of the properties of bistatic radar, which may account for the present high degree of interest, are as follows:

(a) The receiving system is completely passive, and hence undetectable, and is immune to the effects of deliberate directional interference. Because it is passive it may also be simple and cheap.

(b) The dynamic range of signals to be handled is reduced, because of the defined minimum range.

(c) It is necessary to provide synchronisation between transmitter and receiver in respect of (i) instant of transmission of pulse, (ii) transmit antenna azimuth (in the case of a scanning transmit antenna), and (iii) transmit signal phase (if coherent processing is to be employed). This may take the form of a land-line link, although with a co-operative transmitter it is possible to realise a totally independent bistatic system by means of 'flywheel' clocks at the receiver which are resynchronised each time the transmitter beam sweeps past [20]. Additionally, a coherent reference for MTI cancellation may be obtained from close-in stable clutter echoes [11].

(d) There is a co-ordinate distortion effect [16]; targets on the transmitter-receiver baseline have zero bistatic range. Elsewhere, contours of constant bistatic range are ellipses with the transmitter and receiver sites as the two foci (Figure 6). The distortion can be corrected with a knowledge of the bistatic geometry [20].

(e) There are several configurations of transmitters and receivers. Azimuthal discrimination (i.e. directional antennas) at both transmitter and receiver is desirable, since otherwise the system is vulnerable to responses from sidelobes. A directional receive antenna must scan at a non-uniform rate, which practically rules out mechanical scanning. The form of scanning required follows the position of the RF pulse through space, and is known as *pulse chasing*. Thus, either a small number of electronically agile beams or a static set of contiguous beams will be required. Such a receiving system is unlikely to be either simple or cheap, but because the receiver is passive it is much less vulnerable to attack.

(f) The target bistatic cross-section σ_b is not the same as the monostatic cross section, although the range of values of σ_b for a particular (non-stealthy) target will be comparable with the range of values of monostatic cross section. Thus a particular target is unlikely to present a low cross section to more than one transmitter-target-receiver geometry. Additionally, at large angles target glint is drastically reduced, eliminating this contribution to radar inaccuracies.

(g) Stealthy targets are designed to have a low monostatic cross section, partly by shaping so as to scatter energy in directions other than the monostatic direction. Hence the bistatic radar cross section of stealthy targets may be larger. This is especially true in the forward scatter geometry [29] (Figure 9).

(h) Receiving or transmitting stations can be used interferometrically to obtain high azimuthal discrimination; sources of interference can be located by triangulation, and passive detection (correlation) techniques can be employed to locate noise-like interference sources.

(i) The constraints on radar waveform design can be different to those for the monostatic case. As a simple example, a higher-than-normal PRF may be used, and the range ambiguities resolved by triangulation from several receiver sites or by using staggered PRIs.

(j) The transmitter may be located remotely. An example of this is the US SANCTUARY programme [9]. This may be particularly desirable for short-range surveillance applications. In addition, multiple 'winking' transmitters may be employed, as a counter to homing missiles.

Some of these points are developed further in the sections that follow.

4. BISTATIC RADAR GEOMETRY

Many of the particular properties of bistatic radar are a consequence of the bistatic geometry. The geometry of bistatic radar was analysed by Jackson [15]. Jackson's paper is important firstly because it is comprehensive, and secondly because most workers subsequently have use the same notation.

4.1 Bistatic Doppler

Doppler shift depends on the motion of target, transmitter and receiver (Figure 7), and in the general case the equations are quite complicated [15, 27]. In the case when only the target is moving the Doppler shift f_D is given by

$$f_D = \left(\frac{2v}{\lambda}\right)\cos\delta\cos\left(\beta/2\right) \qquad (1)$$

where v is the target velocity, λ is the radar wavelength, δ is the angle of the target velocity with respect to the bisector of the transmitter-target-receiver angle, and β is the bistatic angle. Contours of zero Doppler are ellipses of constant bistatic range. Contours of maximum Doppler are hyperbolae crossing the ellipses orthogonally [15]. Moving targets cannot present zero Doppler to two receiving sites simultaneously. Table 1, taken from reference [28], shows some special cases of equation (1).

β	δ	f_D	condition
0	–	$(2v/\lambda)\cos\delta$	monostatic
0	0	$(2v/\lambda)$	monostatic
180	–	0	forward scatter
–	±90	0	$v \perp$ to bisector
–	$\pm\beta/2$	$(2v/\lambda)\cos^2(\beta/2)$	$v \Rightarrow$ tx or rx
–	0, 180	$\pm(2v/\lambda)\cos(\beta/2)$	$v \Rightarrow$ bisector
–	$90\pm\beta/2$	$\mp(v/\lambda)\sin\beta$	$v \perp$ to tx or rx LOS

Table 1. Expressions for Doppler shift for some special cases of Equation (1).

4.2 Pulse Chasing

If the transmitter scans in azimuth, and if the receiver is to use a directional antenna, then the direction in which the receiver beam must point is a very nonlinear function of time. This means that the receiver must use either a fan of fixed beams, or a scanned beam which, since its scan is nonlinear, will need to be electronically scanned. The receive beam must point instantaneously in the direction from which an echo will come, taking account of the propagation delay of the pulse from the target to the receiver (Figure 8). The beam lag is given by:

$$\begin{aligned}\theta_R &= \theta_T - \beta \\ &= \theta_T - 2\tan^{-1}\left(\frac{L\cos\theta_T}{r_1 + r_2 - \sin\theta_T}\right)\end{aligned} \qquad (2)$$

and the beam scan rate by:

$$\dot{\theta}_R = \frac{c \tan\left(\beta/2\right)}{r_2} \tag{3}$$

5. THE RADAR EQUATION IN BISTATIC RADAR

5.1 The Bistatic Radar Equation

The radar equation for the bistatic geometry is derived in a similar way to that for a monostatic radar. In its simplest, free-space propagation form, this is:

$$P_r = \frac{P_t G_t}{4\pi r_1^2}.\sigma_b.\frac{1}{4\pi r_2^2}.\frac{G_r \lambda^2}{4\pi} \tag{4}$$

where P_r is the received signal power
P_t is the transmit power
G_t is the transmit antenna gain
r_1 is the transmitter-to-target range
σ_b is the target bistatic radar cross-section
r_2 is the target-to-receiver range
G_r is the receive antenna gain
λ is the radar wavelength

The signal-to-noise ratio is obtained by dividing (4) by the receiver noise power $P_n = kT_0BF$ (where k is Boltzmann's constant, T_0 is 290 K, B is the receiver bandwidth and F the receiver noise figure), and multiplying by the receiver processing gain, also taking into account the various losses. This allows the detection performance to be determined as a function of σ_b, r_1 and r_2. Contours of constant detection signal-to-noise ratio are loci corresponding to r_1r_2 = const., which describe *ovals of Cassini* [15].

The quantity $\frac{P_t G_t}{4\pi r_1^2}$ (5)

in equation (4) represents the power density (in Wm^{-2}) of the transmitter signal at the target, and is denoted by the symbol Φ. This is an important parameter in characterising the transmitter for PBR purposes; in practice it is modified by the pattern propagation factor for the transmitter-to-target path, taking into account factors such as multipath and propagation losses.

5.2 Bistatic Radar Cross Section

The bistatic RCS of targets has been studied extensively [7], though relatively little has been published in the open literature. Early work [4, 17] 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.

Three bistatic RCS phenomena that may be exploited as a counter to stealth aircraft have been identified:

- resonance scatter
- forward scatter
- specular reflection

Resonance scatter and specular reflection apply also to monostatic radar; forward scatter applies only to bistatic radar.

The resonance scatter effect for monostatic radars has been well documented for conventional (non-stealth) targets. In the simplest case of a conducting sphere of radius *a*, resonance occurs in the region $0.5 < 2\pi a/\lambda < 10$. Physically, the resonant region can be explained by the interference between the incident wave and the creeping wave, which circles the sphere and either adds to or subtracts from the total field at the leading surface. The net result of these additive effects is that when wavelengths are of the order of discrete aircraft dimensions, for example fuselage, wing, tail, inlet and exhaust ducts, the resulting resonance significantly enhances RCS when compared to the optical region, which for the sphere starts at $2\pi a/\lambda > 10$.

Forward scatter 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 9 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.

Specular reflection will occur when a planar surface on the target is perpendicular to the bistatic bisector. If the target is designed so as to direct such reflections away from anticipated monostatic radar threat locations, for example by using tilted surfaces or facets on stealth platforms, the assertion is that through judicious location of multiple bistatic receivers, these off-normal speculars of large amplitude can be detected and tracked or networked together to support some level of engagement. However, this requires rather specific geometries, and the flashes will be of short duration, so at this time it would appear optimistic to ascribe more than a fence-type alerting and coarse cueing capability when exploiting specular reflections from stealth aircraft.

5.2 Bistatic Radar Clutter

Bistatic clutter is subject to even greater variability than in the monostatic case, because there are more variables associated with the geometry [25]. 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.

6. THE AMBIGUITY FUNCTION IN BISTATIC RADAR

Classically, the performance of a radar waveform is evaluated and presented in terms of the ambiguity function, originated in the 1950s by Woodward [30], and which expresses the point target response of the signal $u(t)$ as a function of delay τ and Doppler shift ν (or equivalently target range and velocity)

$$|\chi(\tau,\nu)|^2 = \left|\int u(x)u^*(x+\tau)\exp(j2\pi\nu x)\,dx\right|^2 \tag{6}$$

and provides an elegant way of showing the resolution, sidelobe levels, and ambiguities of a given waveform, in the form of a two-dimensional plot.

However a bistatic radar ambiguity function also depends on the bistatic geometry. This dependence can be understood and visualized by considering a moving target crossing the transmit-receive baseline: range information becomes indeterminate and the Doppler shift becomes zero. Hence the function 'blows up' on the baseline, giving neither range nor Doppler resolution.

If the ambiguity function is evaluated for target locations elsewhere on the bistatic plane, the peak of the ambiguity function in both range and Doppler broadens with respect to the monostatic peak, and is equal to the monostatic peak only when the target lies on the extended baseline where the bistatic angle is zero. The effect was investigated by Tsao et al. [24], who noted the nonlinear relationships between target velocity and Doppler shift, and between target range and delay, and hence proposed that the ambiguity function for a bistatic radar should be written as:

$$\begin{aligned}&\left|\chi\left(R_{R_H},R_{R_a},V_H,V_a,\theta_R,L\right)\right|^2\\&=\left|\begin{aligned}&\int_{-\infty}^{\infty}\tilde{f}\left(t-\tau_a\left(R_{R_a},\theta_R,L\right)\right)\tilde{f}^*\left(t-\tau_H\left(R_{R_H},\theta_R,L\right)\right)\\&\quad\exp\left[-j\left(\omega_{D_H}\left(R_{R_H},V_H,\theta_R,L\right)-\omega_{D_a}\left(R_{R_a},V_a,\theta_R,L\right)\right)t\right]dt\end{aligned}\right|^2\end{aligned} \tag{7}$$

in which R_R and R_T are the ranges of the target from the transmitter and receiver, V is the target radial velocity, θ_R is the angle of the target measured from the receiver, L is the bistatic baseline, τ is the transmitter-target-receiver delay time, and the subscripts H and a denote hypothesized and actual values respectively.

Evidently this depends on rather more than two variables, so it is not straightforward to plot and display it in a simple manner, in the way that is readily done for the monostatic ambiguity function. They show further, by means of a simulation that a signal whose monostatic ambiguity function has a simple Gaussian shape has a bistatic ambiguity function whose shape depends significantly on the bistatic geometry, and degrades badly when the target is close to the bistatic baseline.

To illustrate this effect, Figure 10 shows the ambiguity function for four different target locations and directions of motion. The waveform in each case consists of a short sequence of three rectangular pulses. In Figure 10(a) the target is on the baseline approaching the receiver and the ambiguity function is essentially the same as for the monostatic configuration. In Figure 10(b) the target approaches the baseline obliquely, but the ambiguity function is little altered. In Figure 10(c) the target approaches the baseline from a perpendicular direction, which broadens the main peak and alters the position of the sidelobes in the ambiguity function. Finally in Figure 10(d) the target crosses the baseline, giving effectively no resolution in either range or Doppler.

7. CONCLUSIONS

This tutorial has attempted to provide an introduction to bistatic radar systems. It is interesting and instructive to study the history of the subject, particularly that of the German Klein Heidelberg system, since this indicates that a practical bistatic radar system was operational as early as 1943, and that very respectable results were obtained. Despite this, interest after WW2 waned, and has subsequently varied cyclically with a period of about fifteen years. Current interest is high, both because bistatic approaches may provide solutions to some current problems and because several of the technical problems that previously prevented practical systems from being realized are now soluble. We can expect that the present activity will continue to increase rather than represent a peak.

8. ACKNOWLEDGEMENTS

I gratefully acknowledge invaluable discussions with many people from whom I have learned much about radar and signal processing in general, and bistatic radar in particular, over the years. I would particularly like to mention Chris Baker, Mike Cherniakov, DEN Davies, John Forrest, Paul Howland, Phil Judkins, Darek Maksimiuk, Chris Pell, Hermann Rohling, Jim Schoenenberger, Michaël Svejgaard, Nick Willis and Gill Yates. I also acknowledge with thanks the various funding agencies who have supported our work.

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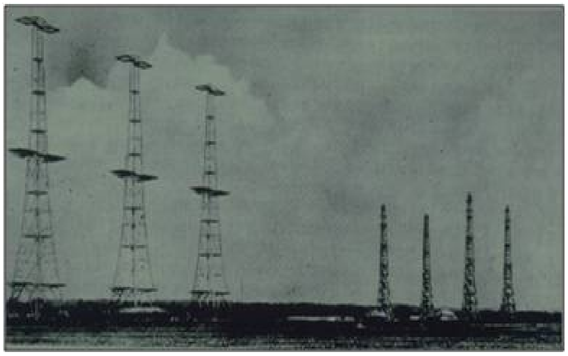

Figure 1: A British CHAIN HOME radar installation, showing the separate transmit and receive antennas.

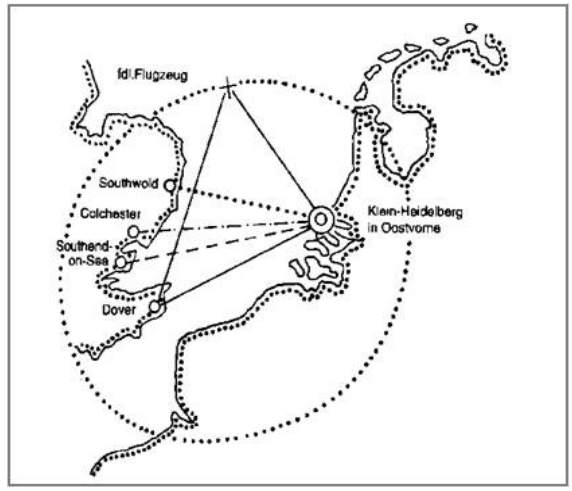

Figure 3: The Klein Heidelberg receiver (in this case at *Stellung* BIBER) could use transmissions from several CHAIN HOME radars [13].

Figure 2: The six Klein Heidelberg *Stellungen* (Col. Michaël Svejgaard [31]).

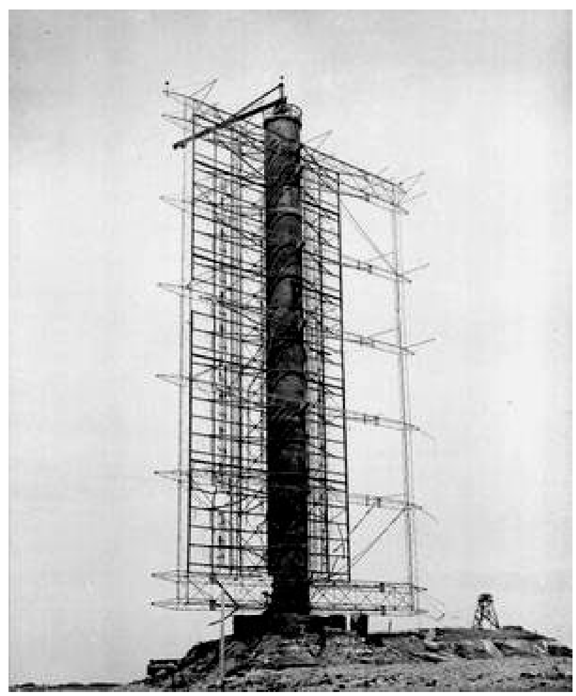

Figure 4: The Klein Heidelberg radar at Cherbourg (*Stellung* TAUSENDFÜSSLER) mounted on a WASSERMANN-S tower. The WASSERMANN antenna is visible on the rear side of the tower (Col. Michaël Svejgaard [31]).

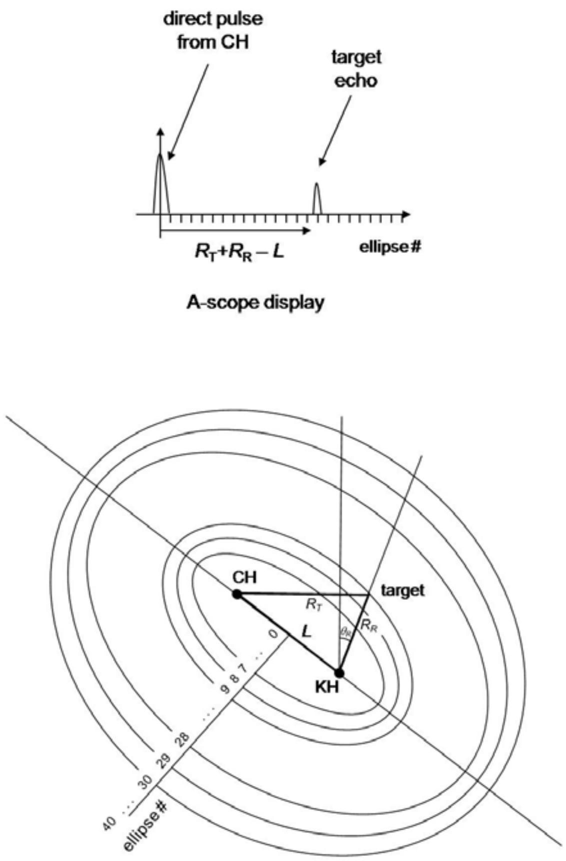

Figure 5: KH was provided with an A-scope display by which the bistatic range $R_T + R_R - L$ allowed the ellipse on which the target lay to be determined. The intersection of this ellipse with the direction of arrival of the echo gave the location of the target.

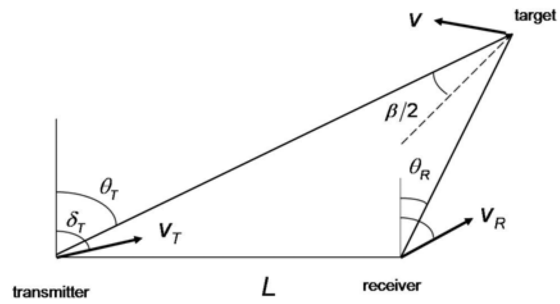

Figure 7: Bistatic Doppler, in the general case when transmitter, receiver and target are all moving.

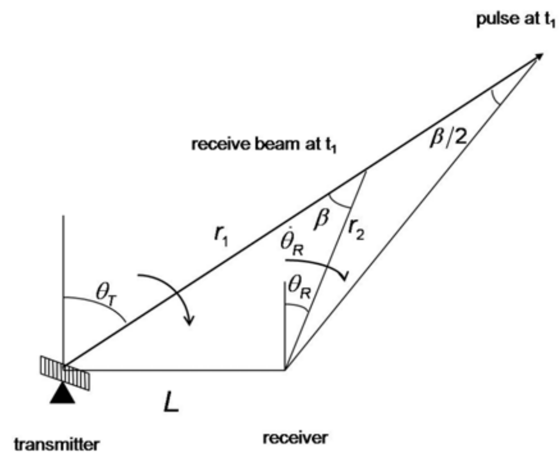

Figure 8: Pulse chasing. The instantaneous receive beam direction and the scan rate are highly nonlinear functions of time.

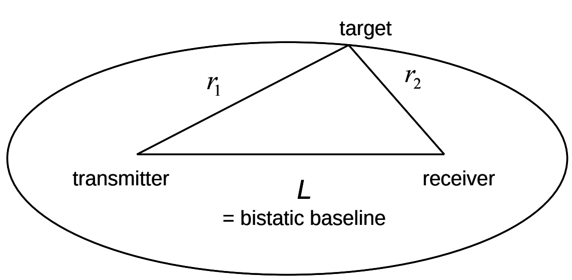

Figure 6: Bistatic geometry [15].

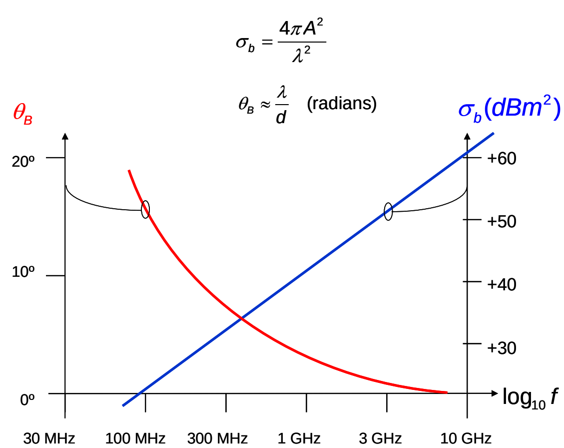

Figure 9: Forward scatter RCS σ_b and angular width θ_B of scatter for a typical small aircraft target ($A = 10\text{m}^2$, $d = 10\text{m}$).

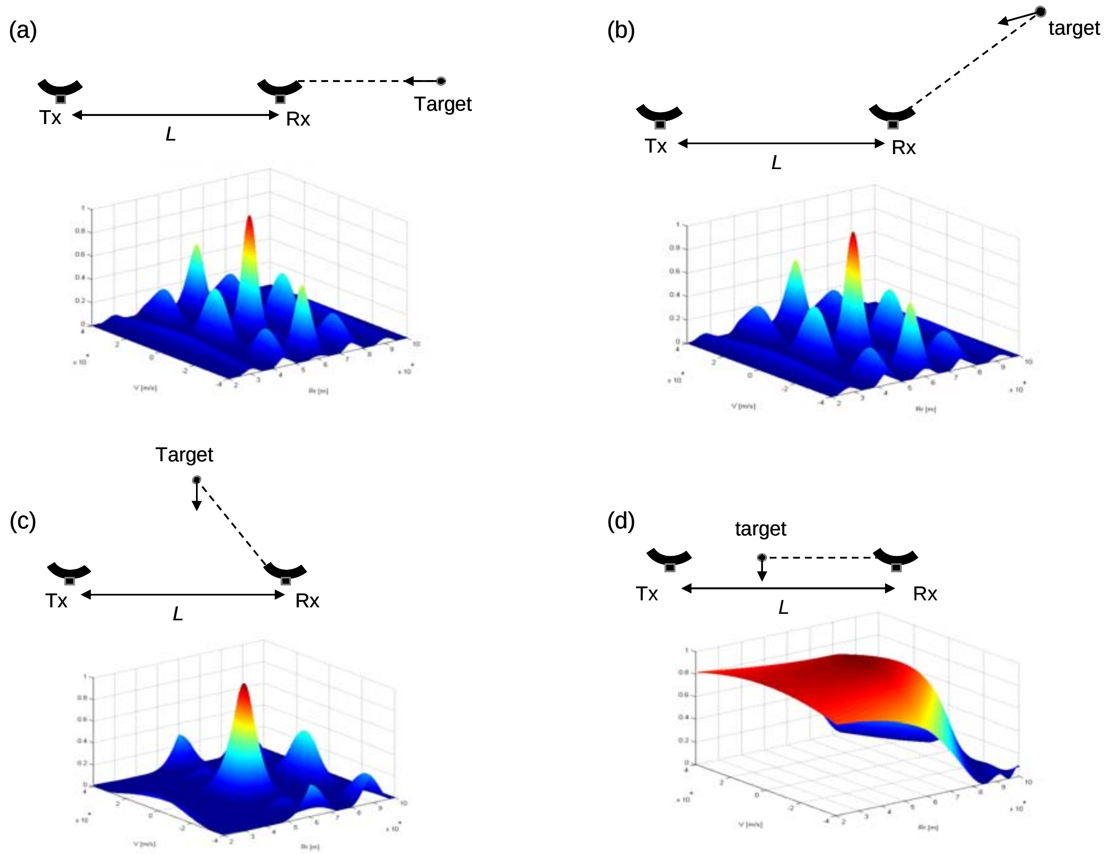

Figure 10: Bistatic ambiguity functions for four different target locations and directions of motion.