Sub-THz Radar sensing of the Environment for future Autonomous Marine Platforms

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Table of Contents

Abbreviations ... 4

1. Introduction ... 5
   - 1.1 Trial Objectives ... 5
   - 1.2 Measurement Site ... 6
   - 1.3 Dataset Overview ... 6
2. Hardware Configuration ... 7
   - 2.1 Equipment used during the Trials ... 8
   - 2.2 Radar Operation ... 8
   - 2.3 Radar Parameters ... 9
   - 2.4 Ground Truth ... 10
3. Data Description ... 11
   - 3.1 Data Structure ... 11
   - 3.2 Frame Velocity ... 11
   - 3.3 Signal Processing Steps ... 11
4. MATLAB Sample Codes ... 13
   - 4.1 Reshaping Data for MIMO mode ... 13
   - 4.2 Selecting $\boldsymbol{\lambda/2}$ spaced Virtual Channels ... 13
   - 4.3 Reading .h5 file from Radarlog ... 14

Abbreviations

UoB	University of Birmingham
IMU	Inertial measurement unit
HDF5	Hierarchical Data Format 5
FoV	Field of view
RLG	Radarlog

1. Introduction

STREAM trials were conducted by the University of Birmingham (UoB) and the University of St. Andrews from 29/08/2022 - 02/09/2022 at Coniston Lake in the UK. The primary aim was to gather propagation data across lakes and measure the returns from the lake surface. The data will be used to develop algorithms to extract the information needed for pilotage.

The experiments were performed with radars operating in the 79, 150, and 300 GHz bands to investigate the Doppler and imaging capabilities of these radars.

This report describes the measurement scenarios and data structure of INRAS Radarlog (76 GHz – 81 GHz) used for data collection campaign.

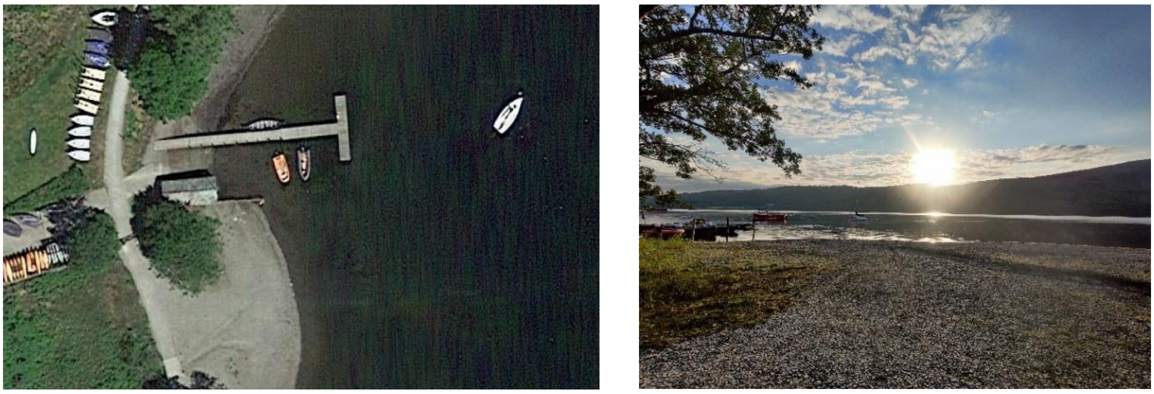
1.1 Trial Objectives

The objectives of the described radar trials are:

1. Collecting data to characterise the lake clutter and provide imagery of water surface.
2. Collecting data to perform anomaly detection.
3. Collecting data on objects which could be a threat to a small vessel or to which the vessel may pose a threat.
4. Obtaining returns from natural and manmade marine objects. The data will be used to produce a library of RCSs of objects at multitude of frequencies and test signal processing algorithms. This includes anomaly detection algorithms for devising object from water surface image.

1.2 Measurement Site

The measurement site is located near Raymond Priestley Centre, Coniston Lake (54.346739,-3.075820). A Google map plan view of the trials site is shown in Figure 1 (a) and the panoramic photo of the test area is shown in Figure 1 (b).



(a) (b)

Figure 1: Pictorial representation of the test area. (a) Google map plan view. (b) Panoramic view.

Weather conditions were moderate throughout, with a sea (lake) state 1.

1.3 Dataset Overview

The full Radarlog dataset collected during the trails is over 6 TB. Due to extremely large files sizes, only the data corresponding to which results are included in the publication is included in the repository.

Additional data may be available upon request.

2. Hardware Configuration

During the trials, the radar equipment was operated in following ways:

1. Sensor suite including all radars, ZED Camera, Velodyne LiDAR, and IMU installed on the same tripod.
2. Sensor suite including 79, 150 and 300 radars, ZED Camera, and IMU installed on one tripod, Radarlog and web camera installed on second tripod.
3. Sensor suite including 79, 150 and 300 radars, ZED Camera, and IMU installed on the moving cart, Radarlog, web camera and IMU installed on the moving boat.

The hardware setup is shown in Figure 2.

Figure 2: Equipment setup.

Radars are operated simultaneously with the Stereolabs ZED and Velodyne LiDAR to obtain time stamped videos and depth maps. All sensors will be controlled via fan less PC or laptops.

2.1 Equipment used during the Trials

The list of equipment used during trials is mentioned in Table 1.

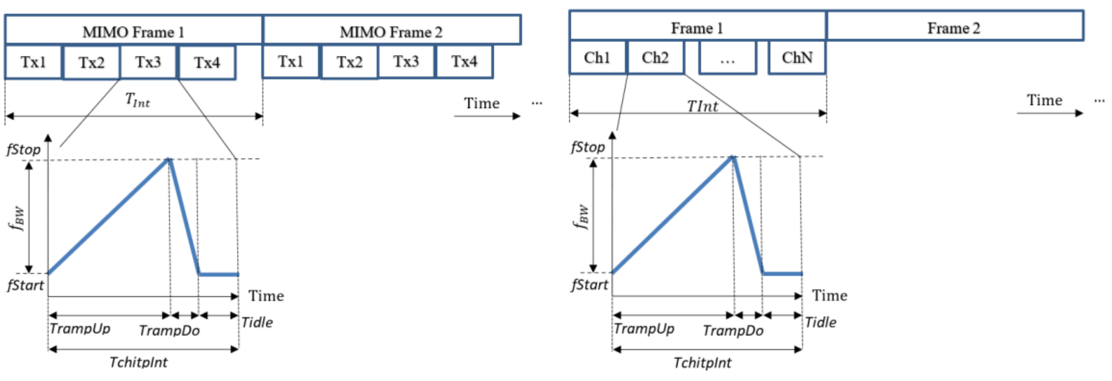
Table 1: Equipment used during STREAM Coniston Trials.

Equipment	Model	Description
Radars	INRAS Radarlog	• MIMO mode: 4Tx – 16Rx • SIMO Mode: 1Tx – 16Rx
Video/ Camera	Stereo labs ZED stereo camera Jelly Comb Webcam	
Lidar	Velodyne VLP-16	
GPS/ Ground Truth	Advanced Navigation Spatial FOG IMU/ GNSS	
Calibration Targets	• Trihedral Corner Reflector (Square plate).	Edge Length: 7 cm Max RCS at 77 GHz: 17.98 dBsm
Targets on water surface	• Swimmers • Pallets • Buoys • Spherical Reflector	
Targets of opportunity	• Boats • Paddle Boats • Swimmers • Birds	

Radarlog, LIDAR and ZED stereo camera are configured to record timestamped data.

2.2 Radar Operation

For the trials, INRAS Radarlog is operated in a) MIMO configuration (all transmitters are active in time-division multiplexing MIMO mode) in order to have an enhanced spatial resolution, and b) SIMO configuration to achieve a higher unambiguous velocity. The chirp and frame configuration for MIMO and SIMO modes are demonstrated in Figure 3 (a) and 3 (b), respectively.



(a) (b)

Figure 3: Chirp and Frame configuration. (a) MIMO mode. (b) SIMO mode

INRAS Radarlog is a 77 GHz radar with four transmit elements at 3.5λ spacing and sixteen receive elements at $\lambda/2$ spacing. It is configured to operate in MIMO and SIMO modes and installed as forward looking and backward-looking sensor.

The computer connected to Radarlog runs Inras RadServe software which captures the radar data, and time stamp information. The radar data and configuration settings are then stored to a HDF5 (Hierarchical Data Format version 5) file. The RadServe software enables high data transfer rate (up to 2.5Gbit/s) and ensures synchronization between the captured Radarlog data and time stamping information.

In MIMO mode, the active transmitters of Radarlog cycle from chirp-to-chirp in the order: TX1-TX2-TX3-TX4. With four transmit elements and sixteen receive elements, the Radarlog produces a virtual array of 64-elements, but the spatial configuration of the antennas on the Radarlog, gives three overlapping virtual elements. After removing these overlapping elements, an equivalent of a 61-element $\lambda/2$ spaced antenna array (one-way only) is formed. Removal of the overlapping elements is done before MIMO processing of the radar signals from the Radarlog.

In SIMO mode, on transmitter is active, Tx1 used in the configured parameters. With one transmit element and sixteen receive elements, the Radarlog produces an array of 16-elements for beamforming.

Raw data recorded to file is the de-ramped FMCW intermediate frequency signal.

2.3 Radar Parameters

Operating parameters for MIMO mode along with the reference variable names are given in Table 2. These parameters have been determined to give the optimal range/ azimuth resolutions, with negligible data transfer loss to the computer.

Table 2: Radar parameters for Coniston trials

Parameter	Symbol	INRAS Radarlog	Unit
		MIMO Mode	
Sweep Time (Ramp-Up)	T_{rampUp}	204.8	µs
Sweep Bandwidth	f_{BW}	2000	MHz
Start Frequency	f_c	76	GHz
Chirp Ramp-Down Time	T_{rampDo}	18.8	µs
Chirp Interval Time	$T_{chirpInt}$	230	µs
Chirps per MIMO Frame		4	Chirps
Active Frame Duration	T_{active}	0.92	ms
MIMO Frame Interval	T_{Int}	1	ms
Chirps in Doppler Interval*		128	
Antenna Configuration		4*16	Elements
Azimuth Resolution		1.9	Degree
Sampling Frequency		10	MHz
Transmit Antenna Gain		14.4	dBi
Receive Antenna Gain		14.4	dBi
3 dB azimuth beamwidth (single element)		76.5	Degree
3 dB elevation beamwidth (single element)		16	Degree
Transmit Power		10	dBm
Number of fast time samples	$n_{samples}$	2048	
Range Resolution	R_{res}	0.075	m
Velocity Resolution		0.015	m/s
Maximum unambiguous range	R_{unamb}	76.8	m
Maximum unambiguous Doppler Velocity	v_{unamb}	± 0.98	ms^{-1}

* Chirps in Doppler interval: This defines the number of individual chirps which are incorporated into a single coherent Doppler processing interval. This is equal to the number of Doppler bins after Doppler FFT in the example post-processed results.

2.4 Ground Truth

Ground truth is collected using a webcam, that is time synchronised with the radar data collected using the same laptop.

3. Data Description

3.1 Data Structure

This section describes the structure of data collected using Radarlog. The structure of the important variables in this file are also described.

The Inras Radarlog parameters are stored as structure with the following fields. Most of the values are either calculated from the FMCW parameters described previously, or are set explicitly.

NOTE: Only those variables used in the signal processing are described. There are other variables in the file that are used for checks during testing, but these are not used during processing and so will not be described here.

- fStart: Start frequency of the FMCW signal in Hz
- fStop: Stop frequency of the FMCW signal in Hz
- TrampUp: Ramp-up time of the FMCW signal in sec
- TrampDo: Ramp-down time of the FMCW signal in sec
- Tint: Frame interval time in secs
- Tp: Chirp interval time in sec
- N: Requested number of samples to be read per chirp

Correct MIMO beamforming requires the application of calibration data in order to account for the fixed phase deviations which can be expected to occur due to the manufacturing variations. This calibration data is based on our measured data and is provided in the form of complex exponential which must be multiplied across the virtual phase array prior to beamforming (i.e., second matrix dimension).

Note that the raw data captured from Radarlog is real and NOT complex.

3.2 Frame Velocity

FrameVelocity_DBSX: Matlab data file containing the platform velocity corresponding to each radar frame. This is obtained from IMU.

3.3 Signal Processing Steps

The basic signal processing steps involved in generating the post-processed results shown in the document are:

1) Reshaping the data according to correct frame structure (MIMO mode)

2) Perform real to complex FFT across the first dimension for range. Since only one half of the real DFT is redundant, it can be discarded.
3) Perform complex to complex FFT across the third dimension for Doppler.
4) Apply phase calibration across the MIMO elements due to platform motion.
5) Perform calibration across the antenna elements.
6) Perform complex to complex FFT across the second dimension for beamforming.

4. MATLAB Sample Codes

Some MATLAB codes for signal processing are described below.

4.1 Reshaping Data for MIMO mode

In MIMO mode, chirps are transmitted by a single active transmitter at a time. The active transmitters cycles from chirp to chirp. Therefore, a simple additional processing step must be performed in order to reshape the matrix prior to the beamforming. If the number of available chirps is not divisible by the number of transmit elements, the remaining chirps should be discarded. For MIMO mode, it is useful to have data in matrix with following dimensions:

- Dimension 1: Number of Fast Time samples
- Dimension 2: Number of Virtual MIMO channels
- Dimension 3: Number of MIMO frames

To reshape the data into a MIMO format, the following MATLAB code sample is useful.

```
%N_Tx:      Number of Transmit Elements
%N_Rx:      Number of Receive Elements
%RawData:   Collected Raw Data from Radar
%N_Samples: Number of Fast Time Samples

N_Samples     = size(RawData,1);
N_MIMO_Frames = floor(size(RawData,3)/N_Tx);
Rx_Data       = zeros(N_Samples, N_Rx*N_Tx,N_MIMO_Frames);

% Reshape Data
  RawData = RawData(:,:,1:N_MIMO_Frames*N_Tx);
  for Idx_Frame = 1:N_MIMO_Frames
      Idx_Start                 = Idx_Frame*N_Tx - N_Tx + 1;
      Idx_End                   = Idx_Frame*N_Tx;
      Rx_Data(:,:,Idx_Frame)  = reshape(RawData_MIMO(:,:,Idx_Start:Idx_End),N_Samples,N_Tx*N_Rx);
  end
```

4.2 Selecting $\lambda/2$ spaced Virtual Channels

The MIMO virtual channels formed by Inras radarlog and radarbook have three overlapping channels. For beamforming by FFT, it is required to have all virtual channels that are $\lambda/2$ spaced with no overlaps. Therefore, only the set of channels are selected where there is no overlap, maintaining $\lambda/2$ spacing. This is done with the code sample below:

```
% Index of Virtual Channels
  Vir_Idx_Radarlog  = [1:15, 17:31, 33:47, 49:64];
  Vir_Idx_Radarbook = [1:7, 9:15, 17:23, 25:32];

% Reshaping Radar Data
  Rx_Data = Rx_Data(:,Vir_Idx_Radarlog,:); % For Radarlog
```

4.3 Reading .h5 file from Radarlog

The following lines of code can be used as a reference to read a single frame from radarlog.

```
%N_FastSamples = Number of fast time samples
%NRead         = Number of chirps to read
%N_Rx          = Number of receive channels
%Filename_RLG  = Radarlog .h5 format filename
%NLoop         = Number of Chirps in 1 frame (4 for Radarlog)
%Frame         = Frame to read

RLGData = zeros(N_FastSamples, N_Rx, NRead);
for iCh = 1:N_Rx
    RLGData(:, iCh, :) = double(h5read(Filename_RLG, sprintf('/Chn%d', iCh), ...
                            [1,NLoop*(Frame - 1) + 1],[N_FastSamples,NRead]));
end
```