

A lightweight, ultra wideband polarimetric W-band radar with high resolution for environmental applications

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Abstract - A lightweight, ultra wideband (UWB), polarimetric millimetre wave 94 GHz radar with high resolution is described for environmental and other short range applications. UWB and random signal W-band radar technologies are combined with polarimetric and super-resolution processing techniques to provide a compact remote sensing capability that is man-portable. An all-weather capability is provided for accurate and high resolution measurement of the physical size, relative distance, bearing, altitude, direction, velocity and classification of stationary and moving objects at ranges of less than 10 km. Attributed information relating to the sensed environment such as local surface features, water depth, terrain topology and object classification is derived from remote millimetre wave radar measurements including polarisation.

Index Terms - binary random phase coding, millimetre wave, polarisation, radar, random signal radar, super-resolution, ultra-wideband

I. BACKGROUND

A major threat to global stability is the inevitable change to the Earth's climate. Average annual temperatures continue to increase and the UK Department of Environment Food and Rural Affairs (DEFRA) reports [1] that the UK may experience wetter winters and drier summers. Extreme sea levels associated with the combined effects of high tides, sea level rise and storms will occur more frequently [2]. These have profound consequences upon the threat to life and economies with wide impact upon assets, changes to natural habitats, political stability, socio-economic and physical boundaries. Uncertainty of the impact of climate change is incorporated into long-term regional, national and international decision-making, and reflected in environmental standards and targets. Our understanding of the complex interaction between the Earth's surface and the atmosphere is required to be greatly enhanced beyond the current state of the art [3],[4]. An accurate description of local surface features (or topography) and timely monitoring by readily available and affordable means are of fundamental importance for all organisations and authorities that are concerned about the impact of climate change.

Q-par Angus Ltd with UK DTI support is developing an all-weather remote sensing capability. UWB and random signal radar (RSR) technology [5]-[7] are exploited together

with polarisation diversity and super-resolution techniques. This powerful combination results in a lightweight millimetre wave radar that is capable of providing accurate measurements of objects down to less than a few millimetres in size. The radar will remotely sense and consequently resolve very small features. This capability is not found in the usual radars that work at centimetre wavelengths and uses a new type of millimetre wave source to produce the radio frequency power, and highly accurate antennas to form very narrow beams. Importantly, since the wavelength is short the radar is smaller and more compact than conventional radars. It is therefore lightweight and readily man-portable. This distinct advantage eases the logistics of physically positioning large and bulky radar systems to overcome obscuration, shadowing, distortion and interference. Furthermore, this approach directly addresses the dichotomy of how to achieve coverage including foliage penetration (FOPEN), with all-weather remote measurements of fine angular resolution. The radar can be located beneath tree canopies to overcome foliage and vegetation shielding. This lightweight radar may also be readily installed upon air platforms with severe size, weight and power (SWAP) constraints such as UAVs and High Altitude Platforms (HAPS).

II. ULTRA WIDEBAND AND RANDOM SIGNAL RADAR

A definition that has come into usage [5],[6] is that UWB radar is any radar whose fractional bandwidth is greater than 0.25, regardless of the centre frequency or the signal time-bandwidth product. This definition is satisfied by a radar system that offers the use of random binary phase coding with a bandwidth greater than 23 GHz centred upon an RF carrier of 94 GHz. This can be approached in a rectangular waveguide based design such as WR-10 covering 75 GHz to 110 GHz for fundamental or dominant transmission modes. The benefits of UWB radar are high accuracy and resolution of range, velocity and angular measurements, target recognition based upon ultra-short response of UWB target scattering responses, enhanced clutter suppression capability, foliage-, ground- and wall-penetrating detection and imaging, immunity to external narrowband electromagnetic radiation and noise, low probability of intercept (LPI) and anti-jamming. However, the detection sensitivity, and

consequently the maximum operating range of UWB radar is severely restricted in systems that transmit signal energy in narrow pulses. This is overcome in this design by the use of a well-known technique of phase coding the transmitted signal. This permits the use of RF signals with a low ratio of peak to mean power.

III. BINARY RANDOM PHASE CODING

A technical review of radar waveforms discounts the use of uncoded CW waveforms because of their inability to measure target range. Linear FMCW has strong coupling of range and velocity and it is difficult to synthesise ultra-wide band FMCW waveforms. Pulsed Doppler waveforms can be used to measure range and velocity simultaneously over a limited unambiguous range and Doppler offset frequencies. The pulse repetition rate can be contrived to match the range and radial velocities of expected targets. However, pulsed waveforms are peak RF power limited and suitable RF sources become increasingly unaffordable at shorter millimetre wavelengths. The term random signal radar (RSR) refers to radars whose transmitted waveform is random or random-like in contrast to conventional CW, pulse, FM or FMCW radars. Several kinds of RSR have been implemented including noise FMCW, compound noise FMCW, dual-random quasi-CW, random phase coding and binary random phase coding.

The signal filtering and processing that is incorporated in a radar receiver is normally a very close approximation to that required to perform matched filtering of the received waveforms from targets and clutter. The ambiguity function is an established tool based on the assumed use of matched filter reception. It is normally used to make an assessment of radar system performance, although for more accurate subsequent analysis a cross-ambiguity function should be used.

For a complex signal described as,

$$s(t) = u_0(t) \cdot \exp(j \cdot 2\pi f_0 \cdot t) \quad (1)$$

where $u_0(t)$ is the complex envelope, the cross-ambiguity function is defined as $|\chi(\tau, f_D)|^2$, where

$$\chi(\tau, f_D) = \int_{-\infty}^{\infty} u_0(t) \cdot u_{01}^*(t + \tau) \cdot \exp(j \cdot 2\pi f_D \cdot t) \cdot dt \quad (2)$$

and $\chi(\tau, f_D)$ can be regarded as the time-reversed complex envelope for the output of the filter that is matched for a signal $u_{01}(t) \cdot \exp(j \cdot 2\pi f_0 \cdot t)$ but receives the signal

$u_0(t) \cdot \exp(j \cdot 2\pi f_0 \cdot t)$ with a frequency shift f_D imposed upon it. The time of the arrival of the signal is considered to be unchanged by the frequency shift.

The magnitude of the $\chi(\tau, f_D)$ function at any point in the (τ, f_D) plane is a direct indication of the interference that will be encountered at the peak output time for the desired signal when a signal of the same magnitude but with offset f_D and relative time delay τ is also received. Hence, the ambiguity surface reveals the degree of sensitivity that the radar processor has to signals arriving with different delays and frequency offsets, and of course these signals can be attributed to targets and clutter with different ranges and velocities.

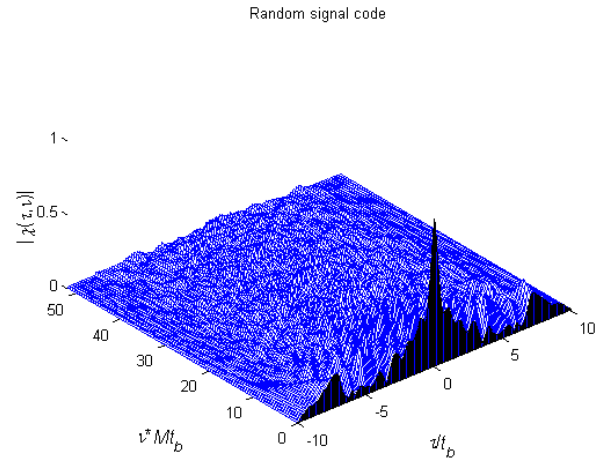


Fig. 1 Cross-ambiguity response for a random phase coded waveform

Random signal waveforms can be shown to have a “thumbtack” cross-ambiguity function and excellent range-Doppler resolution. The cross-ambiguity response of a random phase coded waveform is shown in Fig.1. RSR waveforms also have excellent EMI/EMC capability. Furthermore, random signal waveforms have low peak to mean RF power levels and are compatible with solid-state RF sources such as Gunn and IMPATT diodes. This emphasises the significance of spatial RF power combining that is being developed within this programme to provide a low cost method of reliable low noise RF power generation at millimetre wavelengths. The use of random phase coded modulation with a 3 GHz chip rate results in a slant range resolution of better than 5 cm at 94 GHz with readily available commercial off-the-shelf (COTS) components. With the application of super-resolution techniques this is further enhanced to better than 10 mm. This represents an effective RF bandwidth of greater than 15 GHz with a fractional RF bandwidth in excess of 0.16 that approaches the informal definition of UWB radar. Comparison of random phase coding and random binary phase coding (shown in Fig. 2) by analysis of RF power spectrum and cross-ambiguity functions

show similar characteristics. Importantly, UWB random binary phase coding is much easier to implement and has therefore been adopted in this radar design.

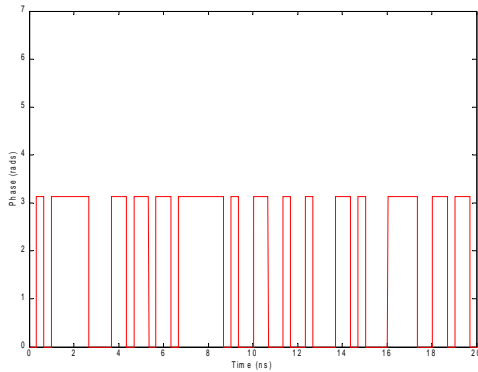


Fig. 2 Random binary phase coded CW waveform

IV. SPATIAL RF POWER COMBINING

The radar transmitter provides a coherent source of low noise electromagnetic radiation greater than 0.24 Watts (mean) at 94 GHz. A novel spatial RF combining technique is used to provide a low cost and relatively high power RF source from an array of low power graded gap second harmonic GaAs Gunn (“hot” electron injection) diodes.

V. PROCESSING

A schematic diagram of the UWB radar is illustrated in Fig. 3. Pseudo-random binary phase coding is imposed by a bi-phase modulator driven by a pseudo-random noise generator running at a clock rate of 3 GHz. An unambiguous range of less than the radio horizon of 10km is produced by this arrangement in association with a reflector-based antenna. The mechanically scanned antenna with a physical dimension of less than 0.75m diameter has low inertia and may be scanned at rates in excess of 400 rpm. A high efficiency, dual-polarisation waveguide-based feed with an RF bandwidth in excess of 3 GHz is incorporated to provide a W-band antenna with mid-band co-polar antenna gain of > 45 dBi and a 3 dB beamwidth of 0.2 degrees.

The received signals are cross-correlated with a delayed replica of the transmitted signal contained within a reference channel to implement complex matched filtering. The amplitude, phase and Doppler offset frequency (and rates of change) are measured between complex received signals in both vertical and horizontal polarisation channels and a reference channel. The phase difference between several transmitted waveforms is measured to determine the slant range of the scattering object. Integration of a large number of randomly binary phase coded pulses provides sufficient

energy for reliable target detection and high resolution imaging.

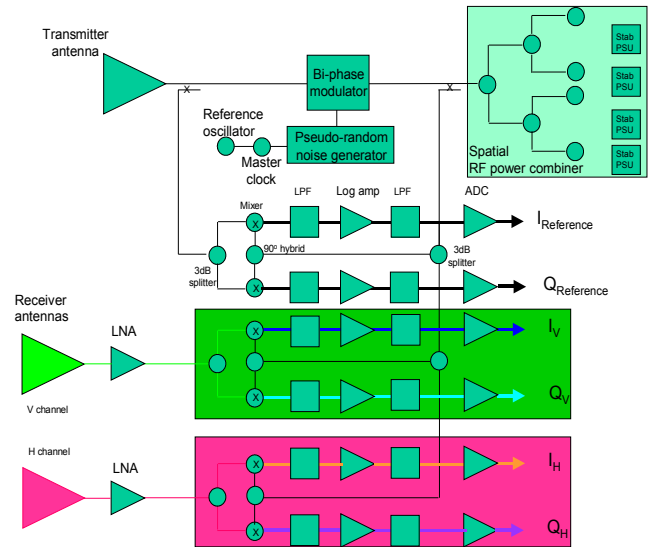


Fig. 3 Random binary phase coded W-band millimetre wave radar

In-phase (I) and quadrature (Q) channels are used in the receiver to extract Doppler and polarisation information from the received signal. I and Q correlators in both polarisation channels (vertical and horizontal) are preceded by low noise amplifiers (LNA). The receiver design is based upon a single down-conversion double balanced mixer design implemented in low loss, precision waveguide. This receiver architecture facilitates the digitisation of complex return signals at 1.5 G samples/s with low cost COTS components [4]. Signal processing is implemented upon a Field Programmable Gate Array (FPGA) and hosted upon a laptop PC to provide a friendly-user GUI. The availability and low cost of modern high speed analogue to digital converter (ADC) technology [8] brings advanced signal processing techniques within affordable reach of this radar design.

VI. PERFORMANCE

Simulated radar performance in terms of signal to noise power ratio as a function of range from the transmitter is presented in Fig. 4. The de-sensitisation due to increased atmospheric attenuation, particularly in rainfall corresponding to rainfall rates of <1 mm/hour and 10 mm/hour are shown. The propagation model used within the simulation includes multipath, which at low altitude and short range can be significant as illustrated. This is mitigated by the use of wideband waveforms and polarisation diversity. A received signal-to-noise power ratio of 10 dB is predicted (worst case) within a single dwell of 7 ms (with an antenna rotation rate of 400 rpm) for a nominal antenna input power of 240 mW

(mean) against a non-fluctuating surface-based target with RCS of 0 dB.m^2 at ranges up to 0.8 km. Detection sensitivity can be significantly enhanced up to the radio horizon at approximately 10 km by the integration of return signals during extended or multiple dwells with rapid rotation of the antenna. The length of time over which the return signal may be effectively non-coherently integrated is dependent upon the statistical stationarity of the scattering environment.

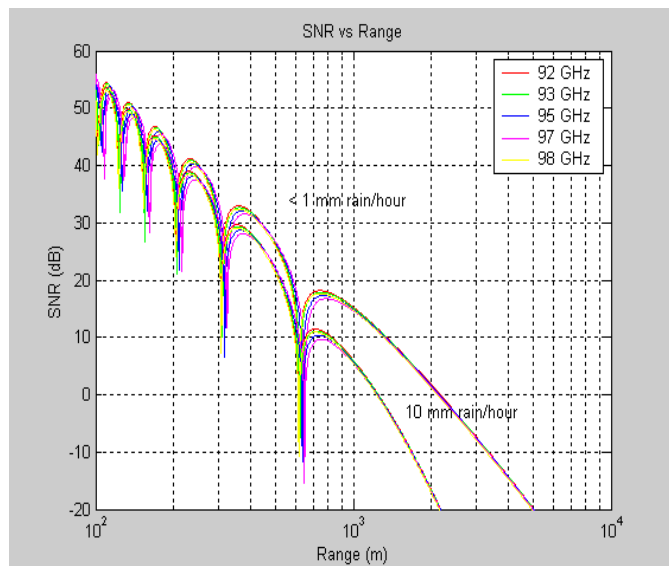


Fig. 4 Radar detection performance in terms of signal-to-noise power ratio as a function of range against a surface based non-fluctuating 0 dB.m^2 target

VII. APPLICATIONS

The primary application of this radar is the observation of surface and near-surface movements of water, thereby providing an aid in flood defence planning, possibly warning of flood escalation and deployment of limited and valuable flood defences. Ripples on water surfaces can be resolved by this radar to indicate flow rates, rate of change, flow direction and below-surface features. This capability will aid the management of water resources, drainage, irrigation planning and pollution detection. Pollution in the form of particulate debris, or oils causing changes in surface features, may be detected and monitored. High resolution surface mapping is part of a requirement for environmental monitoring. This has particular application to bathymetry where knowledge of the depth and currents flowing in water is needed in order to predict future trends and to prevent flooding. Other detailed high resolution measurements of ground surface features can provide valuable environmental data. The radar system that is described has sufficient high resolution for this work and is portable whilst being relatively affordable.

VIII. CONCLUSIONS

An UWB polarimetric millimetre wave 94 GHz (W-band) radar that uses random binary phase coding to provide an all-weather remote measurement capability is under development by Q-par Angus Ltd. This will be demonstrated later in 2006 in a proof-of-concept surface mapping mode with ultra-high resolution at millimetre wavelengths in a representative environment.

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