Navigating with Ranging Radios: Five Data Sets with Ground Truth

Joseph Djugash and Bradley Hamner
Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213
e-mail: josephad@ri.cmu.edu,
bhamner@ri.cmu.edu

Stephan Roth
Sensible Machines, Inc.
Pittsburgh, Pennsylvania 15207
e-mail: sroth@sensiblemachines.com

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Here we present five large data sets with range-only measurements between a mobile robot and stationary nodes. Each data set consists of range measurements, surveyed locations of the stationary radio nodes, dead-reckoned trajectory of the robot, and ground truth from a sophisticated inertial navigation system/global positioning system mounted on a robot traveling several kilometers at a time. Range measurements are made with two radio-based ranging systems: a RFID tag-based ranging system and an ultra–wide band ranging system. All the data are accurately time-stamped and presented in standard formats (i.e., text files). In addition to the raw data, we present some noise characteristics of the two different ranging systems to offer insight into the quality of the range data from each system.

1. INTRODUCTION

In this paper we present a detailed description of range-only data intended for use in position estimation research. These data will be of particular use to researchers interested in both tracking and localization in applications in which global positioning system (GPS) does not provide sufficient accuracy or is not reliable. A key advantage of using radio-based navigation is that the data association problem is solved trivially—each range measurement is easily tagged with the identity of nodes in between which the measurement is made. On the other hand, working with such data is challenging because the probability distributions due to measurements are annuli and thus highly nonlinear. Because such data can also be noisy, simple linearization around an operating point often causes filters to diverge.

The five data sets presented here are noteworthy for several reasons. First, we believe that they are the largest publicly available collection of range data to fixed nodes taken from a moving node. Second, these data have highly accurate ground truth associated with them. The data are gathered in outdoor fields, free of obstacles and other occlusions, using instrumented autonomous robots with highly accurate

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(2 cm) positioning for ground truth using real-time kinematic (RTK) GPS receivers as well as a fiber-optic gyro and wheel encoders. Ground truth position is updated at 100 Hz.

The data presented here were taken with two distinctly different radio-based ranging systems. The first is a radio frequency (RF)–based system that measures the time delay of a message sent between low-cost, low-power, RFID tags placed in the environment and a moving transponder to compute the range. All data sets that use this system are referred to as the *Gesling* data sets because they were collected at the Gesling stadium at Carnegie Mellon University. The second system is also a radio-based system that utilizes ultra–wide band (UWB) signals and measures the range between two homogeneous nodes. These data sets are labeled as the *Plaza* data sets and were collected at a large, flat, grassy site close to the campus of Carnegie Mellon. Whereas both systems use radio signals to measure range, the noise characteristics of the two vary significantly. In both cases the locations of the stationary radio nodes were manually surveyed to 2-cm accuracy using the available GPS. Additionally, each data set has synchronized time stamps between the range, odometry, and ground truth data streams.

All the data presented here are available at the data set website: http://www.frc.ri.cmu.edu/projects/emergencyresponse/RangeData.

The remainder of the paper is organized as follows. Section 2 provides a detailed description of different data that are logged in each of the data sets. An analysis of the noise characteristics of each of the two ranging systems is presented in Section 3. Finally, Section 4 provides a summary of the data access and the log file parsing technicalities.

2. DATA DESCRIPTION

For each of the data sets, we collected three kinds of data: the ground truth path of the robot from GPS and inertial sensors, the path from dead reckoning, and the range measurements to the stationary radio nodes. The path from dead reckoning is computed by integrating over time incremental measurements of change in the robot's heading from a fiber-optic gyro (with a drift rate of 30 deg/h) and incremental distance traveled measurements from the wheel encoders.

The different data sets were designed to create a variety of robot paths, each with a distinct dead-reckoning drift. In data sets A1 and B2 the paths chosen cause a monotonic increase in heading error due to repeatedly turning in the same direction. In contrast, data sets A2 and B1 present paths that minimize the effect of heading error by balancing the number of left turns with an equal number of right turns. Finally, data set A3 highlights a much longer trial in which the robot was driven in a random manner. Table I presents a comparative view of the different data sets. Data sets A1–A3 were collected using the RFID-based ranging system, and data sets B1–B2 were collected using the UWB ranging system.

2.1. System Setup

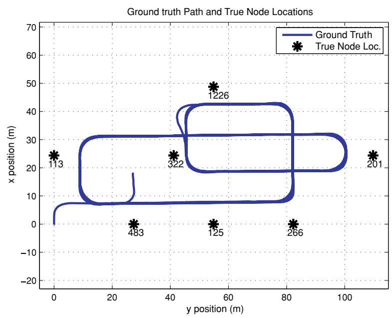
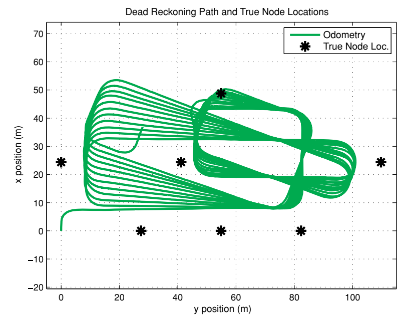
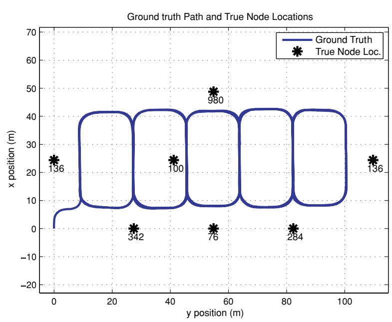
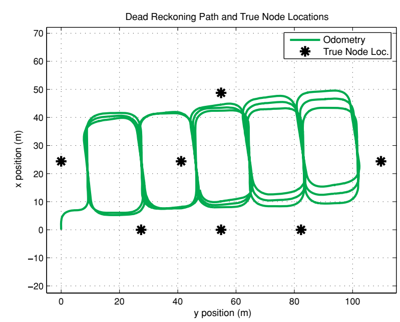
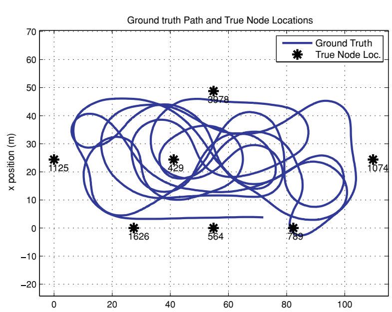
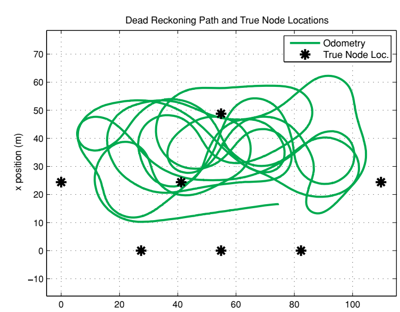
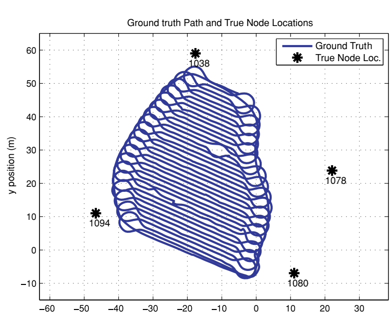
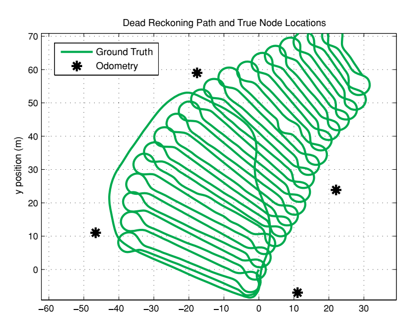
In this section, the system setups for the two different ranging systems are described.

2.1.1. Data Set A: The Golfcart

In our first system, we use a radio tag system (Pinpoint) (Werb & Lanzl, 1998) to measure range between stationary RF tags [see Figure 1(a)] and a moving transponder equipped on an autonomous golfcart. The radio transponder with its four antennae are mounted on the four corners of the robot. The transponders send a "chirp," and any tag that receives that signal responds with its unique ID. The range from the transponder to the tag is then estimated based on the elapsed time between the transmitted "chirp" and the received response.

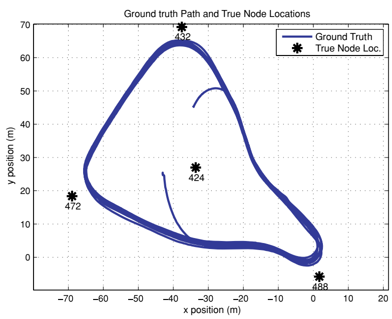
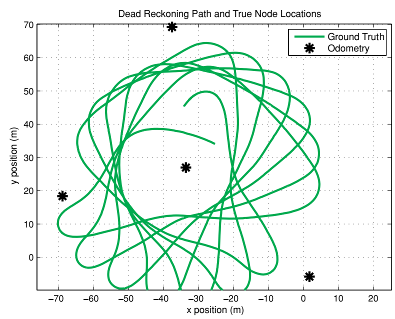
The radio transponder electronics are mounted on the robot with its four antennae mounted on the four corners of the robot (see Figure 1) and pointing in four directions. The robot was also equipped with a computer that controls the tag queries and processes their responses. For each tag response, the system produces a time-stamped distance estimate to the responding tag, along with the unique ID number of that tag and the ID of the antenna that received the response. The distance is an estimate of the distance between the specific receiving antenna on the robot and the beacon. Because the antennae are not colocated at the center of the robot, it becomes critical to know the robot's heading angle in order to determine its position. During data collection, the RF tags are placed atop traffic cones approximately 45.7 cm above the ground. A total of seven RF beacons were distributed throughout the area, and then the robot retraced the path among the beacons guided by RTK GPS.

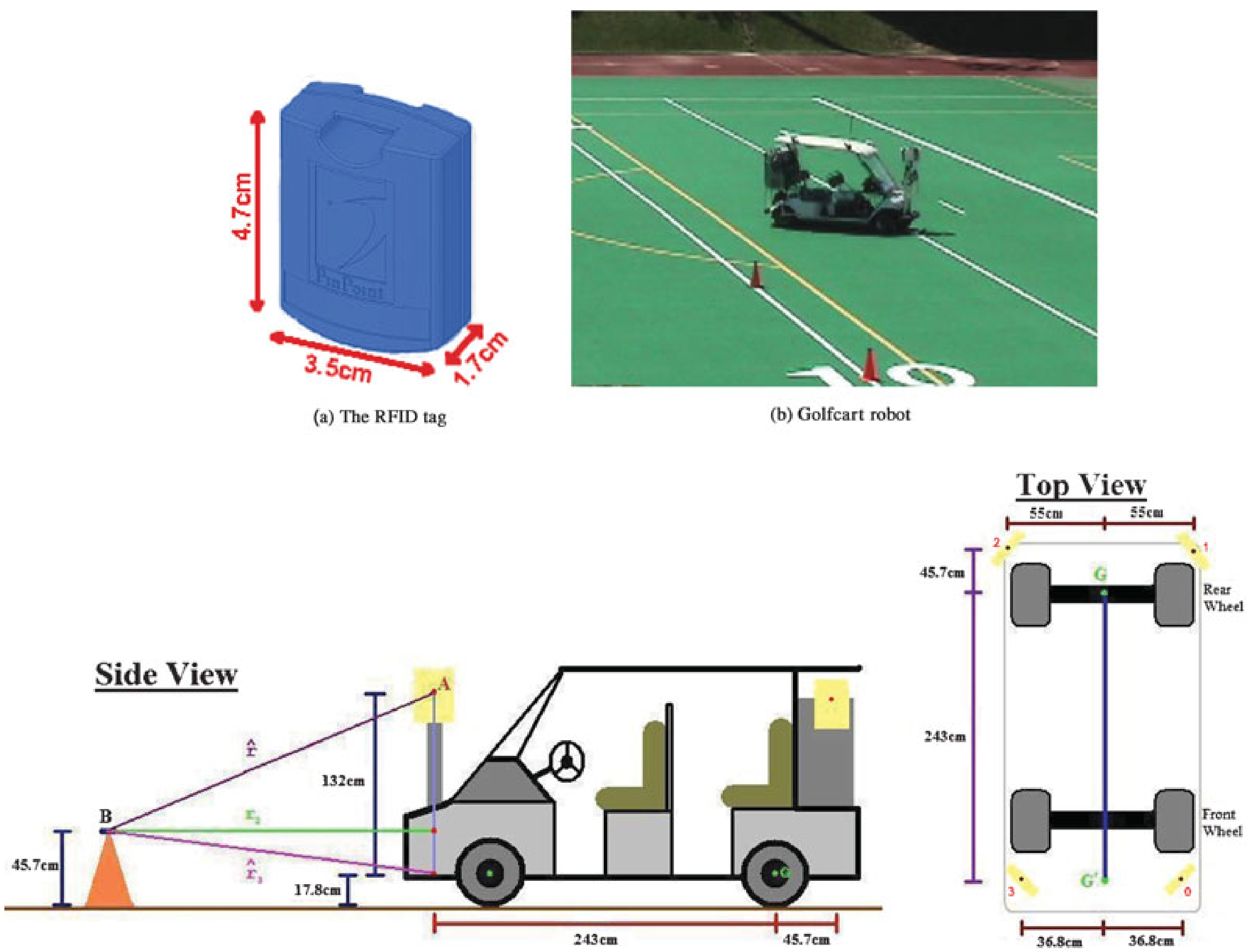
Table I. Plot and description of the different data sets. The numbers next to each node in the ground truth figure present the number of measurements received by the robot to the node.

Ground truth path	Dead-reckoned path	Data set name	Description
		Data set A1 RFID-based ranging	The robot traveled 3.7 km, receiving 2,565 range measurements. This path highlights the effect of heading error by turning in the same direction repeatedly.
		Data set A2 RFID-based ranging	The robot traveled 1.36 km, receiving 1,416 range measurements. This path minimizes the effect of heading error by balancing the number of left turns with an equal number of right turns in the robot's odometry.
		Data set A3 RFID-based ranging	The robot traveled 6.7 km, receiving 10,068 range measurements. This path consists of a very long trial in which the robot was driven in a random manner. To reduce the clutter, only the final 20% of the path is shown.
		Data set B1 UWB-based ranging	The robot traveled 1.9 km, receiving 3,529 range measurements. This path minimizes the effect of heading error by balancing the number of left turns with an equal number of right turns in the robot's odometry (a commonly used path pattern in lawn mowing applications).

(*Continued*)

Table I. (Continued)

Ground truth path	Dead-reckoned path	Data set name	Description
		Data set B2 UWB-based ranging	The robot traveled 1.3 km, receiving 1,816 range measurements. This path highlights the effect of heading error by turning in the same direction repeatedly.



(a) The RFID tag
(b) Golfcart robot
(c) System geometry side view
(d) System geometry top view

Figure 1. (a) The scale of the RF beacon used in our work. (b) The autonomous golfcart alongside traffic cones holding the beacons. (c) and (d) The antenna setup on the golfcart, which is critical to computation of the corrected range measurement to the robot's coordinate frame from the range reported by the antenna.

2.1.2. Data Set B: The Lawn Mower

Our second system utilizes UWB radio nodes from Multispectral Solutions to provide range measurements (MSSI, 2008). The ranging radios are equipped with an omnidirectional antenna, thus enabling a 360-deg ranging capability. These sensors use time of arrival of UWB signals to provide internode ranging measurements through walls. Once again the system produces a time-stamped distance estimate to the responding node, along with the unique ID number of that node and the ID of the node that received the response. Although this system is capable of measuring range between any pair of nodes, in our experiments only measurements between the mobile robot and the stationary nodes are computed. During data collection, the radio nodes are placed atop traffic cones approximately 138 cm above the ground.

Four of these radio nodes were placed around the environment, and one was placed on the robot. The node that is placed on the robot is placed directly on top of the center of the robot's coordinate frame. Additionally, the stationary nodes were placed on top of traffic cones at the same height as the node on the robot, thus removing the need to perform any coordinate transforms to align the odometry with the range measurements. Figure 2 shows the lawn mower robot used in our setup along with the UWB ranging radio.

3. RANGE DATA CHARACTERIZATION

3.1. Range Data

3.1.1. Data Set A: RFID System

Each time the robot logs a range measurement during one of our experiments, we can determine the error in that range, because we know the true location of the robot (to within 2 cm) and of the stationary tags (from surveying with GPS). Figure 3 shows plots from an example data set of the measurements against true ranges using these RF tags and their associated variances. The solid line in Figure 3(a) corresponds to the $y = x$ line when the measured range measurements are equal to the true measurements. Figure 3(b) shows that the variance of observed range measurements varies significantly based on range, thus making the range data challenging to model and use.

Antenna-Specific Characteristics: Directional information obtained from the robot's ground truth system allows us to observe the noise characteristics of the range measurements in relation to the incidence direction of the beacon to the antenna surface. Figure 4 presents the polar plot of the range error observed for measurements received from various directions for one of the four antennae on the robot. Each of the four antennae mounted on the robot, although rated as a directional antenna, displays a wide angle characteristic. Owing to their

(a) Radio node

(b) Lawn mower robot

Figure 2. (a) The UWB radio nodes used in our work. (b) The autonomous lawn mower.

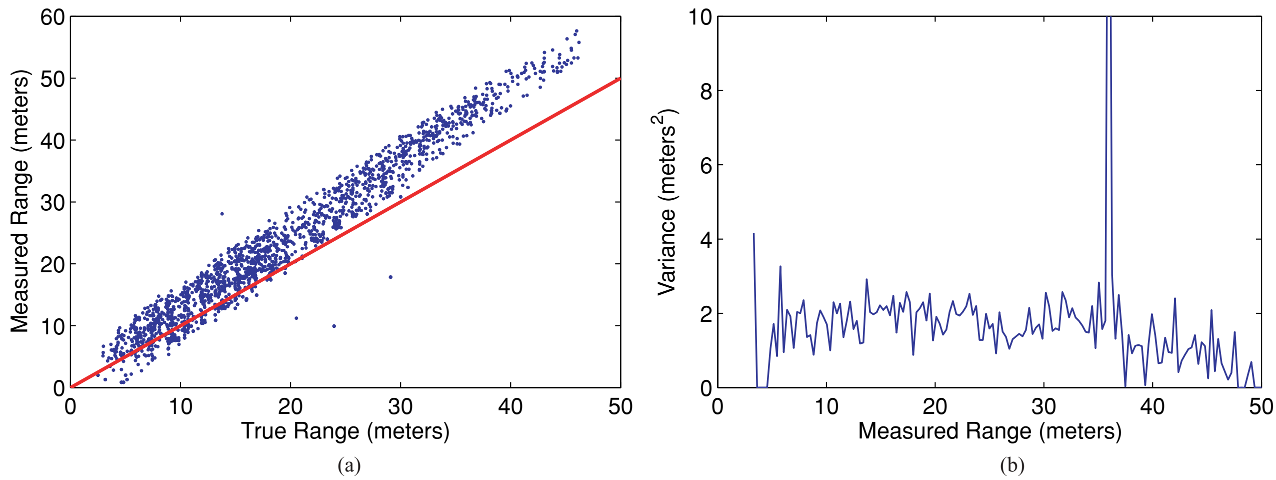


Figure 3. RFID ranging system: (a) A set of measured ranges plotted against the true measurements. The solid line represents the ideal case when the measured range equals the true range. (b) The variance associated with various measured ranges. The particular characteristics of the sensor and the nonuniform variance (uncertainty) in the range measurements can be observed.

near-omnidirectional range characteristics, we find that it might be beneficial to model each antenna as a fully omnidirectional ranging sensor.

3.1.2. Data Set B: UWB System

Once again for the second ranging system we can use the GPS ground truth data to compute the error in the range data. Figure 5 shows plots from an example data set of the measurements against true ranges using the UWB ranging radios and their associated variances. The solid line in Figure 5(a) corresponds to the $y = x$ line when the measured range measurements are equal to the true measurements. Figure 5(b) shows that the variance of observed range measurements is more or less constant.

Antenna-Specific Characteristics: Directional information obtained from the robot's ground truth system allows us to once again characterize the error in the range measurements in relation to the incidence direction of the beacon to the antenna. Figure 6 presents the polar plot of the range error observed for measurements received from various directions for the omnidirectional antennae on the radio. As can be expected, error is uncorrelated to direction of incidence, and thus there is no need for incorporating angle-based noise characterization.

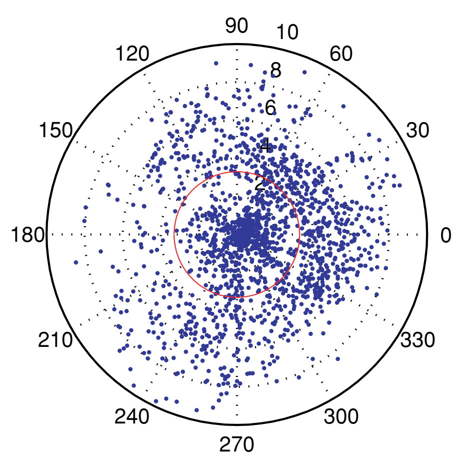
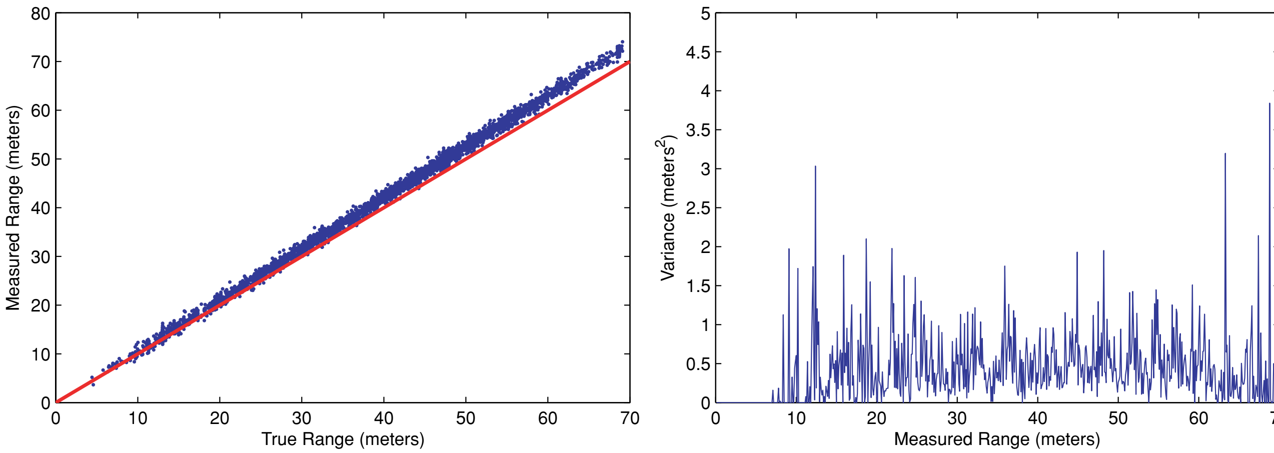


Figure 4. Polar plot showing the absolute range error and the beacon's angle relative to the antenna (computed from ground truth), for one of the four antennae on the golfcart. As can be observed, the antenna has an almost 360-deg field of view, making any angle of incidence–based noise modeling unnecessary.

4. DATA ACCESS AND INTERPRETATION

The data are available for download from http://www.frc.ri.cmu.edu/projects/emergencyresponse/RangeData. To ease the use of the data set, we have also supplied a Matlab-readable *.mat file for each data set, consisting of all the data parsed into individual array structures. The website also links to additional technical articles [such as Djugash & Singh, 2008, and Djugash, Singh, & Corke, 2005]



(a) (b)

Figure 5. UWB ranging system: (a) A set of measured ranges plotted against the true measurements. The solid line represents the ideal case when the measured range equals the true range. (b) The variance associated with various measured ranges. The particular characteristics of the sensor and the nonuniform variance (uncertainty) in the range measurements can be observed.

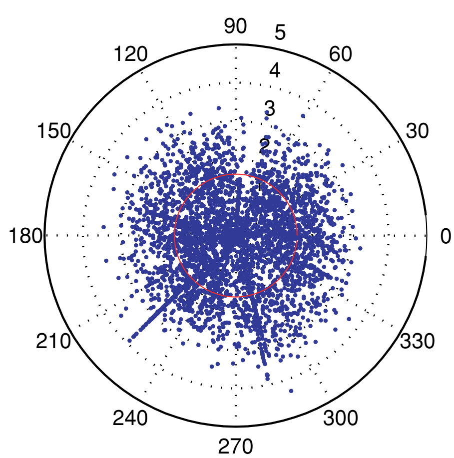


Figure 6. Polar plot showing the range error and the beacon's angle relative to the antenna (computed from ground truth), for the omnidirectional antenna on the UWB radios. As can be observed, the antenna has an almost 360-deg field of view, making any angle of incidence–based noise modeling unnecessary.

that have utilized these data sets to demonstrate the utility of various localization, tracking, and mapping methods.

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