3D mapping of buildings with SAPPHIRE

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Abstract

An experimental radar system is described that is designed to determine a building map in three dimensions by driving past the building with the radar mounted on a vehicle. The radar system, SAPPHIRE, produces full polarimetric reflectivity data in three dimensions with a voxel resolution of <0.5 m in each direction at 10 m distance. SAPPHIRE uses SAR in the driving direction, focused beam forming and MIMO in the vertical direction and FMCW radar in the range direction. The reflectivity data allows interpretation of specular and diffuse scattering behaviour and polarimetric behaviour of the scattering returns. In this paper, we describe the system design, component performance and system calibration. We also present building measurement results with the system mounted on a rail, discuss imaging and mapping methods and show the potential of SAPPHIRE for 3D mapping of buildings.

Introduction

Military operations increasingly take place in urban environments, but surveillance and reconnaissance information is not available once the adversary hides indoors. Research to establish these capabilities in urban area is undertaken in a few technology research programmes [1,2] This paper describes work undertaken in the EMRS-DTC research programme to map buildings in three dimensions by covertly driving past it with a vehicle mounted radar system.

Currently, through the wall radar is commercially available for single walls, generally at close range to the wall. Moving subjects can be detected and in some cases human heartbeat, breathing and room depth and width are observable. Mapping buildings in three dimensions is subject of research now, and several approaches are pursued [3,4].

The mapping capability of our system will allow intelligence, reconnaissance, surveillance and clearance tasks to be performed beyond the building perimeter by driving by the building, thus improving security, response time, covertness and reliability.

Mapping approach

Our approach consists of the detection, identification and characterisation of scatterers in the building and reconstruction of a map based on this information. Scatterer characterisation is based on a 3D radar reflectivity map, which is obtained by gathering radar range data in a large observation plane in front of the building (Figure 1). By measuring in a large plane in all polarisation combinations, specular and diffuse reflection behaviour, as well as polarimetric behaviour can be used for scatterer characterisation. A linear isotropic propagation medium is assumed, and multipath is suppressed by designing a low side lobe system.

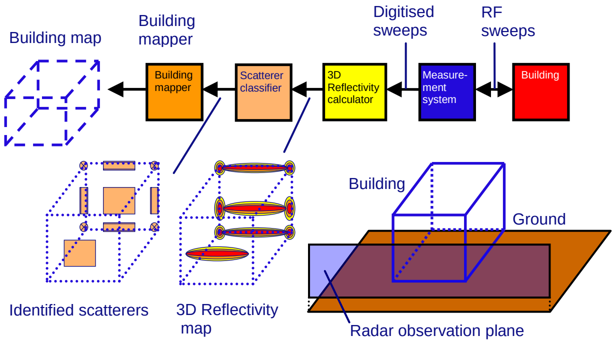
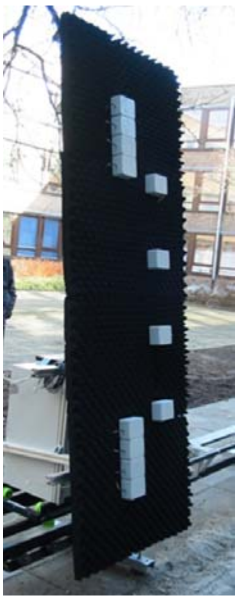


Figure 1 Information sequence from building measurement to building map.

System design

SAPPHIRE, the Synthetic Aperture Polarimetric PHased Array Interferometer Radar Equipment, samples the observation plane by moving a vertical array on a rail along the building. To allow for adaptation to unforeseen results, SAPPHIRE has a flexible array configuration, selectable polarisation configuration (H-V linear or LH-RH circular) as well as definable radar settings. The system is specified to produce a voxel resolution better than 0.5 m in each direction at 10 m distance, which is the estimated position of the second wall. This resolution was specified to provide wall separation in the smallest room, and possibly identify doorways. Furthermore, the system is designed to cover the second wall of two floors.



The horizontal move-ment is realised by a movie camera rail equipped with a laser distance measurement along track. This is used for SAR processing in horizontal direction, providing down to 15 cm azimuth (along track) resolution.

The vertical array is synthesized by a Multiple Input Multiple Output (MIMO) array. The array consists of four transmit (photograph, at the right) and eight receive (left) antennas. Each T/R combination produces a virtual T/R antenna halfway both antenna elements [5]. This way, a vertical array of 32 virtual T/R antennas is synthesized.

The radar consists of an FMCW radar using a 350 MHz linear frequency scan around 2.355 GHz. The range is 81.4 m and avoids confusion from multipath reflections at large range. The radar operates in 16 different transmit-receive configurations. One FMCW sweep is transmitted per configuration. Each configuration consists of the excitation of one of the four transmit antennas and one of the four polarisation combinations of transmit- and receive antennas: VV, VH, HH and HV. The reflection is received at the eight receive antennas simultaneously. The entire sweep sequence duration is 4 ms, allowing Nyquist sampling of the aperture in SAR direction at speeds up to 10 m/s.

SAPPHIRE consists of 12 antenna element modules, an antenna mount, a transceiver and data acquisition module and a laptop mounted on a rail carriage with the distance measurement laser.

Antenna array

Since a complete aperture is sampled, each antenna element can have a large beam width: Digital beam forming allows for synthesizing narrow beams with low side lobes. Low back lobe is required to avoid confusion of back- and front reflectivity, and grating lobes should be avoided to eliminate confusion from reflectivity signals at other angles of incidence.

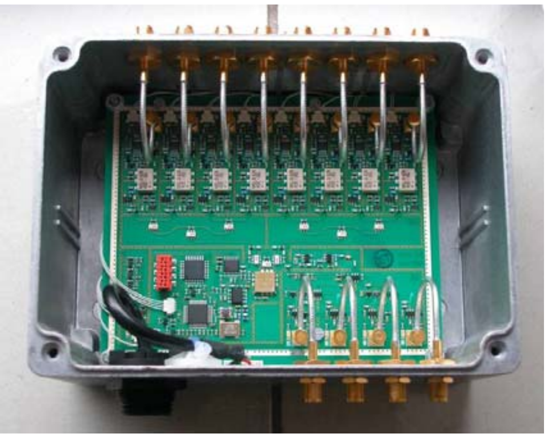
Back lobes are below -30 dB w.r.t the main beam maximum by mounting the antennas on an absorber plated back-reflector. Grating lobes are avoided in SAR direction at speeds below 10 m/s. In vertical direction, the array size is maximised by increasing the virtual element spacing up to the point where grating lobes would appear at observation scan angles. In this way, vertical resolution is maximised.

The antenna elements consist of one active and two parasitic patches. The orthogonal polarisation basis (linear or circular) is chosen by the component mount inside the antenna box. The antenna polarisation (H/V or LH/RH) is remotely set by control signals over the RF line. This reduces the total number of cables and enables reliable calibration. Each antenna is mainly built of commercially available standard parts. The antennas reproduce very well.

The antenna elements have 8 dBi gain, 65 degrees HPBW in both planes and 16,5 % impedance bandwidth (< -9 dB). Cross polarisation is below 20 dB at broadside increasing to 15 dB in the 45 degree plane. Transmit- and receive antenna distance and orientation were chosen such that mutual coupling was sufficiently low to avoid clipping of the receiver.

Transceiver, data acquisition and control

The transceiver consists of a single board with a DDS based FMCW sweep generator, an RF distribution network to the four transmit ports and the eight receivers, and a control and interface section. The board is mounted with the data acquisition and control board in a single module. The module supply is delivered by the USB cable.



The control FPGA on the data acquisition and control board selects the transmit port and the transmit- and receive polarisation, and cycles through the pre-programmed sweep configuration sequence. Low level control signals are transmitted to the transceiver board which sets the transmit port and the antenna polarisations.

The DDS generates the FMCW sweep and transmits the signal via the specified port. The eight receivers down convert the signal and produces video output of the beat signal which is transferred to the data acquisition board. Here, the eight signals are digitised and after buffering they are sent over USB to the laptop.

The transmitter produces 17 dBm RF output to any of the 4 ports with <-100dBc/Hz phase noise at 10 kHz, output power flatness < ± 0.4 dB and output reflection coefficient < -10 dB. The eight synchronous receivers have 7 dB DSB Noise Figure and 60 dB conversion gain with < ± 0.5 dB gain variation and input reflection coefficient < -10 dB.

The 8 ADC’s provide 12 bit sampling at 2 MHz and on the same clock trigger. The 24 MByte/second data stream is buffered locally and transferred in real time to the laptop by USB. This data stream contains the raw video data of every channel for every sweep.

Measurement software

The measurement software loads a measurement file defining the transceiver and data acquisition board settings, allows modifications by the user, and sends the settings to both boards. Before a measurement, the quick-look function allows to verify the proper functioning of all channels and configurations (left-down part of Figure 2). During measurements, radar data acquisition runs in parallel with position measurements. Both data streams are synchronised by a time tag.

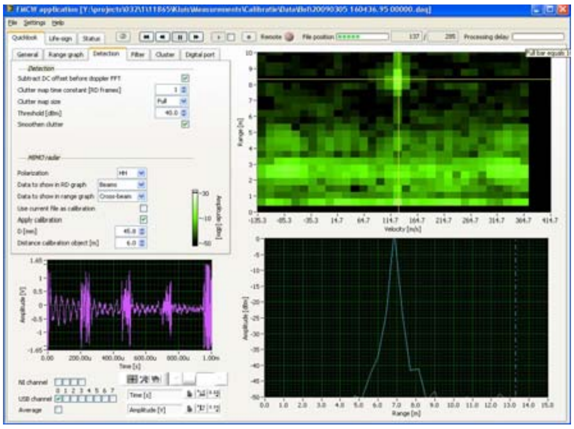


Figure 2 Measurement software screen

The measurement software produces 32 FFT beams in real-time from the 32 virtual MIMO antenna signals. The beam versus range intensity is visible in the upper right part of Figure 2. Beams are on the horizontal axis, range on the vertical axis (up to 10 m). On bore sight at 8 m distance, a calibration reflector is visible, and at closer distances, clutter is observed. The power level across the beams at the reflector range is visible in the lower right graph. The array is calibrated on a different measurement of a target at the same position. Off-bore sight beam signals are below -50 dB. A Hamming window was applied. A target at the edge beams (max. ± 44 degrees scan angle) shows signal 'sidelobes' of the order of -20 dB in the other beams.

MIMO array calibration

The calibration of the array is based on a complex correction factor applied per virtual T/R element. Each virtual element has a phase and amplitude error due to variations in the antennas, the cables and the electronics. Furthermore, phase and amplitude differences are caused by the propagation path differences between the various transmit- and receive antenna combinations and the target.

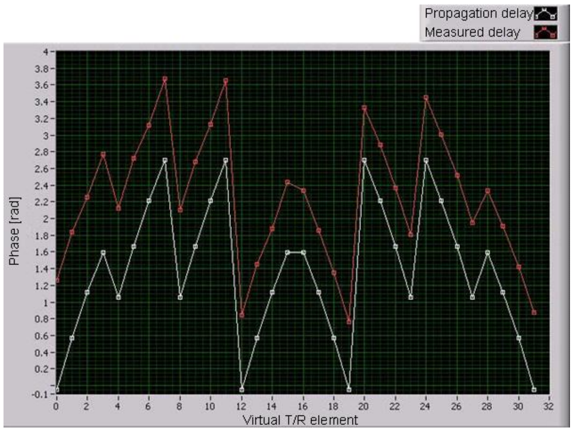


Figure 3 Phase difference as a function of virtual T/R element

The phase differences due to propagation are calculated from the geometry and are shown in Figure 3 by the white curve as a function of virtual T/R element for a target at 6 m. The measured phase difference is given by the red curve. Each continuous line of four points corresponds to the propagation phase difference between one transmit antenna and the upper or lower set of four receive antennas. The constant difference between the geometrically calculated curve and the measured phase provides the distance error to the reflector. Remaining errors provide the element calibration factor for the variation in hardware components per virtual T/R element. No mutual coupling calibration correction is applied.

Reflectivity map processing

Range processing converts the FMCW baseband signal to a complex response as a function of range cell. Assuming a linear isotropic propagation medium, the radar range responses received at the observation plane can be focussed in along-track direction by SAR processing, and in vertical direction by near field beam forming by taking into account the path delays from antennas to focus point. It was found that a dielectric slab like a wall relocates the focus point backward and proportional to the slab thickness without defocusing it. This minor deviation is disregarded. By performing these focussing calculations on a 3-dimensional grid, a 3D reflectivity map is obtained. This map is available in any of the four polarisation matrix scattering coefficients. Signals from other directions and locations are suppressed by the range, azimuth and height side lobes of the three-dimensional point response function of the focused and range processed system.

Detection and classification

Focusing on the dominant phenomenon, specular reflection, different types of scatterers in a building will exhibit different behaviour in phase, polarisation and visibility range of the specular reflection signal. These characteristics can all be used to detect and classify the scatterers.

Planar surfaces exhibit a linear phase change in the reflectivity response with height and azimuth position of the focus point, and little polarisation loss or scrambling. Vertical dihedral corners exhibit a linear phase change in height, a quadratic phase change in azimuth, no polarisation scrambling, high returns in vertical polarisation, and losses in horizontally polarised signal. Horizontal dihedral corners behave the opposite way. Finally, trihedral corners induce a quadratic phase change in both azimuth and elevation direction and may scramble polarisation. The angular visibility of a specular wall reflection is determined by the wall width and height and the direction perpendicular to the wall. The angular visibility of a dihedral corner reflection is given by the quadrant enclosed by the corner and the width or height of the corner. For a trihedral corner, both the vertical and the horizontal enclosed quadrant determine its visibility.

Although specular reflection is dominant, diffuse scattering is a phenomenon that can provide significant additional information in case the observed object has no visibility of its specular reflection. This occurs for floors, ceilings and walls perpendicular to the vehicle track. In that case, diffuse scattering is observable at the focus point and inhomogeneous material properties or small structures in comparison to the voxel resolution will determine the amplitude and polarisation behaviour.

The current resolution is sufficient for detection of reflectors, but insufficient for classification based on linear or quadratic phase change. In SAR direction, resolution can be increased to realise sufficient resolution provided the voxel is visible from a sufficiently large observation angle. In height however, the array size is limited, and the required resolution cannot be achieved.

Identification and characterisation

When specular reflection is dominant, walls can be identified and characterised by measuring the linear phase change over a set of voxels that are observed over a variable visibility width and height. The visibility area corresponding to the wall area will provide maximum return. The linear phase change in vertical and horizontal direction characterises the wall orientation in these directions.

Once the wall orientation is determined, a filter can be constructed for dihedral corners perpendicular to this wall (Figure 4). A forward looking filter (green) calculates the voxel response to a quadratic phase shift until the corner is out of visibility range, which occurs when the radar is perpendicular to the wall at the corner position. A backward looking filter (blue) starts at this point.

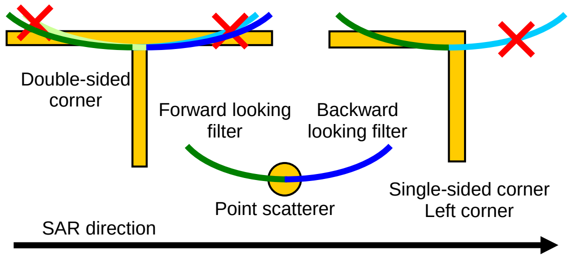


Figure 4 Corner detection filters and their response to different objects.

As is seen in Figure 4, this filter allows identification of single sided corners, but a double-sided corner can be confused with the returns of a point scatterer, since both corners fill in each-other's filter response. In vertical direction, the corner visibility range cannot be exploited due to the limited vertical antenna size, and distinction between linear and quadratic phase behaviour is not achieved.

However, polarisation behaviour at a voxel position can be used to provide dihedral discrimination. The signal of VV - HH provides a clear indication for a vertical dihedral when positive, and for a horizontal dihedral when negative. Of course, forward- and backward looking filters and polarimetric behaviour can be combined.

Building measurements

Measurements were performed on a three story building with a room with closed metallic blinds, an empty room with a corner reflector, a man in a small room, and a room with furniture stock. The focussed reflectivity as a function of along-track and range position at fixed height is shown in Figure 5 for summed returns of a forward looking and a backward looking filter. The color scale covers a range of 80 dB.

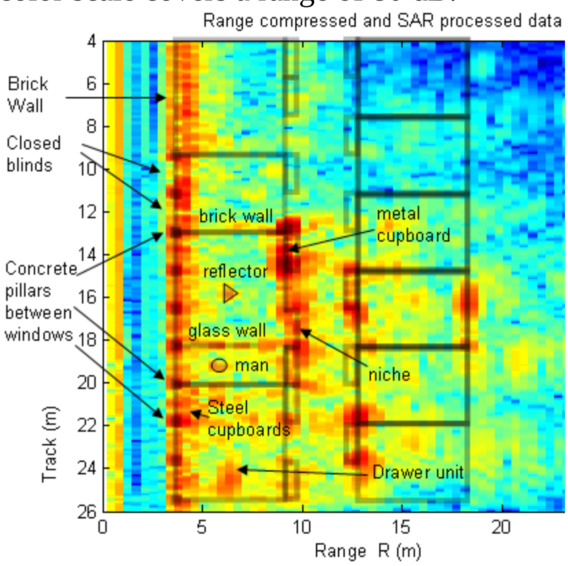


Figure 5 Multi look building reflectivity.

The signatures corresponding to the various objects and the floor plan are indicated in Figure 5. A vertical corner reflection can be distinguished at the back-wall and brick wall junction. The brick wall observation is furthermore supported by diffuse scattering signals, and by the map of the VV-HH signal. Similarly, vertical niche corners are observable. These results demonstrate that identification of vertical corners can be achieved with SAPPHIRE.

The glass wall is also observed, even indicating the wooden frame locations. Doors and pathways are more difficult to distinguish. For example, a closed door is present between niche and metal cupboard, and between niche and glass wall.

Similarly, vertical cross-sections can be made, where the ceiling is observed and the back-wall is visible at many height levels.

Conclusions

A radar system capable of measuring a building structure in three dimensions by driving by has been developed: SAPPHIRE, Synthetic Aperture Polarimetric Phased array Interferometer Radar Equipment. The SAPPHIRE system is characterised and calibrated and the first 3D building measurements were performed. SAPPHIRE has -20 dB to -50 dB elevation side-lobes, has 50 cm resolution in depth and similar resolution in height at 10 m distance, and down to 15 cm in driving direction.

The reflectivity map of the measurements demonstrates the capability of SAPPHIRE to penetrate up to four partitions (walls, windows, doors), and clearly shows walls parallel to the vehicle track. Furthermore, individual pillars, a corner reflector and a man are visible in the reflectivity map.

The main difficulty of building mapping with a single drive-by path is to determine the walls perpendicular to the vehicle path. These walls were found using three different methods, which reinforce each-other's conclusions.

Further work will concentrate on the effective use of the available data in the third (vertical) dimension, which so far was unexplored. These results demonstrate that

SAPPHIRE has great potential for mapping buildings in 3 dimensions.

Acknowledgements

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