Passive Coherent Location (PCL) Radar Demonstrator

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ABSTRACT

The aim of this work is to report on the development of a Passive Coherent Location (PCL) radar system at University College London. Lack of a complete characterisation of a PCL system, from inception to functionality, is the rational behind this work. PCL systems have numerous advantages over conventional radar. For example, they are potentially cheaper than active systems; they are non-intrusive (permitting operation in areas where conventional radars cannot be deployed). PCL systems exploit commercial, non-cooperative emitters, such as UHF/VHF broadcast transmitters. These are known as 'illuminators of opportunity'. This work initially investigates FM broadcast illuminators, the advantage of these include: wide-area coverage, high ERP, reduced susceptibility to ECM.

1.0 INTRODUCTION

Bistatic radar, of which PCL is a constituent, is defined as a radar that uses antennas at different locations for transmission and reception. Fig. 1 shows the bistatic geometry with a transmitting antenna at one site and a receiving antenna at a second site, separated by a distance L, called the *baseline* [1]. The bistatic radar equation is given by:

$$(R_T R_R)_{max} = \sqrt{\frac{P_T G_T G_R \lambda^2 \sigma_B}{(4\pi)^3 k T_o B F_n (S/N)_{min} L}} \tag{1}$$

where

R_T = transmitter-to-target range
R_R = receiver-to-target range
P_T = peak transmitter power output
G_T = transmitting antenna power gain
G_R = receiving antenna power gain
σ_B = bistatic radar target cross section
λ = free-space wavelength
k = Boltzmann's constant (1.38×10^{-23} JK^{-1})
T_o = receiving system noise temperature (290 K)
B = receiving systems' noise bandwidth; in most cases this can be approximated to the 3 dB bandwidth of the receiver
F_n = receiver noise figure
$(S/N)_{min}$ = minimum signal-to-noise power ratio necessary for detection
L = propagation and system losses

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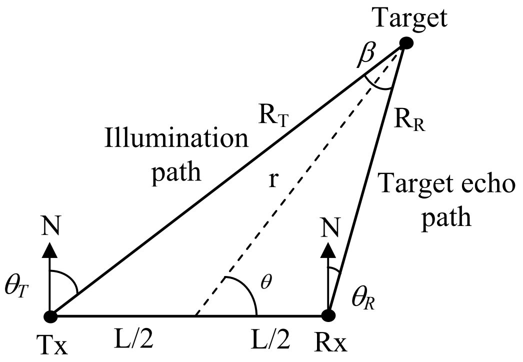

Fig. 1. Geometry for bistatic radar operation.

The angles θ_T and θ_R in Fig. 1 are, respectively, the transmitter and receiver look angles. The bistatic angle β is the angle between the transmitter and receiver with the vertex at the target (Note that $\beta = \theta_T - \theta_R$).

PCL systems are realised using 'illuminators of opportunity', such as existing UHF/VHF broadcast transmissions, GSM-900 mobile base stations or satellite borne emitters. This type of radar can operate more covertly than conventional systems since the location of the receiver is unknown. In PCL the 'coherence' arises from the fact that the target echo is correlated with the directly transmitted reference signal.

VHF FM broadcast signals have a number of attractive characteristics, which make them suitable for radar purposes. The advantages of FM broadcasts are: (i) High availability of FM broadcast stations, (ii) comparatively high ERP, (iii) wide-area coverage, (iv) RCS returns are higher in the FM band, (v) most absorber material used for stealth applications is not optimised for irradiation by lower frequency intercepts ($\lambda \approx 3$ m in FM band), and (vi) reduced susceptibility to ECM. Another desirable feature of FM broadcasts is that some of the transmissions are noise-like and, as a result, their ambiguity function approaches that of the ideal "thumb-tack" response. To approach this ideal, the waveform must contain a single pulse with a large pulse- band-width product. Noise-modulated waveforms yield the most favourable ambiguity response. A caveat here is that the shape of the ambiguity diagram for a particular FM transmission is inextricably a function of program content. Griffiths and Baker et al. in [2] demonstrated that a carrier modulated with fast tempo jazz music resulted in a superior ambiguity response (i.e. had greater potential to resolve targets in range with lower Doppler sidelobes) than a waveform modulated by speech, for example.

The main focus of this paper is on FM radio illuminators of opportunity; however, provided they have a suitable ambiguity function, the principles may be applied to different emitters [3].

2.0 PCL PERFORMANCE PREDICTIONS

The ovals of Cassini, or constant sensitivity contours, provide an estimate of the bistatic radar coverage. The ovals are plotted as a function of the available signal-to-noise power ratio, S/N, and may be expressed mathematically by the equation given in (2):

$$r = \frac{L}{2}\sqrt{\cos 2\theta \pm \sqrt{\frac{16\kappa^2}{L^4} - \sin^2 2\theta}} \tag{2}$$

where (r,θ) relate to the polar coordinates located on the bistatic plane and origin located at the midpoint of the baseline, L. The term κ is the bistatic maximum range product (i.e., $\kappa = (R_T R_R)_{max}$).

Considering the case of the transmitter located at Crystal Palace in south London and the receiver located on the 10th floor of the UCL Engineering building, the baseline distance is thus 11.8 km. The Crystal Palace FM broadcast transmitter has an ERP of 4 kW (vertically polarised). The resulting ovals of Cassini are plotted in Fig. 2.

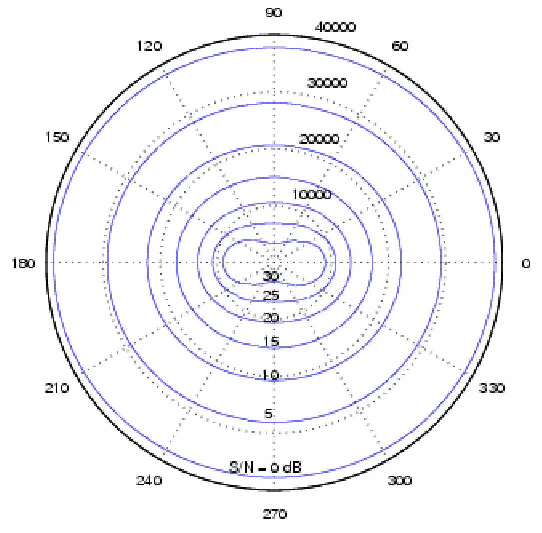

Fig. 2. Contours of a constant SNR – ovals of Cassini, plotted against available S/N (0 dB ≤ S/N ≤ 30 dB) for the parameters in Table 1.

Table 1. Operational parameters of PCL demonstrator

System Component	Numeric Value
Transmitter ERP ($P_T G_T$)	4 kW (36 dBW)
Rx Antenna gain	2.2 dBi (dipole)
λ	3 m
Bistatic RCS	100 m^2
Channel bandwidth	150 kHz
Rx Noise Figure (F_n)	4.5 dB
Noise Floor ($kTBF_n$)*	-148 dBW
Bistatic baseline L	11.8 km

*This is the noise floor of the reference channel where $F_n = 4.5$ dB

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For the same parameters quoted in Table 1, Fig. 3 shows that an SNR of approximately 10 dB can be achieved out to a range of about 25 km.

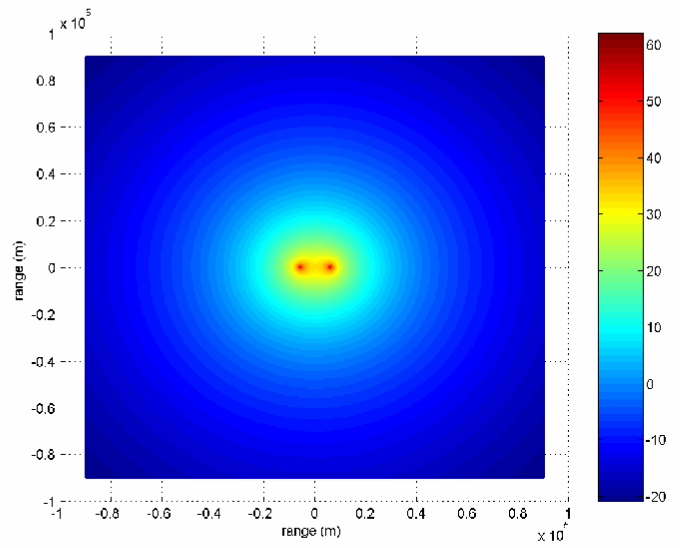

Fig. 3. **Detection range for the FM radio transmitter at Crystal Palace and receiver at UCL. It can be seen that an SNR of 10 dB can be achieved out to a range of about 25 km.**

Fig. 4 illustrates the constant detection contours again, but this time with a processing gain term (G_p) in the radar equation. As in Fig. 2, the S/N varies between 0 and 30 dB. All other radar parameters have the same values as those in Table 1. The additional processing gain term in the numerator is given by $G_p = T_{max} \times B_{eff}$, where T_{max} is the maximum integration time and B_{eff} is the effective broadcast bandwidth (≈ 50 kHz). In this instance $T_{max} = 1$ second, which corresponds to a processing gain of 47 dB [4].

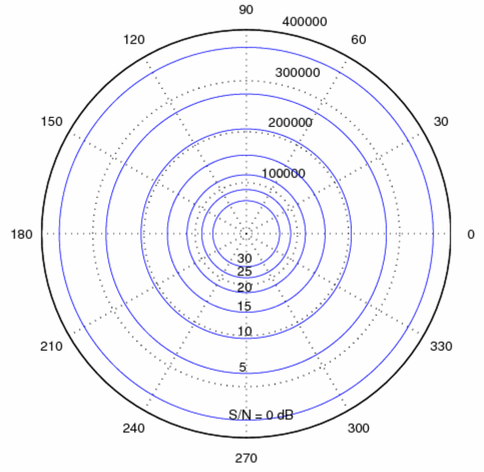

Fig. 4. **Contours of a constant SNR – ovals of Cassini, with 0 dB ≤ S/N ≤ 30 dB for the parameters in Table 1 with an additional processing gain term.**

From Fig. 4 it can be seen that there is a very significant improvement in the theoretical detection range with the maximum contour for constant SNR extending to approximately 365 km. This range, however, will reduce considerably along the propagation path. For given target, transmitter, and receiver altitudes, the target must be simultaneously within the line of site (LOS) of both the transmitting and receiving sites. The maximum propagation range, or radius, of these coverage circles is approximated by (3).

$$r_R = 130(\sqrt{h_t} + \sqrt{h_R}) \tag{3a}$$

and

$$r_T = 130(\sqrt{h_t} + \sqrt{h_R}) \tag{3b}$$

where h_T, h_R = heights of radar transmit and receive antennas, respectively (km)
h_t = target altitude (km).

Using 3a to deduce an estimate of the LOS from the receiver site with a receive antenna height of 30 m and a target altitude of 1 km (estimate of target altitude awaiting stacking over central London), yields a maximum propagation range, or receiver LOS, r_R = 153 km (obtained by geometry). Similarly, the coverage circle at the transmitter site has a radius, r_T = 203 km for a target altitude of 1 km and a transmit antenna height of 313 m (height of Crystal Palace transmitter). Since $r_T \geq L + r_R$, the common coverage area, A_C, is πr_R^2. That is, the transmitter's coverage oval contains all or the receiver's coverage oval.

3.0 SIGNAL AND INTERFERENCE ENVIRONMENT

The UCL PCL radar operates in an extremely congested urban environment. Fig. 5 shows the transmitter-to-reference site LOS. It can be seen that there are numerous multipath hazards along the propagation path.

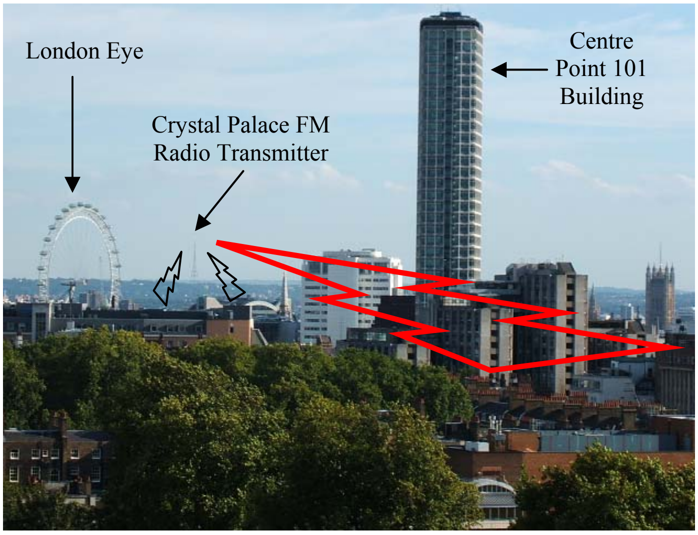

Fig. 5. Propagation path viewed from the reference channel receiver site showing the LOS between the transmitter and highlighting potential multipath hazards.

The noise and interference with which the desired target echo must compete for detection can be severe. The main cause of interference in bistatic radars is the presence of the strong transmitted signal leaking into the surveillance channel/s. This is called the *direct signal interference* (DSI).

Measuring the VHF FM radio broadcast band (88 – 108 MHz) in central London, using a vertically polarised folded dipole antenna, it was found that direct signal levels of the order of -26 dBm could be received in a resolution (approximate noise) bandwidth of 300 kHz. This is illustrated in Fig. 6.

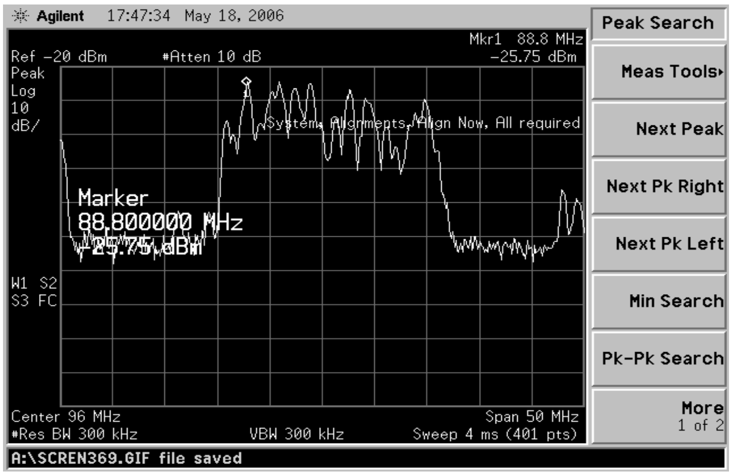

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Fig. 6. FM radio broadcast band from 88 – 108 MHz measured at the reference channel site. Horizontal scale = 5 MHz/div.; vertical scale = 10 dB/div.; resolution bandwidth (RBW) = 300 kHz; reference = -20 dBm.

With a priori knowledge of these signals and their power levels, an estimate may be found for the amount of DSI suppression that will be required (in the surveillance channel) to reduce the direct signal to a level below that of the system noise floor. Ideally, only the component of the target return would be present in the surveillance channel.

In an urban environment such as central London, the spectrum is extremely congested. It is therefore expedient to take a system noise figure (F_n) of 25 dB, for example. Using this value of noise figure, and taking a system bandwidth of 150 kHz (bandwidth of a single FM channel), then the system noise floor may be found as follows:

$$\text{System noise floor} = kT_oBF_n = -97 \text{ dBm.}$$

As stated previously, the DSI appearing in the surveillance channel is -26 dBm. So the suppression level required to bring the DSI to a level equal to the system noise floor is:

$$\begin{aligned}\text{Suppression} &= \text{DSI} - \text{system noise floor}\\ &\approx 70 \text{ dB.}\end{aligned}$$

There is benefit to be gained by equipping PCL radars with analogue suppression capabilities prior to digitisation to improve the dynamic range performance of the radar. A schematic of the analogue signal suppression circuitry is given in Fig. 7.

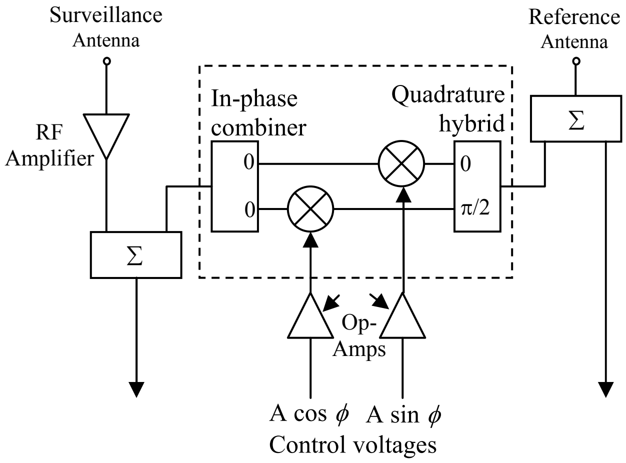


Fig. 7. Analogue signal suppression circuit for the cancellation of direct signal leakage for use in PCL radar systems.

The vector modulator stage (within the dashed box) controls the phase and amplitude of a signal using a weighted combination of in-phase (I) and quadrature (Q) signals, which introduce a variable phase shift over a ±180^{o} range. Using this configuration, with the reference and surveillance antennas connected as in Fig. 7, at the front end of the PCL system yields a significant degree of suppression of direct signal leakage at the output. Analogue suppression on its own will not entirely mitigate the problem of the DSI in the surveillance channel; it will at best yield suppression of the order of 30 dB.

4.0 PCL RECEIVER DESIGN

The receiver system in Fig. 8 comprises three channels, a reference channel and two surveillance channels. Following the antennas are the frequency band pre-selectors, which are low-loss bandpass (BPF) filters, centred on the FM radio band. These filter stages were designed and constructed in-house, and have an insertion loss of the order of 2 dB. The low noise amplifier (LNA) stages amplify the received RF signal. The two surveillance channels will require additional amplification as they are shielded from the directly transmitted signal by the UCL building. This additional amplification is accomplished by incorporating DC – 150 MHz (AD8330) variable gain amplifiers to both of the surveillance channels. This facilitates greater flexibility in the receiver design because if the system is to be operated in different environments, the amplifier gains can be easily adjusted to provide the appropriate signal level at the output. The gain ranges from 0 dB to 50 dB for control voltages between 0 V and 1.5 V. The digitiser card is a dual-channel PARSEC PM480, with a fixed sampling rate of 100 MS/s.

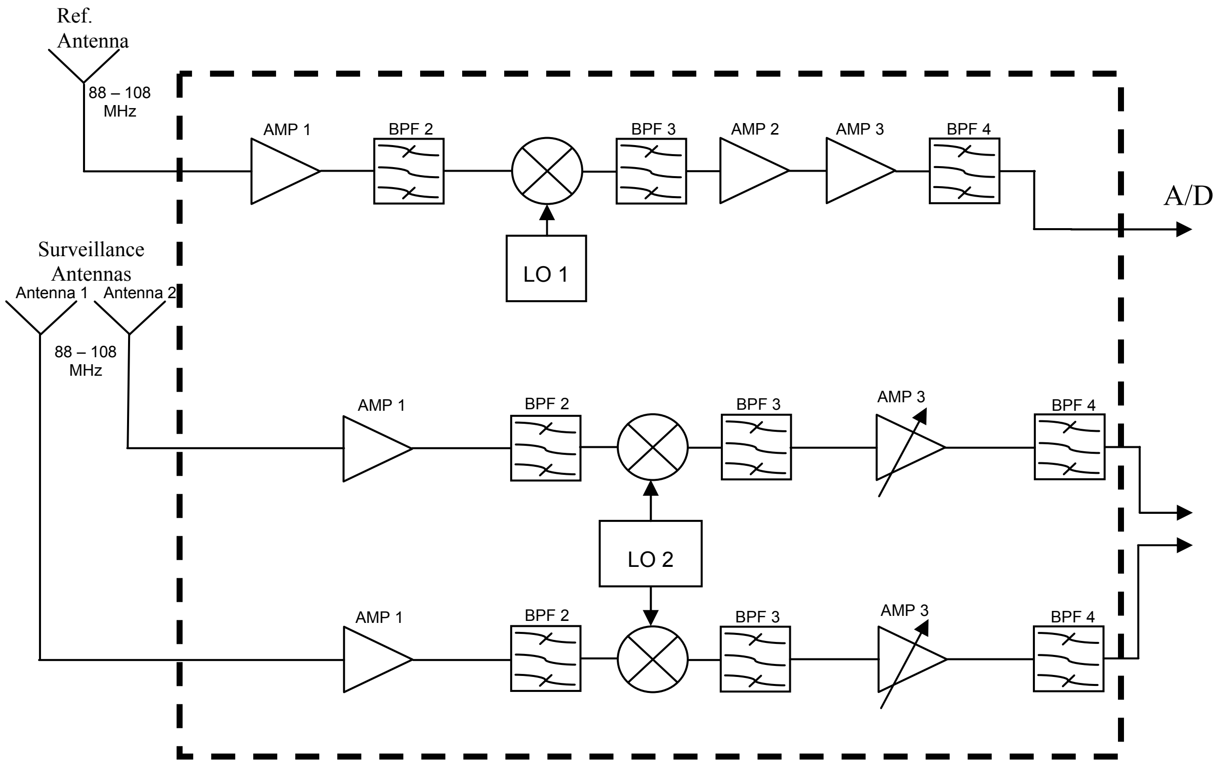
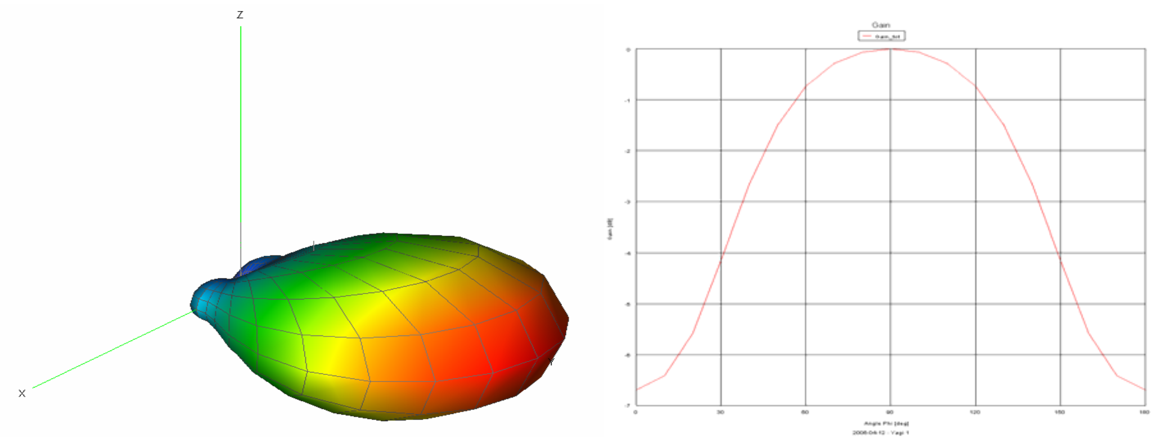


Fig. 8. PCL receiver system.

The surveillance antennas are four-element, folded dipole, Yagi-Uda antennas. Their radiation pattern was modelled using FEKO, as shown in Fig. 9 (a). Furthermore, the half-power beamwidth (HPBW) of the same antenna was also modelled and found to be approximately 105°, as can be seen in Fig. 9 (b):



(a) (b)

Fig. 9. (a) Radiation pattern of the four-element Yagi-Uda surveillance antennas. (b) The HPBW is approximately 105°.

Fig. 10 shows the reference channel under test in the laboratory. A detailed analysis of the third-order intermodulation products of each channel was also carried out to ensure these do not appear within the passband of the amplifiers as this would result in a serious limitation on system performance.

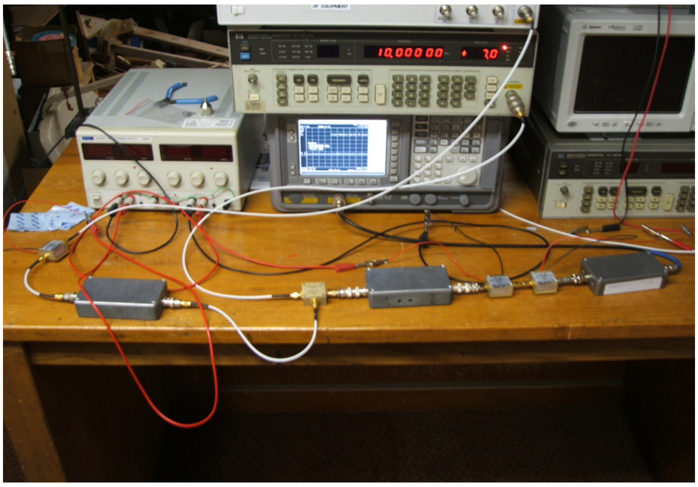


Fig. 10. Reference channel under test.

5.0 CONCLUSIONS

This paper reports on a PCL demonstrator that is currently being developed at UCL. The radar will operate in a congested urban environment, and the extent of the signal and interference has been investigated. Furthermore, an analogue signal suppression circuit for the suppression of the direct interference signal in the surveillance channel/s was also proposed. Since the unwanted direct signal interference in the surveillance channel correlates perfectly with the reference signal, range and Doppler sidelobes will occur, which are much greater than target returns. Analogue suppression will only remove a portion of this undesirable leakage, and so it will be necessary to perform adaptive interference cancellation in the receiver, this is also an area that requires further investigation.

6.0 REFERENCES

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[2] H. D. Griffiths, C. J. Baker, H. Ghaleb, R. Ramakrishnan, and E. Willman, “Measurement and analysis of ambiguity functions of off-air signals for passive coherent location,” *IEE Electron. Lett.,* vol. 39, no. 13, December 2003, pp. 1005-1007.

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