# 220 GHz wideband 3D imaging radar for concealed object detection technology development and phenomenology studies.

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## ABSTRACT

We present a 220 GHz 3D imaging 'Pathfinder' radar developed within the EU FP7 project CONSORTIS (Concealed Object Stand-Off Real-Time Imaging for Security) which has been built to address two objectives: (i) to de-risk the radar hardware development and (ii) to enable the collection of phenomenology data with ~1 $cm^3$ volumetric resolution. The radar combines a DDS-based chirp generator and self-mixing multiplier technology to achieve a 30 GHz bandwidth chirp with such high linearity that the raw point response is close to ideal and only requires minor nonlinearity compensation. The single transceiver is focused with a 30 cm lens mounted on a gimbal to acquire 3D volumetric images of static test targets & materials.

**Keywords:** Millimeter wave, imaging radar, FMCW, DDS, security.

## 1. INTRODUCTION

The ability to detect person-borne concealed threats remains an ongoing and pressing requirement in many scenarios such as airports, border crossings and military checkpoints. Indeed the last decade has seen millimeter wave security scanning portals emerge as the dominant technology for passenger body screening and have become a near ubiquitous presence at major international airport hubs around the world[1]. However, despite the commercial success of these systems, the requirement for security imaging technology that facilitate higher passenger throughput rates remains a highly desirable goal for security agencies and transport hub operators.

To address this requirement, in 2011 the EU issued a call for proposals under FP7 Topic SEC-2012.3.4-5 "Further research and pilot implementation of Terahertz detection techniques (T-Ray)" soliciting collaborative projects which would reduce the time needed for security checks while maintaining or increasing the level of detection. Project proposals were expected to develop a prototype imaging system operating at a single or multiple sub/millimeter wave frequencies, including frequencies above 300 GHz, which had to be safe for use on the general public and allow concepts of operation which respect privacy.

The authors are with the CONSORTIS (Concealed Object Stand-Off Real-Time Imaging for Security) project[2] which is funded under the above scheme. The consortium comprises 11 project partners across 5 EU member states and aims to demonstrate high resolution, real time security imaging with significantly improved throughput rates using sub-millimeter wave technology. As part of that effort we have developed a 220 GHz single pixel experimental radar called 'Pathfinder'. This has been designed as a test bed for (i) novel transceiver technology from project partner Wasa Millimetre Wave AB and (ii) wideband chirp generator architecture from the University of St Andrews, both of which are candidate technologies for the future CONSORTIS security scanner. Additionally, Pathfinder has been useful as a data gathering platform to collect sub-$cm^3$ volumetric resolution phenomenological data to aid the development of automatic anomaly detection algorithms by project partner the Swedish Defence Agency FOI.

We introduce the overall design and architecture of Pathfinder in section 2 then describe the chirp generator and 220 GHz transceiver in sections 3 and 4 respectively. Section 5 details the focusing optics and presents spatial resolution characterisation. In section 6 we discuss the radar point response characterisation and calibration and present sub-$cm^3$ voxel resolution 3D radar imaging results.

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Passive and Active Millimeter-Wave Imaging XIX, edited by David A. Wikner, Arttu R. Luukanen, Proc. of SPIE Vol. 9830, 983009 · © 2016 SPIE
CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2222780

## 2. SYSTEM OVERVIEW

Pathfinder is a laboratory test bed built around a single pixel transceiver and focusing lens mounted on a two-axis gimbal which enables the focused spot to be rastered across a target of interest. Due to the slow sped of image acquisition it is only really suitable for collecting 3D data on static targets, such as mannequins. Figure 1 shows a CAD model of Pathfinder imaging a mannequin and a photo of the actual system as mounted on a trolley, including laboratory power supplies and supporting test equipment.

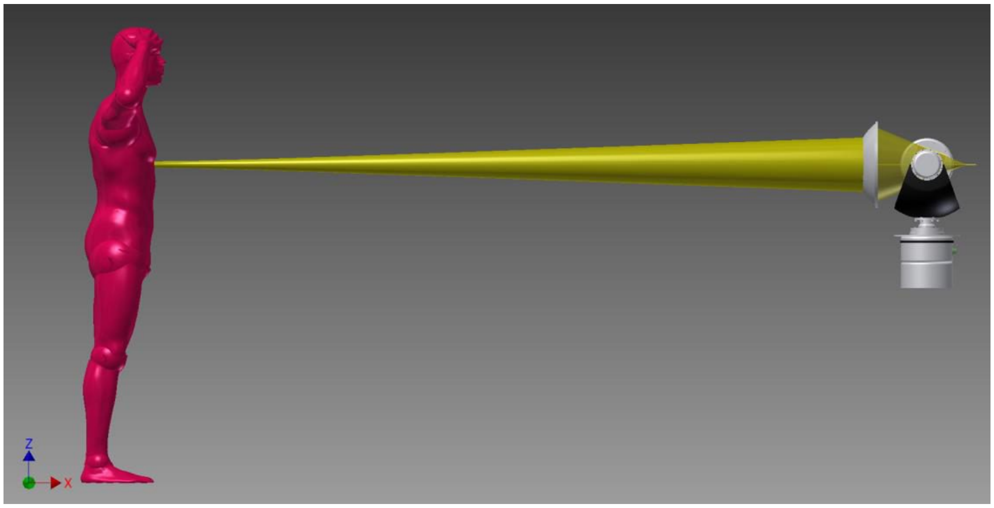


Figure 1. CAD model of Pathfinder 220 GHz radar scanning a mannequin (left). Photograph of Pathfinder radar (right).

Like many wideband millimeter wave radars, Pathfinder uses a solid-state FMCW architecture with frequency multiplication to achieve the final 30 GHz bandwidth chirp from 200 to 230 GHz. This bandwidth yields 0.5 cm range bins to enable the discrimination of small details in range. At the carrier frequency, this represents a very wide 14% fractional bandwidth, much higher than other radars with the same bandwidth operating at higher frequencies, and presents challenges in the design of the chirp generator (section 3) and x24 frequency multiplication chain (section 4).

However, unlike many other sub-millimeter wave radars[3,4,5], Pathfinder uses a homodyne rather than heterodyne architecture due to the novel transceiver technology described in section 4. As a result, the IF signal is obtained directly at baseband and commercial low noise amplifiers and filters are used prior to digitization. Data acquisition is performed using a 50 MSa/s USB digitizer. Software written in C controls both the gimbal motion and data acquisition and provides real-time raw radar data output (time series, A-scope range profiles and azimuth scans). Further radar signal processing is performed offline in MATLAB.

## 3. CHIRP GENERATOR

Achieving high fidelity FMCW radar measurements over very wide bandwidths requires wideband chirps which have excellent linearity and low phase noise[6]. Future submillimeter wave 3D imaging radar systems aim to achieve high frame rates (of order 10 Hz) and, given that typically only a few transceivers will be used in combination with some form of rapid beam steering, the individual pixel rates can be quite high thus mandating short duration chirps. This places demands on the chirp generator, which usually operates at microwave frequencies, and the spectral characteristics of all the components in the subsequent frequency multiplication chain, such as amplitude flatness and group delay variations, which contribute to distortion of the radar's point response[3,5]. The phase noise of the chirp generator output is further degraded by 20log(N) where N is the frequency multiplication factor.

The Pathfinder chirp generator, developed by the University of St Andrews, uses a direct digital synthesis (DDS) chip to generate the chirps which are upconverted onto a low phase noise, fixed frequency, stable local oscillator (STALO) and then frequency doubled to yield a 1.25 GHz wide chirp centered at 8.958 GHz. This arrangement achieves low phase noise, wideband, high linearity chirps of short duration. We have used an Analog Devices AD9914 DDS evaluation board which is clocked at 3.5 GHz and programmed from C using a microcontroller-based custom control board.

The chirp generator output power is +7 ±2 dBm, sufficient to drive the transceiver – see Figure 2 (left). The phase noise of the chirp generator is dominated by that of the STALO, which in the experiments described below was an Anritsu MG3692C synthesizer. The measured phase noise at the center frequency is shown in Figure 2 (right). Chirp duration is easily configurable and is typically in the range 10 to 100 µs.

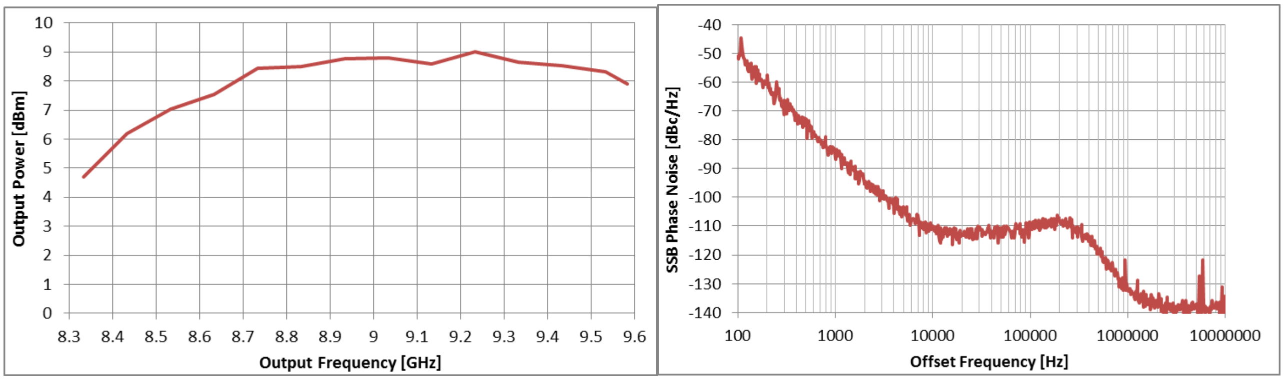


Figure 2. Chirp generator output power versus frequency (left) and CW phase noise at 8.953 GHz (right).

## 4. 220 GHZ TRANSCEIVER

One main aim for Pathfinder has been to prove the novel transceiver technology originally developed at Chalmers University of Technology, Sweden, which was selected for the future CONSORTIS radar. Whilst that system will operate at 340 GHz, transceivers of this type were already available at 220 GHz. The transceiver consists of a x24 frequency multiplication chain in the sequence x4 MMIC – x3 Schottky – x2 Schottky. The key novelty in this design is the use of a self-mixing doubler as the last stage: this acts as both the final doubler in the transmit path but also acts as a sub-harmonic mixer on receive[7]. This function is realized by using a balanced circuit configuration of two diode pairs which provides noise immunity to local oscillator (LO) noise. Internal waveguide branch-line coupler hybrids provide the necessary phasing at the LO and RF ports and the IF is coupled via a transformer which also provides the connection for DC bias of the diodes. A photograph of the complete x24 transceiver module, fitted with a conical feedhorn, is shown in Fig. 3 (left) – the visible side port is the unused port of the 110 GHz input hybrid with the external load not fitted.

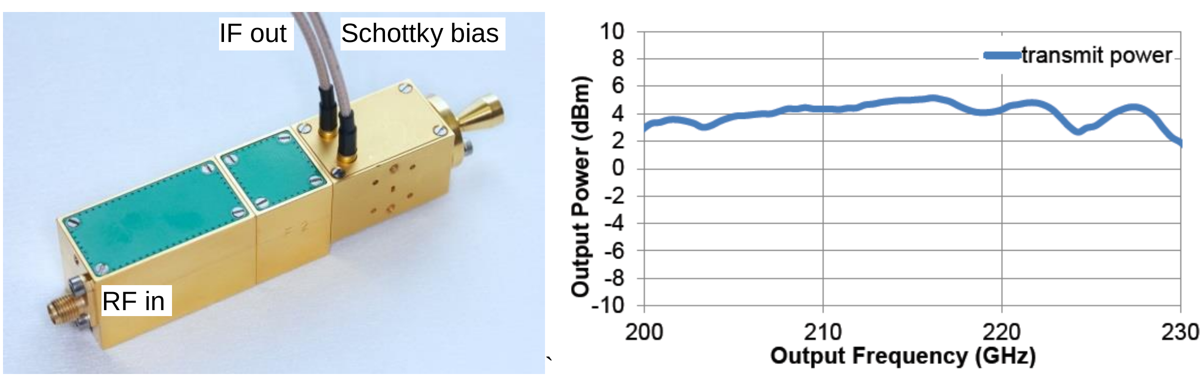


Figure 3. Frequency multiplier chain (x4-x3-x2mix) including self-mixing multiplier final stage (left) and output power versus frequency over 30 GHz bandwidth (right).

The transceiver output power is quite flat over the full 30 GHz bandwidth, yielding 3 ±2 dBm - Fig. 3 (right), which is desirable for high fidelity radar measurements. Inevitably there is compromise with this design compared with having separate multiplier and mixer components and the receive conversion loss is around -17 dB. However, in the envisaged security imaging applications, signal-to-noise ratio is rarely the limiting factor in target detection. The compact form factor of the modules and their significant advantage of not requiring an external transmit-receive duplexer (either in waveguide or quasi-optics) makes them ideal for assembly into 1-D or 2D arrays, suitable for imaging.

## 5. OPTICS

To obtain image data with a resolution similar to that proposed for the CONSORTIS radar, Pathfinder has been designed to have a focal spot size of ~1 cm. This has been achieved using a feedhorn illuminated plano-convex lens. In order to fit the assembly within the yoke of the gimbal, the transceiver points vertically downward and a 45° mirror deflects the beam towards the 30 cm diameter lens. A commercially available smooth-walled conical feedhorn[8] was available and was characterized to aid the lens design. Far-field antenna patterns for E- and H-planes were measured at the band edges of 200 and 230 GHz - Fig. 4 (left). The mainlobe shows reasonable symmetry down to -8 dB and there is little variation in beamshape with frequency down to -10 dB. Additionally, the WR-04 waveguide port return loss of the feedhorn was measured on an Anritsu Lightning VNA equipped with OML 140-220 GHz frequency extension heads. Fig. 4 (right) shows the return loss is below -20 dB across 200 – 220 GHz which ensures a good match to the transceiver RF port.

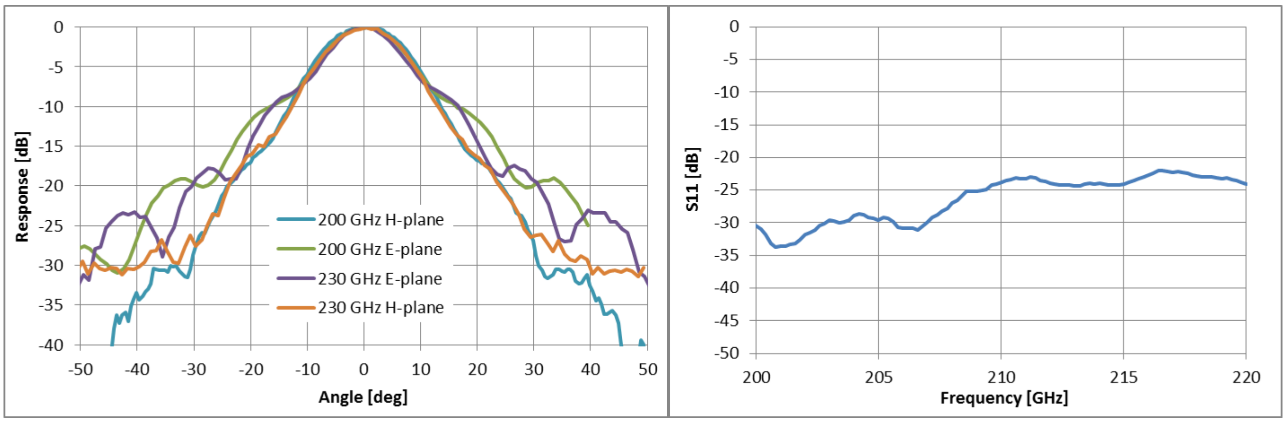


Figure 4. Conical feedhorn measured far-field antenna patterns at 200 and 230 GHz (left) and input port return loss (right).

The aspherical lens was manufactured from HDPE on a 3-axis CNC milling machine and has a smooth finish, without anti-reflection treatment. The lens focuses the beam to a spot of ~1 cm diameter at a stand-off distance from the lens. The diffraction behavior of the beam was characterized by repeatedly making azimuth radar scans of a sub-beamwidth point target reflector (a miniature corner cube with ~6 mm edge length) which was progressively positioned at increasing range. Fig. 5 (left) shows the beam diffraction results which demonstrate that the beam focus is located at 1.55 m as measured from the rear planar surface of the lens.

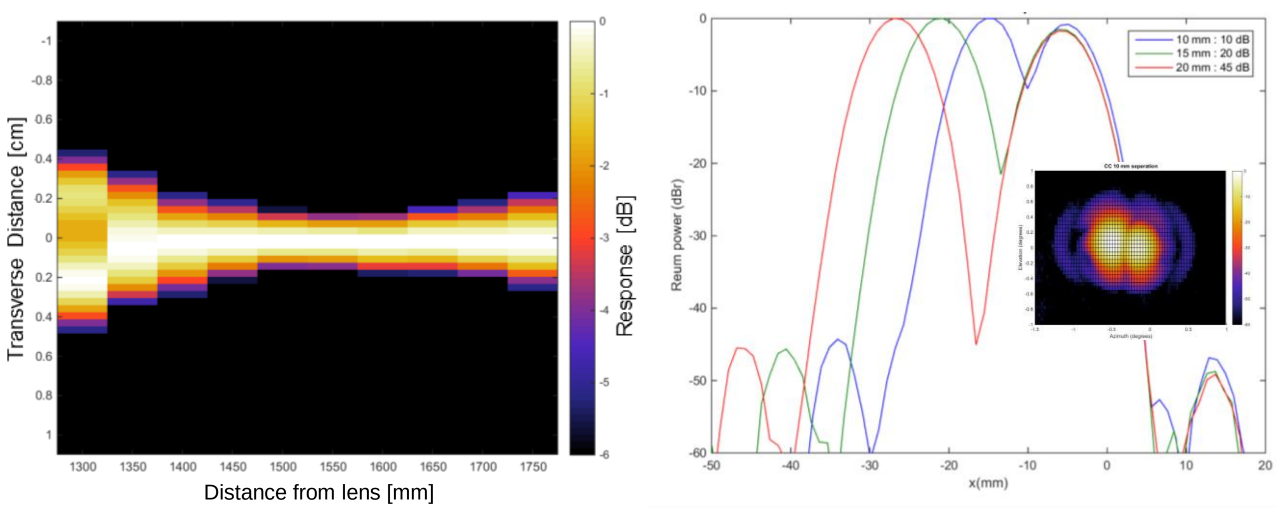


Figure 5. Beam diffraction showing focus at 1550 mm from lens (left) and transverse cuts for two-target separation test showing 20, 15 and 10 mm separations plus radar image of two point targets separated by 10 mm, inset, (right).

The spatial resolution achievable with the lens was characterized by recording azimuth radar scans of two small point target reflectors positioned at the beam focus as they were brought closer together with separations of 20, 15 and 10 mm.

The main figure of Fig. 5 (right) shows the two-way radar measurements in a plane through the center of the point targets whilst the inset figure shows a 2-D image of both targets when separated by 10 mm. The radar spot size is clearly <1 cm and the point targets are still well resolved when separated by 10 mm. The two-way sidelobe level is around -45 dB i.e. the one-way sidelobes due to the lens are at the -22.5 dB level. In summary, Pathfinder achieves excellent optical performance with a <1 cm spot size and low sidelobes, both of which are required for high quality imagery.

## 6. RADAR IMAGING PERFORMANCE

In order to achieve high volumetric resolution Pathfinder not only requires good lateral spatial resolution but also good range resolution. The 30 GHz chirp bandwidth theoretically should yield 0.5 cm range bins but in practice non-linearity effects typically degrade the raw point response in wideband radars. Pathfinder's point response was characterized by measuring the range profile to a point target located at the beam focus. The target was a miniature corner cube which is smaller than the 3 dB width of the beam that has a large radar cross section and provides a high signal-to-noise ratio. Despite the very wide chirp bandwidth, the raw point response of Pathfinder is very clean with relatively little spectral spreading and quite low level range sidelobes. Previously reported results for wideband submillimeter wave radars have exhibited very messy raw point responses, broadened over many range bins and barely showing a distinct peak, which are only usable once compensation routines are applied to the data. In contrast, Pathfinder has a very clean raw point response with a distinct peak and range sidelobes no higher than -30 dBc. As is the established practice for such wideband high frequency radars, residual nonlinearities in the transmitted chirp can be compensated for by calibrating the point response from a reference target at a specific range and normalizing the received radar spectrum[3]. Whilst the calibration is strictly only valid at that range, it is effective over a reasonable range swath, and at least over the depth of field of the beam. Fig. 6 (left) shows the raw and calibrated point response of the radar for a chirp duration of 100 µs compared with that of an ideal sinewave. It can clearly be seen that the corrected point response follows the theoretical resolution limit over a dynamic range of over 60 dB. The high quality raw point response is attributed to a combination of the high linearity and good amplitude flatness of the chirp generator and the well-controlled group delay and good power flatness of the transceiver multiplier chain.

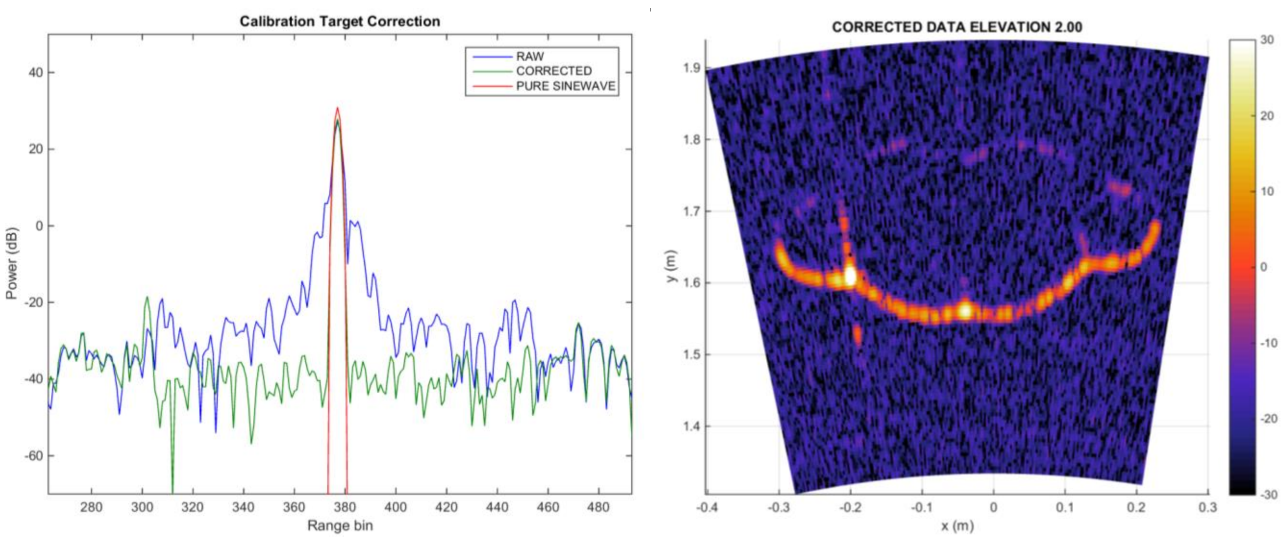


Figure 6. Raw and corrected point responses compared with Fourier transform limited sinewave (left) and azimuth slice through mannequin highlighting range resolution and exhibiting residual phase noise from specular reflections (right).

With 0.5 cm range bins and <1 cm lateral resolution with low sidelobes, Pathfinder is capable of collecting 3D imagery with sub-cm$^3$ voxel resolution with high dynamic range. A simple example of the high lateral and range resolution is shown in Fig. 6 (right) which is a azimuth radar scan of the torso of a mannequin positioned at the beam focus of 1.55m with the beam scan taken at chest height. The contour of the chest and upper arms is very clearly defined with ~cm resolution. The bright radial streak is reflected transmitter phase noise which is only seen for the very brightest reflections. The dynamic range in this particular image is over 50 dB. Note that the brightest reflection is lower than that of the calibration target.

To collect 3D imagery, the gimbal rasters the beam in azimuth and elevation over the subject, with one range profile collected at every angular position. The chirp duration was 100 μs. Image acquisition is slow due to limitations of the data capture card so only static targets can be used. For example, a 0.6 x 0.6 m field of view image with 1 m range swath takes 90 minutes to acquire. Fig. 7 shows the mannequin test target, the corresponding intensity image viewed in front projection and the corresponding 3D point cloud in isometric projection. The point cloud is obtained by selecting the range value of the peak intensity for each line of sight. This data set took 5 hours to collect.

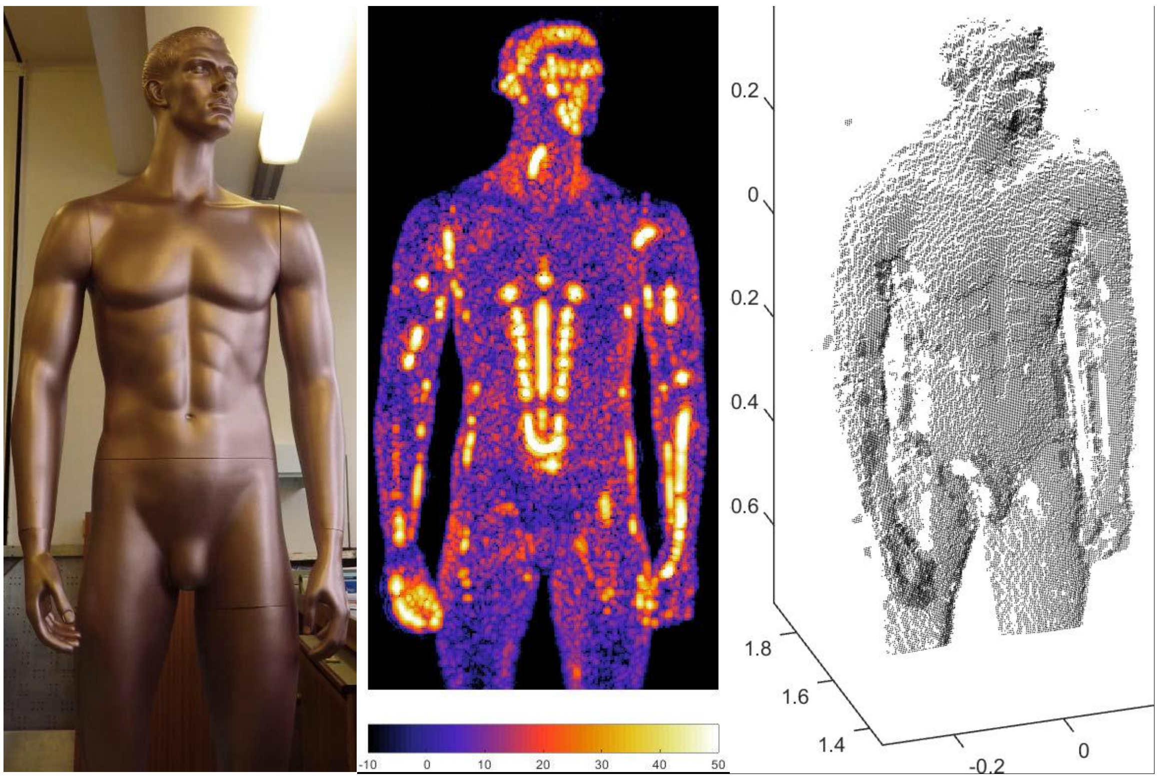


Figure 7. Mannequin test subject (left), 220 GHz radar intensity image (middle) and 3D radar point cloud (right).

Firstly, the high resolution obtainable with Pathfinder is clearly evident. It can be seen that the intensity image demonstrates a coherent speckle pattern typical of radar imaging and that the intensity varies with the degree of specular reflection over the surface of the mannequin. The point cloud data reveals the sub-$cm^3$ voxel resolution is capable of resolving significant amounts of detail including the facial features, collar bone and abdominal muscles.

A final aim for Pathfinder has been to collect 3D phenomenology data with a volumetric resolution representative of the future CONSORTIS radar in order to assist the development of automatic anomaly detection algorithms. As an illustration of Pathfinder's capability to detect dielectric targets concealed by clothing we collected data from the mannequin (i) when bare, then (ii) with a dielectric test object attached and then (iii) with a fleece jacket covering the target. The dielectric test object was a 10 x 6 x2 cm slab of Blu-Tack (poster tack / adhesive putty) attached to the mannequin with electrical insulating tape.

Fig. 8 (left) shows the three cases with the corresponding radar intensity images and photographs – the location of the target is circled. The intensity images do not reveal the presence of the dielectric target and the speckle pattern dominates the interpretation of the images. Fig. 8 (right) shows a range difference image obtained by subtracting the range image of the bare mannequin from the range image of the fleece covered dielectric target. The presence of the dielectric target is then revealed on the mannequin's chest as a region which differs from the surrounding surface by ~2 cm. Whilst this is a slightly artificial scenario benefitting from the perfect registration of a static set up, it does illustrate the potential for wideband sub-millimeter wave 3D imaging radar to detect dielectric objects concealed under clothing.

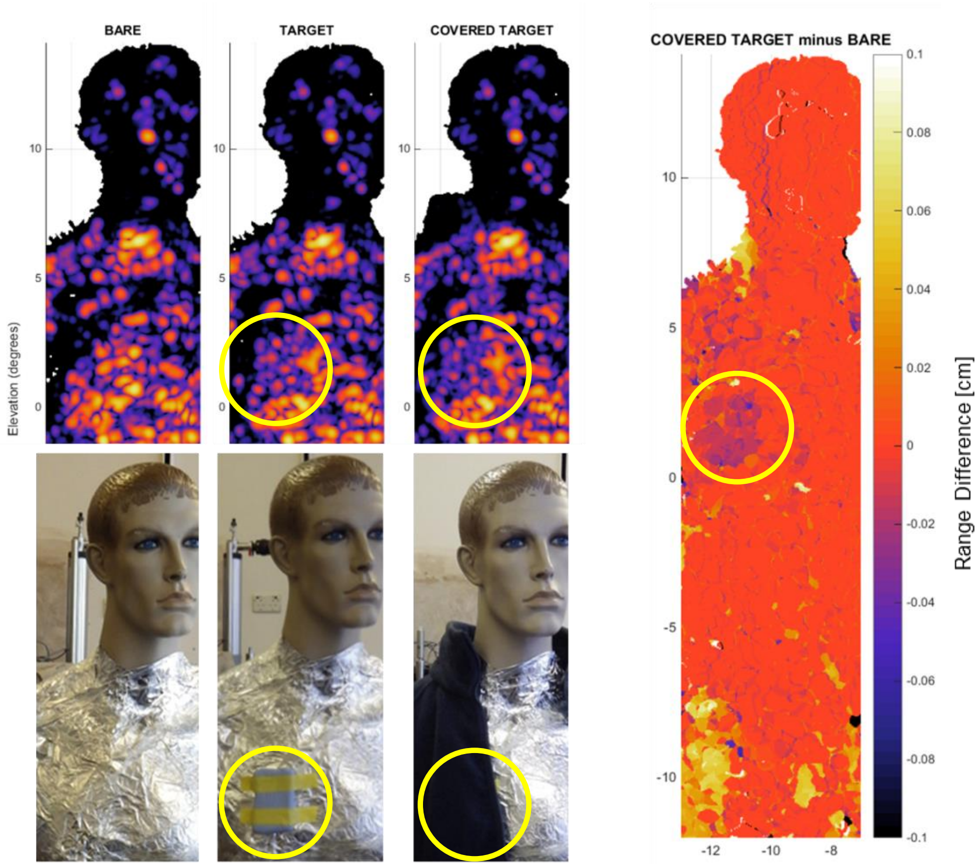


Figure 8. Intensity images of mannequin test subject: bare, with 10 x 6 x 2 cm Blu-Tack target, target covered with fleece (left), range difference image showing depth discrimination of 2 cm thick dielectric concealed target (right).

## 7. DISCUSSION & CONCLUSIONS

We have demonstrated the Pathfinder 220 GHz single-pixel, gimbal rastered, 3D imaging radar which achieves sub-cm$^3$ voxel resolution through the use of 30 GHz chirps and a 30 cm focusing lens. This radar has been a test bed for proving key technologies identified for use in the future CONSORTIS 340 GHz radar which is being built to address future airport security requirements for higher throughout and improved detection performance.

Pathfinder has enabled the de-risking of two key elements of the radar design. Firstly, the chirp generator which achieves 14% relative bandwidth at an output frequency of 8.9 GHz with good amplitude flatness, excellent chirp linearity, high speed chirps and low phase noise. Secondly, the frequency multiplication chain transceiver, based on novel self-mixing multiplier technology, that achieves good power flatness and low chirp distortion over the 30 GHz bandwidth in a compact package which does not require an external duplexer.

The raw point response of Pathfinder is particularly clean and with compensation of the residual nonlinearities the range resolution is transform-limited over a dynamic range of over 60 dB. With 0.5 cm range bins and a <1 cm spot size obtained from the focussing lens at 1.55 m range, Pathfinder achieves a sub-cm$^3$ voxel resolution. Radar imagery of mannequins and test targets show the fine detail which can be resolved due to the high volumetric resolution. Pathfinder's ability to penetrate clothing and detect the presence of concealed dielectric targets has been demonstrated.

Pathfinder is a useful platform for the demonstration of key radar technologies which, through its high performance, enables the collection of valuable phenomenological data for de-risking the development of future sub-millimeter wave security radars and associated automatic anomaly detection algorithms.

## 8. ACKNOWLEDGEMENTS

The authors thank Dr Ewan Finlay of InDepth Optics Ltd. for Zemax lens design, the University's Mechanical Workshop for fabricating the hardware, and Alistair Moore for making the feedhorn antenna pattern measurements. Part of the research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 312745.


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