Multistatic Radar: System Requirements and Experimental Validation

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***Abstract*—Multistatic radar provides many advantages over conventional monostatic radar, such as enhanced information on target signatures and improvements in detection which are due to the multiple perspectives and differences in the properties of clutter. Furthermore, the fact that receive-only multistatic nodes are passive may be an advantage in military applications. In order to quantify potential performance benefits of these advantages a comprehensive understanding of target and clutter behaviour in multistatic scenarios is necessary. However, such information is currently limited because bistatic and multistatic measurements are difficult to make, their results depend on many variables such as multistatic geometry, frequency, polarization, and many others, and results from previous measurements are likely to be classified for military targets. Multistatic measurements of targets and clutter have been performed over the past few years by the NetRAD system developed at the University College London and the University of Cape Town. A new system, NeXtRAD, is now being developed in order to investigate some of the many aspects of multistatic radar. This paper discusses the results obtained with the previous system and the lessons learnt from its use. These points are then discussed in the context of the new radar, defining key important factors that have to be considered when developing a new multistatic radar system.**

I. Introduction

Multistatic radar is being investigated in several countries as a means to detect and track low-signature targets. The advantage over traditional monostatic radar comes from enhanced target signatures in bistatic configurations, advantageous differences in the properties of clutter, and improvements in detection that are due to the ability to view targets from multiple perspectives. In addition, the fact that receive-only bistatic sites are passive may be an advantage in military applications. We also note that such a coherent, networked radar is inherently a MIMO system, and can be utilised for experiments in this field.

Over the past decade, the University of Cape Town and University College London have collaborated on a program to make multistatic measurements of sea clutter and targets. This work has provided some interesting and novel results, as well as providing valuable experience on how to set up a multistatic system, conduct such measurements, and analyse the results [1].

In order to further quantify the performance benefits of multistatic radar, and to design practical systems, it is necessary to gain an extensive understanding of target and clutter behaviour. In particular clutter diversity, i.e. the variation of sea clutter characteristics over the numerous controllable and uncontrollable parameters, such as bistatic geometry, frequency, sea state and meteorological conditions, polarisation, as well as many others. It has been shown that sea clutter, especially the amplitude statistics, varies significantly as a function of bistatic geometry. Hence the detection performance of a multistatic system will depend strongly on the geometry used. In order to select the most advantageous geometery, and use clutter diversity in the radars favour, firstly knowledge of how the clutter varies must be obtain. Such information is currently limited, firstly because such measurements depend on many variables, secondly because such measurements are difficult to make, and thirdly, for military targets the results are likely to be classified. The successor of the NetRAD system, is now being developed in the light of the acquired experience to gain deeper knowledge of targets and clutter in multistatic scenarios.

Section II discusses the hardware and achievements of the NetRAD system, that operates in the S-Band. We continue in Section III to describe the new system, NeXtRAD, which has been designed to operate at multiple frequency bands, X and L. It will be fully polarimetric in X-Band, and to allow hybrid polarimetry in L-Band. We also discuss the proposed measurement campaigns for the new radar. The paper draws conclusions and gives an indications of future work.

II. The NetRAD System and its Results

The predecessor to NeXtRAD, NetRAD, has been used in a series of large scale trials which have provided some interesting and novel results reported in numerous publications in the multistatic radar domain [2]–[9]. The team involved in the design and implementation process have learnt a great deal about the advantages and disadvantages of this system and are transferring this knowledge into the development of the new NeXtRAD system.

The NetRAD system was originally designed as a low cost, COTS (Commercial off-the-shelf) system. The initial goals of the low powered system (0.2 W of transmitted power) were simple, multistatic measurements over short distances at a single polarisation and frequency. This system was then upgraded over its lifespan to enable it to be suitable for longer distance (5-10 km bistatic range) measurements, [3]. This was achieved by using increased power provided by a 400 W HPA (High Power Amplifier) and wireless timing and synchronisation solution [7], [10]. At these long distance geometries it was possible to generate data at much greater bistatic angles whilst still measuring targets at significant distance from the baseline. A great advantage of the NetRAD system is the ability of recording simultaneous monostatic and bistatic data of the same scenario, allowing a direct comparison of their performance.

The practical issues of deploying a portable multistatic radar in a coastal environment over baselines of multiple kilometres were overcome allowing multiple successful trials campaign [8], [9], see Table. I. Performing bistatic/multistatic measurements is orders of magnitude more challenging than conventional monostatic measurements. The transmitter and receiver nodes are physically separated but they need to be synchronized to the same time and phase reference, geometries of the nodes and targets must be accurately evaluated, alignment of antennas is critical, environmental data (e.g. wind speed and direction, swell direction, sea state) need to be known and recorded during the measurements, video images of the sea surface are also recommended to detect possible braking wave phenomena and relate them to the data. The process of setting up the nodes, pointing the antennas to a precise direction, and then changing azimuth and elevation consistently to perform different measurements is also not trivial, considering the presence of strong wind in coastal environments. Furthermore, the calibration of a bistatic/multistatic system cannot be performed using trihedral corner reflectors as for monostatic systems. It is not trivial to find and position calibration targets with simple geometry and radar cross section independent of bistatic angle (a large metallised sphere or a vertical cylinder may be suitable under certain conditions) [1].

The most significant trials campaign undertaken using the NetRAD system was completed in 2010 / 2011 in South Africa, centred around the Cape Point area. The aims of these trials were to record both simultaneous monostatic and bistatic sea clutter and target data. The bistatic detection of a target data from this trial can be seen within Fig. 1. The target present in a small rigid-hulled inflatable boat, that was moving in a circular pattern. The data was generated in horizontal polarisation, with a baseline between the monostatic and bistatic node of 217 m. It is of significant importance to understand how bistatic/multistatic targets signatures vary in order to optimise the implementation of real world multistatic radar systems. As important as target signatures is the variation of the clutter. Sea clutter data was also generated using NetRAD, see Fig. 2. These figures show simultaneous monostatic and bistatic sea clutter measured in horizontal polarisation with a baseline of 1827 m. The marked differences in the wave structure and statistics clearly demonstrate the diversity of clutter behaviour when recorded using bistatic/multistatic radar.

In the light of the experience acquired, the areas that were identified for improvement in the planning stage for the new system included:

- Greater accuracy in steering multiple antennas to a selected direction, and the development of an automated procedures to avoid human error during the calibration and pointing phases.
- Increase the reliability of the RF hardware by replacing in-house parts with commercially produced ones.
- Ensuring that hardware components are well protected from the external environment, in particular from the salt-laden atmosphere of the coastal environment.
- Improved User Interface (UI) for selection of radar parameters, such that the selection of the PRF, pulse, power and section of range to be digitized could be automated depending on the measurement desired.
- The requirement to move to an open source software environment for greater flexibility. A move away from a C# designed GUI was required to allow for easier development of the C&C (Command and Control) interface.

TABLE I
AN OVERVIEW OF THE VARIOUS 2009-2011 NETRAD DEPLOYMENTS AND PRIME OBJECTIVES.

Year	Site	Volume GB	Objective
2009	Peacehaven (UK)	132	Sea Clutter and range calibration
2010	Peacehaven (UK)	61	Sea Clutter and range calibration
2010	Peacehaven (UK)	198	Sea Clutter and range calibration
2010	Cape Peninsula (RSA)	224	Small targets mostly sea clutter
2011	Simon's Town and Misty Cliffs (RSA)	165	Small targets VV bistatic sea clutter
2011	Misty Cliffs (RSA)	269	VH bistatic sea clutter VV bistatic sea clutter

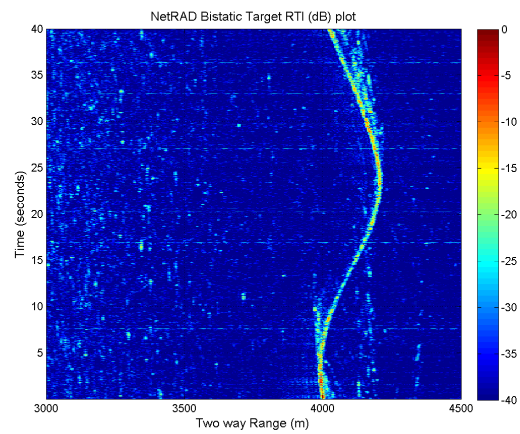
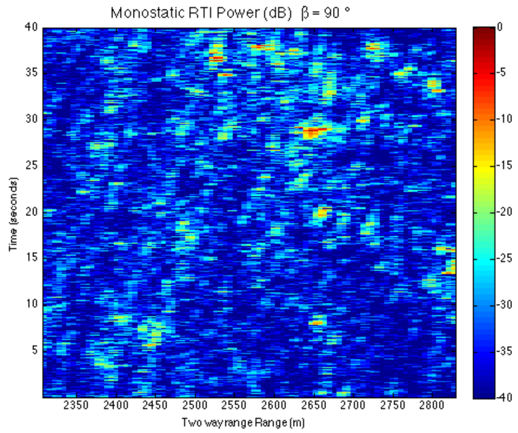


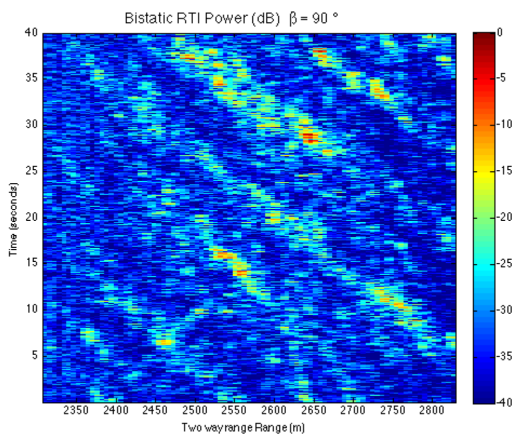
Fig. 1. NetRAD Monostatic and Bistatic RHIB Boat Target detection

III. NEXTRAD

In this section the necessary system improvements in the development of the novel NeXtRAD system, together with the desired multistatic experiments to be performed are discussed. A description of key aspects of the proposed system are then provided.



(a) Monostatic



(b) Bistatic

Fig. 2. NetRAD RTI Plot Showing Sea Clutter (dB) (a) Monostatic (b) Bistatic

A. System Upgrade and Desired Measurements

The possibility of operating at X and L-Bands as well as performing polarimetric measurements has been identified as a priority for the development of the novel NeXtRAD system. These additional degrees of freedom allow for a greater understanding of how these parameters effect the behaviour of multistatic target returns. Also the clutter diversity will be better characterized as a function of frequency and polarization. X and L-Bands capabilities have been also required by project collaborators, in order to compare the results with existing operational systems. Furthermore, the significant use of WiFi at 2.4 GHz, i.e. within S-Band used by the NetRAD system, makes this frequency band no longer so attractive.

The ability of performing simultaneous monostatic, bistatic, and even multistatic measurements for bistatic ranges up to 5 km is a requirement for the NeXtRAD system. This can provide an interesting comparison of monostatic and multistatic performance for the same target, clutter, meteorological and sea conditions. Making it possible to evaluate directly the potential advantages of bistatic/multistatic systems in a variety of geometries.

NeXtRAD remains basically a pulse Doppler system, as NetRAD. However the new system allows for a variety of waveforms, i.e. arbitrary pulsed waveforms, in anticipation of novel waveform experiments. The need for range multilateration and tracking (i.e. four active transceivers) was set aside initially, due to the transmitter cost, especially in the power amplifier.

Taking advantage of the aforementioned system improvements, the planned measurement campaigns for the new system include:

- Low observable maritime target measurement campaign, including small sea crafts as well as swimmers in the water.
- Multistatic multi-band dual polarised sea clutter measurements, recorded over a range of meteorological and sea states.
- A wind farm measurement campaign, with the aim of investigating the effects that multistatic, dual polarised measurements have on the returns from wind farms.

Further measurements of sea clutter and small maritime targets, in addition to the prior NetRAD trials, remain highly desirable in order to develop more advanced models for targets and clutter in a greater variety of multistatic geometries. The NetRAD system allowed for the publication of some interesting and novel bistatic sea clutter data covering a small section of the possible combinations of RF, geometry, sea and meteorological conditions. NeXtRAD will allow data collection in a variety of novel multistatic geometries and allow to further investigate clutter diversity, for instance looking at polarisation and frequency diversity.

Although the focus of previous bistatic experimental campaigns has been mostly on sea clutter and targets, NeXtRAD will be suitable also for land based measurements. It will provide the same advantages in terms of investigation of the returns at different frequencies and polarization, as well as comparing simultaneous monostatic and bistatic/multistatic measurements of the same scenario. The mitigation of wind farm signals within monostatic radar is currently an important topic in the radar research field. Multistatic measurements of wind farms are a topical and novel application for NeXtRAD, as the aspect of multistatic radar in conjunction with polarimetric and frequency diversity has not been fully explored in prior research literature. The added diversity from these aspects of the NeXtRAD radar is likely to show favourable scenarios that suppress the signals returned from a wind farm.

B. The NeXtRAD System

In the development process for the NeXtRAD system we have followed a tailored system engineering process. This implies the derivation of a User Requirement (UR), followed by functional analysis and performance requirements, especially in the light of the results and experience achieved using the NetRAD system and the desired additional measurements.

A first decision involved the use of, mostly, commercially built subsystems to increase hardware reliability. The analogue heart of the dual band system from Reutech Radar Systems has been identified as suitable to meet the reliability needs and affordable. For the digital back end to the new radar, we decided to use the Rhino card developed at UCT, since, again, it was commercially produced, and considerable inhouse experience exists for the programming of waveforms and flexible digitization.

Additional requirements have been set by the desire to improve system deployment and facilitate data capture in the field, for instance improvements in the inter-node communications for operators, in the video capture of the scene at each node, in the automated antenna pointing, and in the simple geolocation of each node and calibration of bistatic angles based on digitized local maps.

Space precludes a detailed system block diagram, therefore only a top level version is shown in Figure 3. A comprehensive specifications are currently being developed, and we offer the interim values used in design work in Table II. In the following subsections, we give more details of the key design decisions.

TABLE II
INTERIM NEXTRAD SPECIFICATION

Parameter	Value	Comments
X Band frequency range	8.5 to 10.5 GHz	In practice, limited by power amplifier
L Band	1.2 to 1.4 GHz	Full band possible.
Instantaneous Bandwidth	50 MHz	Both bands
Peak power X Band	400 W	20% duty cycle
Peak power L Band	1.4 kW	20% duty cycle
X Band NF	2.5 dB	
L Band NF	1.5 dB	
Max node separation	10 km	must be LOS for WiFi
Max PRF	20 kHz	L and X locked
Max Pulse length	20 μs	PRF selected for duty cycle

C. Antennas & Mounts

NetRAD uses antennas with 10° beam-widths that were linearly polarised, allowing the recording of either V or H polarisation. The polarisation could only be changed via manually rotating antennas in between gathering measurements. This did not allow for comprehensive polarimetric analysis of targets or sea clutter.

For the prototype phase of NeXtRAD, we have preserved the beam width at both X and L band, but have added dual polarisation at X-Band. The proper design and calibration of the antenna system is just starting, and is only likely to complete late in 2015. Horn antennas will be used in the interim period.

The new antennas for NeXtRAD will maintain the same beam width to allow for a direct comparison of the NetRAD data, at S-band, with the NeXtRAD X and L-Band data. As maintaining the same beam width will keep the same cross range and pointing requirements on the antennas, therefore illuminating an equal patch on the sea surface.

The new NeXtRAD system will be fully polarimetric in X-Band i.e. both co- and cross-polar components can be simultaneously received. The transmitter will have to be switched between PRIs. Hybrid polarimetry, where we transmit circular polarisation and receive two linear components is also planned. This reduces peak power per polarisation (by at least 3 dB), but retains a higher ambiguous doppler frequency than alternating transmissions.

From the lessons learnt using the NetRAD system we now understand how important pointing accuracy and automated steering is to multistatic radar. NeXtRAD will use mechanically steerable antenna mounts capable of sub degree pointing accuracy that can be controlled over a wireless network. This will remove the human error in aligning antennas and significantly speed up data acquisitions via the mechanical control.

In addition to the 10° beam width antennas we aim to test narrow beam antennas at X Band. This will provide greater system sensitivity for use with long range or low observable targets. Tests can be performed with a combination of interchangeable antennas to develop a good understanding of the optimal setup for detection of low observable targets using a multistatic radar.

Each mount will also carry a networked camera that can stream images of the illuminated scene to be stored locally and used for referral later during data analysis. A live stream is also available to the main control node and the local operator. It is critical during large data collect campaigns as much information is documented as possible, using video feeds will enhance the understanding between target or clutter visual behaviour and the radar signals received.

D. Command and Control

Local nodes are controlled by laptops connected to local network switches, whereas inter-nodal communication is via wireless links. Radar parameters are downloaded from the master controller to the nodes. The local operator will be provided with a camera to record real time views of the target scene, and a VOIP call system will be set up to allow operators at different nodes to communicate; this system has been preferred to the radios previously used for NetRAD. Quicklooks of digitised data, including pulse-by-pulse compressed data, are available at each node or remotely at the master node to provide the operators with a real-time quality check on the measured data.

E. Trigger and Phase distribution

The nodes are synchronized, triggered, and kept locked in phase by using GPS Disciplined Oscillators (GPSDO), as this method was already effective for the NetRAD system. The sample clock for each node is driven by a 100 MHz signal derived from the GPSDO's 1 Pulse Per Second (PPS) signal. The 100 MHz GPSDO signal is also fed to the synthesiser subsystem, responsible for tuning over the L and X-Bands, and producing the 125 MHz centred IF signal, which is directly sampled and streamed to the disk in the local laptop.

F. Mechanical and Power

All the electronic components of NeXtRAD will be housed in a hermetically sealed box with viewports to prevent corro-

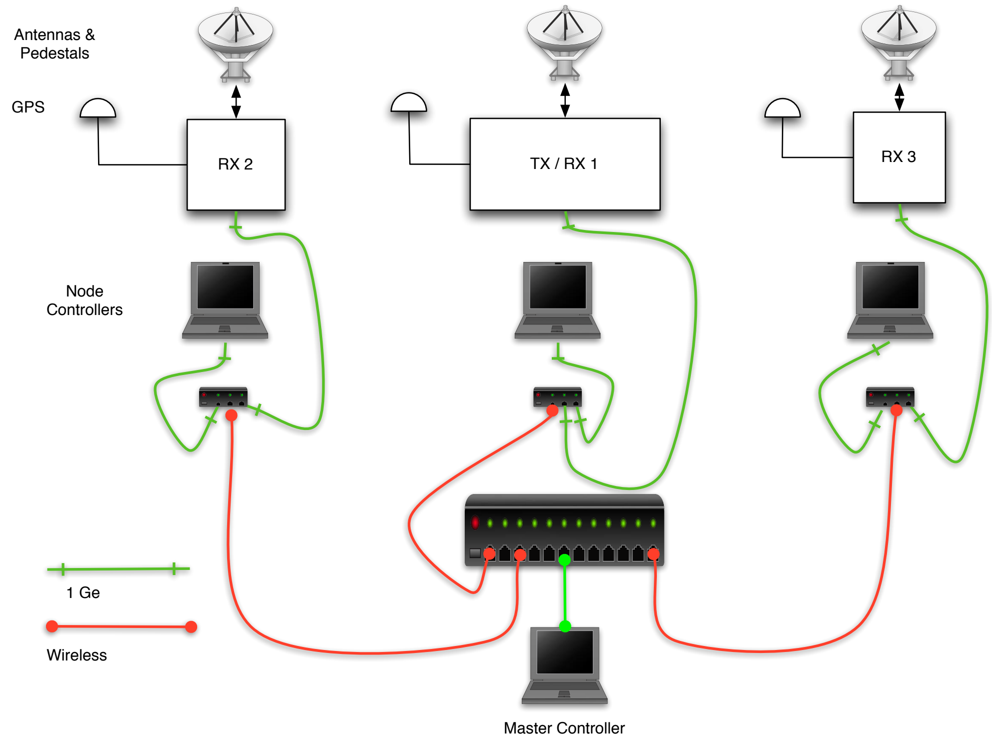


Fig. 3. Simplified system block diagram of NeXtRAD, showing one active, mono static node, and two, receiver-only nodes. Trigger and phase synchronisation is via GPSDOs, and the command and control links between the nodes is via WiFi.

sion from the salt-laden sea winds. The car batteries previously used to power up NetRAD will be replaced by a small generator set to provide multiple hours of operations for longer experimental trials, yet still allow for deployment away from mains power.

G. Waveforms and Digitisation

Rhino cards FMCW150 and FMCW164 are used for the digital hardware of the NeXtRAD system, the former to store and convert to analogue the transmitted waveforms, and the latter to carry out the digitization [11]–[13]. The PRF generation, is also carried out by the Rhino, using the on board FPGA. The PRF is carefully tied to the sampling, to avoid the modulation effect of pulse to pulse phase jitter. A detailed description of the digital subsystem is given in another paper in this proceeding [14]. These cards have been chosen for their flexibility in selecting sampling parameters and because there was considerable experience in their development and use. As well as the fact they will allow for experimentation in the field of OFDM [15], [16].

IV. Conclusions and Future Work

In order to use multistatic radar for the detection of low signature targets, it will be important to have a full understanding of target and clutter properties. The NetRAD and NeXtRAD systems will allow this to be achieved. In the paper we have discussed the important factors in designing such systems and in conducting multistatic experimental trials.

The achievements of the NetRAD system in generating an important database of clutter and target data in multistatic geometries have been described. These results represented the multiple firsts in the bistatic radar domain regarding sea clutter and bistatic Doppler.

In the light of this experience, big steps forward for the development of the new NeXtRAD systems have been highlighted, such as improvements to the Command and Control system, protection from the environment, extension to L and X-Bands, and possibility of performing polarimetric measurements. Trials of a mono static node will begin in July 2014, first at lower power and then high power. A further two receive-only nodes will be completed by the end of the year, and multi static, polarimetric, calibration can start in early 2015.

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