# Wide Angle SAR Data for Target Discrimination Research

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## ABSTRACT

An airborne circular synthetic aperture radar system captured data for a 5 km diameter area over 31 orbits. For this challenge problem, the phase history for 56 targets was extracted from the larger data set and placed on a DVD for public release. The targets include 33 civilian vehicles of which many are repeated models, facilitating training and classification experiments. The remaining targets include an open area and 22 reflectors for scattering and calibration research. The circular synthetic aperture radar provides 360 degrees of azimuth around each target. For increased elevation content, the collection contains two nine-orbit volumetric series, where the sensor reduces altitude between each orbit. Researchers are challenged to further the art of focusing, 3D imaging, and target discrimination for circular synthetic aperture radar.

Keywords: SAR, 3D SAR, Wide Angle SAR

## **1. INTRODUCTION**

In August 2008, an airborne circulr synthetic aperture radar (SAR) collected data for 31 orbits of a 5 km diameter scene. The designed experiment included clusters of vehicles (such as those displayed in Figure 1), various individual vehicles, and geometric objects (such as trihedrals and tophats). Since the complete data set consists of many terabytes, we extracted 59 spotlights for the 31 sensor orbits to a phase history format that fits onto a DVD. These spotlights include 33 civilian vehicles, 22 reflectors, and an open area. There are three additional spotlights to cover areas associated with two of the targets that were moved during the experiment.

Prior public release challenge problems contain data related to a circular SAR. Among those are a data set<sup>1</sup> containing 8 orbits of spotlight phase history for a parking lot near the scene center. The lot contained several distinct identifiable vehicles. Also, in an effort to gain more insight into vehicles in a circular SAR application, the Civilian Vehicle (CV) Domes data set<sup>2</sup> contained 10 synthetically generated data domes. The large elevation and azimuth range of the CV Domes data set allow the researcher to create custom imagery that can simulate

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Figure 1. Six types of civilian vehicles were parked in three different areas during the data collection. The locations of the parking lots were designed such that vehicles experienced a variety of elevations with respect to the moving sensor.

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Figure 2. It is possible to generate a variety of imagery from the challenge data set. For example, a vehicle is imaged with a 5-degree aperture from its rear (a), driver side (b), front (c), and passenger side (d). A composite of 5-degree aperture images shows a 2D representation of the vehicle using a non-coherent sum (e) and a coherent sum (f).

a vehicle placed anywhere in a 5 km diameter scene. Alternatively, a vehicle could be simulated at the scene center with different sensor elevations with respect to the scene center.

Using the CV Domes data, Dungan and Potter<sup>3</sup> showed that a vehicles signature varies enough throughout a large scene to complicate target discrimination. The 2008 circular SAR data collection, associated with this challenge problem, contains repeated make and model vehicles placed in three parking lots near and away from the scene center (Figure 1). This allows researchers to compare the signatures of vehicles under a variety of sensor elevation conditions. In addition, there are seven confuser vehicles that are included during various orbits of the radar. Researchers are challenged to develop target discrimination algorithms that take advantage of the wide angle SAR.

An additional challenge associated with vehicle identification is generating well focused imagery. Location information for the targets is limited due to the accuracy of the altitude information of the target and a fine tuned location of the sensor. Researchers are challenged to develop algorithms that will determine more accurately the altitude of the ground under the target and to refine and focus the sensor location. The solution can be strictly data driven and/or take advantage of the 12 four-corner trihedrals that are scattered about the scene. For the 2006 dataset, a prominent point focusing algorithm, using a tophat, was applied to the local parking lot.<sup>1</sup> Researchers are challenged to find a more robust solution for focusing over the entire large scene.

Many of the targets in the 2008 data collection are stationary during most of the 31 radar orbits. Among those orbits are two separate nine-orbit volumetric series, where the sensor decreases in altitude between each orbit. This variation in altitude yields a variety of elevation angles between the scattering features of the stationary targets and the sensor. Extracting 3D information using wide-angle SAR may be useful for visualizations and target discrimination.<sup>4–9</sup> Also, the focusing problem may be enhanced by multipass 3D information generated from the data.<sup>10, 11</sup> Researchers are encouraged to apply existing algorithms and create new algorithms for extracting 3D and focusing information from this new data set.

The data set for this paper was extracted for spotlights that are large enough to contain the vehicles of interest. Example imagery for one of the vehicles from Figure 1 is shown in Figure 2. The images in Figure 2 (a)-(d) show selected 5-degree aperture images generated for the rear, driver, front, and passenger sides of the vehicle. The images in Figure 2 (e)-(f) show a composite of 5-degree aperture images summed over the entire sensor orbit, where (e) shows a sum of absolute values and (f) shows a coherent sum. The distribution contains a basic MATLAB imaging tool<sup>12</sup> for creating images from the provided phase history data.

The remainder of the paper is organized as follows. Section 2 provides a brief overview of the process that was used to extract the spotlight phase history from the full 5 km data set. Next, Section 3 details the organization of the released DVD along with a description of the included targets. Finally, Section 4 provides additional information and insight into challenges that can be investigated with the data.

# 2. SPOTLIGHT EXTRACTION

The radar used a sensor bandwidth of 599.9977 MHz with 21,232 frequency samples, which implies a frequency sample spacing of  $\Delta f = 28.2591$  kHz/sample. This results in an unambiguous range<sup>12</sup> in the slant plane of

$$R_0 = \frac{c}{2\Delta f} = 5.304 \text{ km},\tag{1}$$



Figure 3. As the sensor orbits the aimpoint, reflected information on the ground is associated with some piece of the range profile represented by the thick blue line in the side view. The entire scene shown in the top view is bounded by the beam pattern and the spherical wave fronts represented by the minimum and maximum ranges, Rmin and Rmax.

which, projected to the ground, is larger than desired illuminated 5 km scene.

With a center frequency of 9.7 GHz, the maximum sensor frequency is  $f_M = 10$  GHz. Thus, Maintaining an unambiguous cross-range<sup>12</sup> of  $X_0 = R_0$  requires an angular sample spacing of

$$\Delta \theta_0 = \frac{c}{2X_0 f_M} = 2.826 \times 10^{-6} \text{ rad/pulse.}$$
<sup>(2)</sup>

The data was collected with a constant pulse rate frequency of 8000 pulses per second; depending of the velocity of the sensor over the 31 orbits, the angular sample spacing varied in the range of 2 to  $4 \times 10^{-6}$  rad/pulse. The 21,232 complex double precision samples per pulse at a rate of 8000 pulses per second result in 2.718 GB of data each second. Due to the large amount of data, computational complexity, and variable sensor velocity, the phase history pulse data was interpolated to a uniform grid of 4000 pulses per degree or

$$\Delta \theta_0^t = 4.363 \times 10^{-6} \text{ rad/pulse.}$$
(3)

The sub-optimal angular pulse rate allows a small amount of high frequency aliasing, effectively raising the noise floor slightly.

For this challenge problem, we highly compressed the data in both range and cross-range into spotlights around targets of interest. First, the phase history data for each pulse is transformed to a range profile in the slant plane (as displayed in the side view of Figure 3) using a  $2^{17}$  zero padded shifted IFFT, which is just over 4 times oversampling. Next, the segment in the range profile that is associated with the desired target is extracted; the length of the segment in the range profile is determined by the extent of desired spotlight size on the ground. The minimum elevation between the ground and sensor in the 5 km illuminated patch is approximately  $35^{\circ}$ . Thus, a desired square region about a target on the ground with a side length *d* requires a sufficient segment length of  $R_s = d \ \overline{2} \cos 35^{\circ}$  in the slant plane. The segment is phase corrected to the target center and bins are linearly interpolated such that range bins in each pulse are aligned with respect to the target center. For computational simplicity, all target segments in the data set were extracted simultaneously during this step.

Due to the small spots, the angular sample frequency can also be reduced via decimation across range bins. To be on the conservative side, the unambiguous cross-range of the spot is designed as  $X_s = 1.2R_s$ . The decimation factor 1

$$M = \frac{\Delta \theta_{\rm s}}{\Delta \theta_{\rm 0}^{\rm f}} \quad , \tag{4}$$

where

$$\Delta \theta_{\rm s} = \frac{c}{2X_{\rm s} f_{\rm M}} \tag{5}$$



Figure 4. This is an example spotlight range profile encompassing a 10 m by 10 m scene. The azimuth extent shown over time is approximately 410 degrees. The periodic bright areas represent the rear, driver, front, and passenger sides of the vehicle.

is the required angular distance between pulses in the spotlight. The decimation with factor M is achieved using a downsampled polyphase low pass filter with a hamming window and a cutoff of  $\pi/M$  and  $0.4\pi/M$  transition band. The data set for this challenge problem contains targets that fit in  $5 \times 5$ ,  $10 \times 10$ , and  $15 \times 15$  square meter scenes. After decimation, the resulting phase history files contain approximately 10, 20, and 30 pulses per degree respectively. Targets near the edge of the scene will express more or fewer pulses per degree based on their proximity to the radar during its orbit.

An example spotlight range profile for one of the targets is shown in Figure 4. The images in Figure 2 a-d were generated from 5-degree backprojections around the cardinal vehicle angles. In Figure 4, the bright streaks at a quarter from the left represent the rear of the vehicle, at the half way point represent the driver side, at the three-quarter mark is the front of the vehicle, and finally the passenger side.

Finally, for storage and distribution, the data is transformed to the frequency domain by converting the range profile segments using a shifted FFT. The zero padding is removed, and the resulting files are relatively small. Each pulse of the phase history has been multiplied by a hamming window for side-lobe suppression during imaging; the user will need to window the frequency content over time based on the desired imaging aperture. Each phase history pulse is stored along with a sensor location that is referenced to the target center.

# **3. TARGET DETAILS**

This section describes details of the targets that are provided in the challenge problem data set. The DVD contains spotlight phase history for 33 vehicles. Some of the vehicles are the same make and model placed at different locations around the scene. The 31 sensor orbits are labeled in the range 214 to 244. Throughout these orbits, the vehicles vary in their pose and articulation. Some vehicles are present during the entire data collection, while others are only visible for a few orbits. The data set also contains one continuously empty area and 22 reflector targets such as dihedrals, trihedrals, and tophats.

# 3.1 Vehicles

The primary vehicle experiment contains 26 vehicles from 6 classes. The vehicles are parked in 3 parking lots, facilitating the comparison of same class vehicles at different locations with respect to the sensor. Figure 5 shows an example image for each of the 6 vehicle classes, and Figure 1 shows a radar image of vehicles as they are parked in the 3 lots. Detailed information about the 26 vehicles (and one open area) is provided in Table 1 in six columns. The first column is a label that is used to identify the vehicles in the data files on the DVD, while the second column shows the actual make and model; all vehicles were rental cars from the 2008 model year. The third column lists the physical dimensions of each vehicle.<sup>13</sup>

All vehicle and sensor locations are stored in an Earth/North/Up (ENU) Euclidean coordinate system with a primary origin at the SAR aimpoint. Column 4 of Table 1 provides the location of each target's individual origin



(a)

(b)

(c)



Figure 5. Six models, including sedans, SUVs, and a minivan, were included in the data collection. The vehicles in (a)-(c),(e), and (f) were repeated in three different parking lots, while five versions of (d) were parked in the center lot.

Table 1. Repeated Vehicles

| Label  | Make/Model              | (L,W,H) meters     | (E,N,U) meters            | Size | Rotation       |
|--------|-------------------------|--------------------|---------------------------|------|----------------|
| fcarA1 | Chevrolet Impala LT     | (5.09, 1.85, 1.49) | (-57.56,185.00,-0.76)     | 10   | moved 234      |
| fcarA2 | Chevrolet Impala LT     | (5.09, 1.85, 1.49) | (-201.53,1119.13,-1.84)   | 10   | CW 90°234      |
| fcarA3 | Chevrolet Impala LT     | (5.09, 1.85, 1.49) | (-1869.46,-547.55,-5.53)  | 10   | CW 90°220      |
| fcarB1 | Mitsubishi Galant ES    | (4.85, 1.84, 1.47) | (-46.16,154.53,-0.56)     | 10   | none           |
| fcarB2 | Mitsubishi Galant ES    | (4.85, 1.84, 1.47) | (-212.69, 1104.33, -1.83) | 10   | CW 90°234      |
| fcarB3 | Mitsubishi Galant ES    | (4.85, 1.84, 1.47) | (-1845.58,-534.37,-5.52)  | 10   | CW 90°220      |
| fsuv1  | Toyota Highlander       | (4.79, 1.91, 1.73) | (-49.85,164.71,-0.66)     | 10   | moved 234      |
| fsuv2  | Toyota Highlander       | (4.79, 1.91, 1.73) | (-214.84,1116.25,-1.84)   | 10   | CW 45° 234     |
| fsuv3  | Toyota Highlander       | (4.79, 1.91, 1.73) | (-219.00,1129.04,-1.84)   | 10   | 180°234        |
| fsuv4a | Toyota Highlander       | (4.79, 1.91, 1.73) | (-1886.73,-535.48,-5.54)  | 10   | CW 45° 234     |
| fsuv4b | Toyota Highlander       | (4.79, 1.91, 1.73) | (-1889.73,-536.48,-5.54)  | 10   | CW 45° 234     |
| fsuv5  | Toyota Highlander       | (4.79, 1.91, 1.73) | (-1868.35,-528.97,-5.53)  | 10   | articulate 234 |
| mcar1  | Chevrolet HHR LT        | (4.76, 1.76, 1.60) | (-89.82,202.16,-0.96)     | 10   | articulate 234 |
| mcar2  | Chevrolet HHR LT        | (4.76, 1.76, 1.60) | (-84.93,189.42,-0.86)     | 10   | articulate 234 |
| mcar3  | Chevrolet HHR LT        | (4.76, 1.76, 1.60) | (-80.22,176.72,-0.76)     | 10   | articulate 234 |
| mcar4  | Chevrolet HHR LT        | (4.76, 1.76, 1.60) | (-71.11,153.61,-0.66)     | 10   | articulate 234 |
| mcar5  | Chevrolet HHR LT        | (4.76, 1.76, 1.60) | (-74.92,163.82,-0.76)     | 10   | none           |
| msuv1  | Pontiac Torrent         | (4.80, 1.81, 1.76) | (-54.18,174.16,-0.66)     | 10   | moved 234      |
| msuv2  | Pontiac Torrent         | (4.80, 1.81, 1.76) | (-197.54,1107.16,-1.83)   | 10   | CW 90°234      |
| msuv3  | Pontiac Torrent         | (4.80, 1.81, 1.76) | (-1933.50,-558.89,-5.55)  | 10   | moved 226      |
| msuv4  | Pontiac Torrent         | (4.80, 1.81, 1.76) | (-1920.34,-546.24,-5.55)  | 10   | moved 226      |
| msuv5  | Pontiac Torrent         | (4.80, 1.81, 1.76) | (-1903.12,-544.63,-5.54)  | 10   | CW 90°234      |
| van1   | Chrysler Town & Country | (5.14, 1.95, 1.75) | (-38.65,186.40,-0.66)     | 10   | moved 234      |
| van2   | Chrysler Town & Country | (5.14, 1.95, 1.75) | (-185.17,1122.36,-1.84)   | 10   | CW 45° 234     |
| van3   | Chrysler Town & Country | (5.14, 1.95, 1.75) | (-187.99,1137.15,-1.84)   | 10   | 180°234        |
| van4   | Chrysler Town & Country | (5.14, 1.95, 1.75) | (-1905.44,-560.67,-5.54)  | 10   | none           |
| van5   | Chrysler Town & Country | (5.14, 1.95, 1.75) | (-1882.86,-554.84,-5.54)  | 10   | none           |
| open   | Empty asphalt           | N/A                | (-78.52,214.16,-1.07)     | 10   | N/A            |

Table 2. Unique Vehicles

| Label/info               | Orbits   | (E,N,U) meters            | Size |
|--------------------------|----------|---------------------------|------|
| 1992ChevyBlazer          | 214      | (-441.63,800.68,-1.90)    | 10   |
| 1998AcuraTL              | 214-234  | (-143.40, 1145.37, -1.84) | 10   |
| 2000DodgeDurango         | 214, 219 | (877.07,141.93,38.93)     | 10   |
| 2000FordWinstarVan       | 214-219  | (1291.27,571.74,53.41)    | 10   |
| 2001F150SuperCrewPUtruck | 227-233  | (1554.12, 1.30, 55.50)    | 10   |
| 2005HyundaiSonata        | 214      | (-441.08,804.85,-1.90)    | 10   |
| panel_truck              | 214-244  | (-67.52,202.16,-0.76)     | 15   |



Figure 6. RF reflectors were place in various locations during the data collection. The reflectors include (a) a dihedral, (b) 5 inch quad-trihedrals, (c) a Bruderhedral, (d) top hats, and (e) 2 ft quad-trihedrals.

in meters with respect to the aimpoint. As described in Section 2, each target file in the data set is spotlighted, phase corrected, and stored as an independent phase history with its own origin; the sensor coordinates are stored with respect to each target. The elevation of the ground under each target is only accurate to around a meter. In addition, the data revealed orbit to orbit focusing errors on the order of 1-2 meters, predominantly in the Up coordinate. The ENU coordinate of each local origin tends to be below the ground under the target by around a meter; thus an image plane generated on the target's origin would yield image layover in the direction of the sensor. The unambiguous range and cross-range for each target was designed such that all scattering from the target would backproject into a square image at the origin with a side length in meters of size shown in column 5 of Table 1.

The final column of Table 1 provides information about vehicle movement during the data collection. Beginning with orbit 214, all vehicles are stationary; during the experiment, some of the vehicles are moved. For example, "CW 90° 234" means that the vehicle was rotated clockwise at orbit 234. Some vehicles were moved completely from the spotlight as indicated with "moved". The vehicle fsuv4 was rotated, but not placed inside the same spotlight; hence, it was included in two overlapping spotlights fsuv4a and fsuv4b. Finally, mcar1-4 undergo articulations after orbit 234 including: mcar1 windows rolled down, mcar2 trunk opened, mcar3 driver door opened, and mcar4 mat draped over part of roof and driver window (it fell of later at an unknown time).

In addition to the 26 vehicles in Table 1, Table 2 provides information for 7 unique vehicles. Most of these vehicles were involved in moving experiments; however, they were stationary for the orbits indicated in column 2. Column 3 shows the ENU coordinate of the spotlight with respect to the aimpoint, while column 4 shows the designed square image plane side in meters.

# 3.2 Reflectors

Spotlight phase history data for various RF reflectors is included in the data set. Figure 6 displays several examples of the targets including a dihedral (a), 5 in quad trihedral (b), bruderhedral (c), tophat (d), 2 ft quad trihedral (e), and a small corner reflector (not pictured). (The 5 in and 2 ft for the quad trihedrals indicates that each face of each trihedral is 5 in  $\times$  5 in and 2 ft  $\times$  2 ft squares respectively.) Table 3 details the reflectors with labels and descriptions in the first two columns. The third column shows ENU coordinates in meters for

Table 3. Reflectors

| Label      | Description            | (E,N,U) meters            | Size |
|------------|------------------------|---------------------------|------|
| brud       | Bruderhedral           | (-106.08,1156.90,-1.54)   | 5    |
| dihed      | Small dihedral         | (-99.02,1165.59,-1.53)    | 5    |
| scr1       | Small corner reflector | (-102.72,1166.82,-1.54)   | 5    |
| str01 _1   | 5 in quad trihedral    | (-110.88,1166.69,-1.54)   | 5    |
| str02 _1   | 5 in quad trihedral    | (-94.24,1165.93,-1.54)    | 5    |
| tophat1    | Tophat 1 stationary    | (-97.51,1155.46,-1.62)    | 5    |
| tophat2a   | Tophat 2 214-223       | (13.48,1247.49,-2.42)     | 5    |
| tophat2b   | Tophat 2 224-241       | (-89.11,1145.26,-1.82)    | 5    |
| tophat3    | Tophat 3 stationary    | (17.28,1247.49,-2.42)     | 5    |
| tophat_2_3 | Tophats 2 and 3        | (14.98,1247.49,-2.42)     | 10   |
| tri01      | 2 ft quad trihedral    | (341.57,1621.29,2.58)     | 5    |
| tri02      | 2 ft quad trihedral    | (986.19,1397.11,40.59)    | 5    |
| tri03      | 2 ft quad trihedral    | (1039.74,11.29,43.88)     | 5    |
| tri04      | 2 ft quad trihedral    | (1323.79,658.40,53.62)    | 5    |
| tri05      | 2 ft quad trihedral    | (1839.02,-744.16,57.56)   | 5    |
| tri06      | 2 ft quad trihedral    | (582.59,-1516.74,31.62)   | 5    |
| tri07      | 2 ft quad trihedral    | (281.79,-761.67,11.17)    | 5    |
| tri08      | 2 ft quad trihedral    | (-1121.28,-1185.75,-0.08) | 5    |
| tri09      | 2 ft quad trihedral    | (-467.17,-724.69,1.58)    | 5    |
| tri10      | 2 ft quad trihedral    | (-1648.05,-751.59,-4.85)  | 5    |
| tri11      | 2 ft quad trihedral    | (-1837.86,-261.15,-4.93)  | 5    |
| tri12      | 2 ft quad trihedral    | (-1626.30,1251.18,-8.59)  | 5    |
| tri13      | 2 ft quad trihedral    | (-1042.78,841.32,-4.21)   | 5    |
| tri14      | 2 ft quad trihedral    | (-642.23, 1061.40, -3.55) | 5    |

the target locations with respect to the aimpoint. The ENU coordinates were derived from GPS information and are accurate within 1-2 meters. All of the physical scattering components of each target are contained within the spotlighted region. The final column shows the square image size that will comfortably fit in the spotlight with a side length in meters.

The reflector targets are starionary during the 31 orbits of the data collection except for tophat2. During orbits 214-223, tophat2 is placed near tophat1 and moved progressively away as follows: begin 6' 10" apart, at orbit 217 moved to 9' 10" apart, at orbit 218 moved to 11' 4" apart, at orbit 220 moved to 12' 10" apart, at orbit 221 moved to 14' 4" apart, and at orbit 222 moved to 15' 10" apart. With few exceptions, the target label and the spotlight label are the same. The spotlight labeled tophat2 awatches the area around tophat2 as it is moved, while tophat\_2.3 watches a larger area with both tophat2 and tophat3 in the scene. Eventually, at pass 225, tophat2 is moved to the spotlight identified with label tophat2b for the remainder of the data collection.

The 14 2-ft trihedrals are place over a large area as represented in Figure 7. These targets are designed for calibration research.

## 3.3 Files and Imaging

The top level of the DVD contains a descriptive document called "Readme.pdf" along with the four directories including:

- Data 59 target directories each with 31 MATLAB binary files
- Utilities MATLAB codes for image processing and \*.mat files containing related data
- Images Select images generated with this data set and code
- Documentation This conference paper and listing of all files on this DVD

The phase history data is organized into a set of folders and identified using the format Data/{target label}/PH\_{target label}\_{orbit ID}.mat. For example, the phase history data corresponding to the dihedral reflector with label "dihed" during orbit 225 will be located on the DVD as Data/dihed/PH\_ dihed\_ 0225.mat. Each MATLAB file contains phase history, frequency values, and an ENU sensor location relative to the target.

The DVD includes two MATLAB files in the utilities directory called bpGUI.m and bpBasic\_v2.m to assist users in visualizing the data. These codes should be copied to a local disk drive since they require write permission to perform optimally. The file bpBasic\_v2 is a modified version of bpBasic<sup>12</sup> function with additional capabilities that include the generation of sub-aperture images; bpGUI is a MATLAB script that interfaces to bpBasic\_v2

#### Table 4. Parameters in bpGUI



1. The value for the Image size in meters is listed for each target in the tables.

- A typical value for pixel density is 16 pixels per meter. For 5 meters that would be 80 pixels.
- 3. For each sub aperture image generated, the aperture size can be specified.
- 4. The interval is how frequent an image is generated. Sub aperture images can overlap in which case a pulse will contribute to more than one image. If the interval is set larger than the aperture size, a pulse will contribute to only one image. In this example, an image is generated every 5 degrees with no gaps between images.
- 5. The image plane height can be adjusted to offset the image plane above or below the center. This may be useful in conducting auto focusing studies.
- 6. Sets the dynamic range for plotting results.
- 7. This last value defines an oversampling factor for the ifft operation via zero padding; a typical factor is 4. Alternatively, to set a fixed size ifft, simply enter it as a negative number and the code will adjust it accordingly.

with user input via two simplified GUIs and creates images. Results are passed back to the MATLAB workspace for further analysis. The first GUI in bpGUI is a file browser that allows the user to select one of the \*.mat phase history data files for processing, and the second GUI allows the user to input several parameters described in Table 4.

## 4. CHALLENGES

A primary purpose for releasing this challenge problem is to advance the art of SAR target discrimination. Some target discrimination algorithms may benefit with improved focusing and 3D information. Thus, in this section, researchers are challenged to develop new or apply existing focusing and 3D methods to the new data set, which may be intermediate steps necessary for a robust target discrimination. However, some researchers may present target discrimination algorithms that work well without additional focusing and 3D processing. The following sections motivate the development of focusing, 3D, and target discrimination algorithms to the challenge data set.

## 4.1 Target location and sensor focusing

Radar image formation algorithms combine returns over the synthetic aperture to produce images which greatly exceed the resolution of the real antenna beam. In order to fully realize the benefits of coherently combining these returns, the correct data response for each candidate voxel must be accurately modeled. A crucial component of this voxel-wise impulse response is precise knowledge of the sensor position relative to the voxel in question over the synthetic aperture. Ideally, we require the 3D position of both the sensor at the time of each pulse transmission along with an accurate topological model for the ground patch of interest. Here we challenge researchers to address both of these problems for the Gotcha data set.

Most SAR processing computes a single phase correction for each pulse to address residual phase errors after motion compensation. Common approaches include techniques<sup>14</sup> like map drift, prominent point processing, and phase gradient autofocus. Other techniques attempt to maximize a sharpness metric for the image,<sup>15-17</sup> or to leverage subspace approaches.<sup>18</sup> However, these one-dimensional corrections are only valid over a sufficiently small scene. Furthermore, they do not allow correction of the 3D position of the sensor platform. The airborne circular SAR concept requires processing returns from multiple successive passes, further complicating the autofocus challenge. Lee-Elkin provides a discussion of using data from multiple radar orbits to do interferometry and autofocus.<sup>19</sup> It is worth mentioning that the phase corrections computed by autofocus algorithms can correct effects other than position errors, including propagation effects.

The challenge for the Gotcha data set is to focus the formed imagery while simultaneously improving estimates of the platform motion. A more general problem might also include motion estimation for moving targets in



Figure 7. The location of the 14 2ft quad trihedrals is shown on a Google map<sup>20</sup> that is centered on the SAR aimpoint.



Figure 8. A 2ft quad trihedral return is displayed over approximately 7m of range for 7 orbits. The range to the stationary target drifts on the order of 1-2m. A composite backprojection image of 5-degree apertures is shown under the range profile for each orbit.

the scene if present or assume that no initial guess for the platform motion is available. Researchers might consider data-driven approaches using sharpness or entropy metrics possibly combined with parametric models for platform motion. Alternatively, the scene contains a set of four-corner trihedral reflectors depicted in Figure 7. A generalization of prominent point processing utilizing these known reflectors could be employed to estimate phase corrections at each of these locations. These estimates could be combined to estimate errors in platform motion. Tracking of these targets in phase history data would also allow the application of methods based on the theory of geometric invariants, such as the technique developed by Ferrara and Arnold.<sup>21</sup>

A second challenge is to improve the image focus by estimating the topology of the ground over the scene of interest. As depicted in Figure 8, an incorrectly assumed height results in defocusing of a point-like target. Researchers are challenged to develop an approach for correcting the topology estimates in concert with motion estimation. The problems of autofocus and height estimation using phase differences between multiple looks, so called interferometric processing, are coupled as discussed by Lee-Elkin.<sup>19</sup> Vertical resolution can also be obtained by combing data over a wide viewing aperture from a single pass.<sup>22</sup> Approaches combining ideas from



Figure 9. The data collection includes two sets of volumetric data consisting of nine orbits each. In (a) the sensor path is represented in 3D for orbits 225-233, while (b) displays a side view of orbits 225-233 and (c) displays a side view of orbits 235-243.

both wide viewing angles, the confocal imaging perspective, and multiple passes, the interferometric perspective, might yield interesting approaches to this challenge problem.

## 4.2 3D imagery from multiple orbit SAR

Traditional SAR imagery produces a 2D map of the electromagnetic reflectivity of a scene. The 2D map, however, can suffer from significant distortion due to layover effects wherein elevated targets not lying on the 2D focus plane are projected onto the plane in a manner that depends on the target's height and the sensor elevation angle (for e.g., see Sec. 4.3 and Fig. 10). Alternatively, 3D imagery enables a more general scene model supporting elevated targets without layover effects. The reduced distortion and additional information provided by 3D imagery is useful in a number of applications, including tomographic mapping, foliage penetration,<sup>23</sup> target discrimination, and general scene visualization.

Estimating target locations in a third (height) dimension generally requires additional data collection efforts providing a diversity of measurements in the elevation dimension. In spotlight mode SAR, this is typically accomplished by multiple orbits at slightly different elevation angles(see Figure 9). There are, however, a number of challenges frequently encountered in forming 3D images: 1) Sampling in the elevation dimension is usually sparse due to the large time and operational demands involved in elevation sampling; When using traditional unconstrained Fourier imaging, this results in low resolution in the elevation dimension due to a broad main lobe in the point spread function in this dimension. 2) For realistic flight paths, sampling in elevation is typically not uniform; eliminating the ability to use standard array processing methods based on this assumption. 3) Elevation sampling is not constant throughout the circular passes. 4) For large synthetic apertures, realistic targets do not persist over the collection window, thus violating the isotropic assumptions typically made in tomographic imaging. For limited spot sizes, these challenges have been addressed by a number of researchers and signal processing approaches, including incoherent subaperture combining<sup>8, 24</sup> (for anisotropy), sparse reconstruction methods<sup>8, 25, 26</sup> (for data sparsity), and resampled subspace methods<sup>27</sup> (for irregular sampling). See, e.g., the recent papers by Austin<sup>8</sup> and Zhu,<sup>28</sup> and references therein, for a survey of 3D methods for limited spot sizes.

The phase history provided in the current data set includes two volumetric passes appropriate for 3D target and scene reconstruction, however there are a number of additional challenges associated with the large scene size. Related to Sect. 4.1, a method of autofocusing the data is required as the data are not coherent between passes. Additionally, for large scene sizes, the point spread function is location and aspect-angle dependent. Thus, wide-angle 3D imaging based on subaperture combining—including varieties of IFSAR, Tomo-SAR, and sparse reconstruction—will require new approaches to combine subapertures of disparate resolutions.

As 3D reconstructions are frequently used as inputs in target discrimination and decision making algorithms, researchers are encouraged to develop reconstruction approaches that quantify their uncertainty about 3D predictions. It is expected that the method of encoding uncertainty will depend on the 3D representation used, e.g.,



Figure 10. From left to right fsuv2,3,1,5,4 expresses different layover based on its proximity to the scene center as shown in these composite images. For example on the left, fsuv2, on the north edge of the scene, shows a bulge to the north. Sensor defocus and imprecise ground altitude can also change the shape.

parameterized surfaces, voxel occupancy, or collections of 3D point scatterers. No single representation is suggested, as, it is itself a challenge problem to explore the merits of various 3D representations with respect to their ability to incorporate prior knowledge about the scene, support tractable estimation methods with uncertainty characterizations, and facilitate incorporation with target discrimination algorithms.

## 4.3 Civilian vehicle target discrimination

The large field of view and data rates of modern imaging systems necessitate a system of target discrimination. The current state of target discrimination performance is, however, limited by our rate and effectiveness in exploiting image products—not by sensor coverage rates. As such, the development of improved target discrimination algorithms continues to be of interest. By providing measured SAR data of real-world targets in relevant environments, this data set is expected to facilitate the development and evaluation of SAR-based target discrimination algorithms.

For target discrimination, the most appropriate targets in this dataset are the civilian vehicles, which, relative to typical military vehicles, generally have lower radar cross sections and require greater observation apertures for effective discrimination.<sup>29</sup> As outlined in Table 1, phase history data are available for 26 vehicles distributed throughout the observation spot. Each vehicle belongs to one of the six model classes {Chevrolet Impala LT, Mitsubishi Galant Es, Toyota Highlander, Chevrolet HHR LT, Pontiac Torrent, Chrysler Town & Country}, and all vehicles within a model class are approximately identical (same year, same trim, potentially different color). As such, a subset T of the vehicles may be used in training an target discrimination algorithm and the balance  $T^c$ —which may include identical targets at different positions and orientations within the scene—can be used for testing.

The large spot size of the radar in this collection, and the wide apertures dictated by civilian vehicles, make the dataset particularly interesting and relevant for target discrimination challenge problems due to spatially varying levels of defocus and distortion. One particular challenge presented by the large spot size is the variation in layover effects resulting from differences in sensor elevation angles for targets in different portions of the scene. Thus, for example, otherwise identical targets will appear differently at scene center than at the edge of the spot (see Figure 10). The dataset supports a variety of operating conditions (OCs) that the researcher is encouraged to consider in developing and testing target discrimination algorithms. Sensor OCs include bandwidth, azimuth aperture, and elevation aperture. Any of these quantities may be selectively limited in order to 1) consider performance as a function of the data used (e.g., bandwidth, aperture size, aperture location relative to target), and 2) consider performance under scenarios of train-test discrepancy. For example training could be done at one elevation angle while testing is done on a different pass at a different elevation angle.

The availability of multiple identical targets also enables the dataset to provide a variety of target OC variables whose impact on target discrimination performance can also be explored in a manner similar to, and simultaneously with, the sensor OCs above. Target OCs include orientation, relative position in the scene, and limited target articulations and perturbations. Related challenges include identifying targets with OCs that differ from the training set, such as articulated targets or targets with apparent changes related to spatial location. Researchers are particularly encouraged to incorporate physical models with training methods in order to generate target discrimination algorithms that are robust to variations within the model—without requiring

training exemplars over the OC dimensions of the model. For example, a model describing apparent feature variation as a function of in-spot target location would only require training data from a single location, such as the scene center.

The dataset includes phase history data for all targets, thus allowing researchers to adopt an imaging method of their choice (polar format algorithm, backprojection, etc.). Similarly, features have not been provided for the targets in order to encourage the research community to explore different types of features (e.g., templates,<sup>30</sup> or attributed points<sup>3</sup>) and their utility in the target discrimination problem.

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