**CAMWAR Model**

1. **Overview**

The CAMWAR model should include tree basic parts: environment scene model, radar model, and radar imaging.

1. Environment scene should include:
2. discrete targets, such as pole, car, helicopter, drone, wires, etc.
3. distributed objects, such as ground, road, etc.
4. volumetric scatterers, such as rain, clouds and brownout.
5. Radar model should include:
6. Antenna beam model and the beam projection model
7. Signal and noise calculation in single coherent processing interval (CPI) cycle based on expected CAMWAR radar specs
8. Doppler processing
9. Threshold selection and detection
10. Binary integration, or m of n processing
11. Doppler beam sharpening mode
12. Analog and digital scan
13. Monopulse operation.
14. Radar imaging provides radar “vision” of the environment objects limited by the radar sensitivity and resolutions and should include:
15. PPI and 3-D perspective view modes
16. 3-D terrain mapping algorithm
17. Elevated target positioning on the 3-D image.
18. **Radar environment scene model**

We can assume the compact objects, like a poles, cars, or helicopter, as **discrete objects**, which differ only with RCS value. Let’s assume RCS of the pole equaled 1m2 (0dBm2) and no fluctuated. The cars and helicopter would have 10dBm2 as average value and be fluctuated with aspect angle and frequency. The type drone has about -10dBm2 RCS. Fluctuated target model should be built as randomly distributed point scatterers with total volume size fitted to target dimensions. The poles staying along highway sides, cars are moving on the highway, and helicopter and drone are flying around. The moving cars, helicopter, and drone will have different from clutter Doppler values, which allow to separate them from ground or volumetric clutter.

Radar airborne platform would be either hanging over the ground or flying linearly with constant speed. Altitude of the platform may vary from 30m to 300m.

Flat **ground model** may be used for simplicity. Reflectivity of the ground for any specific radar beam is statistical value with exponential relative probability distribution. Statistically average reflectivity value is proportional to the surface elimination area and , where is ground scattering coefficient and is grazing angle at the surface in radian. For rough farmland ground, W-band and E-band the typical value of the = -10dB/m2. Surface elimination area by the radar beam and for single range bin is equal to , where R is range from the surface to the radar, is radar range resolution, and is radar beamwidth in horizontal direction (2° nominally). Thus, the ground RCS is determined with following expression:

We expect to have varied from 0.5m to 2m, depending on mode of the operation, and = 2⁰ (0.035 rad).

We can add road (highway) to the surface model. Width of the highway is about 30m (100 feet) and surface reflectivity coefficient in 20dB below rough ground reflectivity.

RCS of the **volumetric scatterers** is calculated by using next formula:

Where is volume reflectivity coefficient, and is radar vertical beamwidth (4° nominally).

For 77 GHz frequency the value of rain reflectivity coefficient is equal to 1.15\*10-4m2/m3 for 1 mm/h rain rate, 2.5\*10-4 m2/m3 for 3 mm/h rain rate, and 5.82\*10-4 m2/m3 for 10 mm/h rain rate as follow from the book: “Range Equations for Modern Radar” by David K. Barton.

Typical clouds reflectivity coefficient of the clouds is 1.05\*10-8 m2/m3.

Rain and fog attenuation effects will be considered in the radar model section.

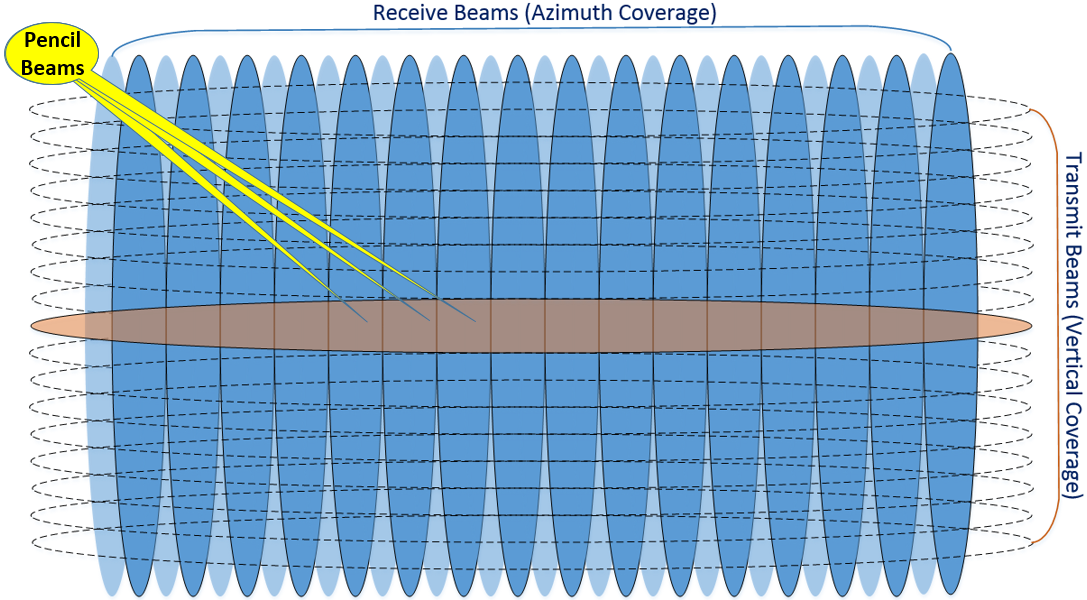
As mentioned in NATO RTO technical report (Rotary-Wing Brownout Mitigation: Technologies and Training, 2012) the millimeter wave radars have been demonstrated to have negligible attenuation in

dust. However, the brownout dust clouds reflectivity is not reported. Probably because it doesn’t look as a problem. The ability to see through dust reported continuously as major benefit of the millimeter wave radar. Although, information obtained from private conversation with engineers participated in Sandblaster and HALS tests of the 94 GHz radar programs (Sierra Nevada Corp.) give us knowledge that the brownout clutter is high enough to effect on radar sensitivity, the absence of the trusted data force us to assume the factor as negligible.

1. **Radar model**

**3.1** **Antenna beam and the beam projection model**

CAMWAR radar beam has been created by multiplying of the transmit and receive fan-type beams, as shown on the drawing below.



The wide in azimuth and narrow in elevation transmit beam is scanning in elevation from boresight to -30⁰ as results of analog beamforming (phased array) operation. It can be expressed as follows:

where is azimuth angle relatively antenna boresight, is elevation angle relatively to boresight, is transmit antenna gain nominally equaled to 100 (20dB), - transmit azimuth beamwidth nominally equaled to 1.05 rad (60⁰), and - transmit elevation beamwidth nominally equaled to 0.07 rad (4⁰).

The narrow in azimuth and wide in elevation receive beam is result of digital beamforming and MIMO parallel operation, which cover +/-30 degree in azimuth. The fixed wide elevation beam is tilted to -10⁰ (0.175 rad) relatively to horizon. The receive beam can be expressed as follows:

where is receive antenna gain nominally equaled to 640 (28dB), - receive azimuth beamwidth nominally equaled to 0.035 rad (2⁰), and - receive elevation beamwidth nominally equaled to 0.52 rad (30⁰).

Thus, the resulted two-way radar beam is equal to .

If projected to the ground, effective illumination area on the ground will be stretched in the range direction proportionally to the cosine of the incident angle.

**3.2** **Signal and noise calculation in single CPI**

Radar unit SNR is calculated by using basic radar equation for pulse-Doppler radar and discrete target:

(4π)3

Where is total transmit power (0.76W nominally), are gain of the transmit and receive antennas consequently as function of the azimuth angle (see antenna beam section for details), is coherent processing interval (10-3s nominally), is wavelength for 77 GHz, is RCS of the discrete or distributed target, R is range to the target, k = 1.38 x 10-23 is Boltzmann constant, T=290K is standard temperature, NF – noise figure of the radar receiver (4dB or 2.5 in linear scale nominally), and – radar total losses (4dB or 2.5 in linear scale nominally), is clear weather atmospheric attenuation, is rain attenuation as function of the rain rate (rr), and is fog attenuation as function of the water content M (g/m3).

For MATLAB model radar signal and noise will be calculated separately. For discrete fluctuated target, energy of the signal at the radar receiver input during single CPI cycle is equal to:

(4π)3

where is target RCS for different frequency carrier (F) and aspect angle (Θ). Fluctuated target model should be built as randomly distributed point scatterers with total volume size fitted to target dimensions.

Radar receiver noise will be simulated in MATLAB by using Monte Carlo algorithm. Root mean value (RMS) of the noise should be equal to .

Atmospheric attenuation in clear weather and on sea level altitude is equal to 0.8 dB/km for 77 GHz, or in linear scale

Rain attenuation coefficient in dB/km is determined by using following expression [REF]:

where a=0.85 and b=0.79 for 77 GHz

Thus, , , and

In linear scale in or , and .

Fog attenuation coefficient [REF] in dB/km is proportional to water content M (g/m3) and equal to . For dense fog with 50 m visibility the M=0.5, and for moderate fog with 300 m visibility M=0.05. Thus, in linear scale the fog coefficients are equal to 1.38 for dense fog and 1.033 for moderate fog.

**3.3** **Doppler processing**

Radial velocity resolution, provided by Doppler processing, allows to separate moving targets such a car, helicopter, or drone from strong reflection of the still objects, when other remedies for the separation like angular and range resolutions appear as not enough. The radial velocity resolution is determined by following formula: . So, for mm and ,

Since the CAMWAR should provide radar image of the environment scene, which include as still ground clutter as the moving flying or ground vehicles, the CAMWAR Doppler processing is not going to filter out the still clutter. We need the Doppler algorithm for objects separation improvement only.

Another application of the Doppler processing, Doppler beam sharpening (DBS) will be explained below.

**3.4** **Threshold selection and detection**

To map the terrain landscape with the radar and implement proper operation of the height above the terrain (HAT) algorithm (see details below), the threshold operation should provide probability of the false alarm (Pfa) equaled about 10-6, which corresponds 14.4 dB [REF] ratio of the threshold level to the noise RMS (root-mean-square) value. The radar return values above the threshold are considered as detection events.

For detection of the discrete targets, either still or moving, two-dimensional range-Doppler CFAR algorithm will be applied. To avoid missing of the low RCS the CFAR threshold should be set up to relatively high 10-4 level.

To improve the target detection statistic binary integration will be applied. The binary integration, or m-of-n processingallow significantly reduce Pfa and improve Pd rates. The processing proves the detections if at least m threshold crossing from n tries occurs in the specific range and Doppler area. Preliminary, we plan to use 2 of 10 version of the binary integration, but we are going to play with different m and n numbers and threshold levels in our model and probably will apply different binary integration set.

The m-of-n processing advantage is coming at expense of detection time increase. Thus, if n=10, data from 10 radar frames should be processed. To avoid increasing latency of the radar detection, we plan to apply two level of the detection. First, quick level takes only one radar frame (10ms) but requires higher level of the threshold to provide Pfa ≤10-8. Second level will use several frames (from 5 to 10, which takes from 50 to 100 ms) with m-of-n processing, which provide better probability of detection of the low RCS targets.

To make the m-of-n processing useful, the target RCS should be decorrelated on the frame-to-frame level. One of the reasons of the decorrelation is aspect angle diversity. Min changing of the aspect angle for the RCS decorrelation is equal to λ/2L1 [REF], where L1 is target width as viewed along radar line of sight. Due to very small wavelength (≈4mm) of the CAMWAR radar, the target RCS decorrelation due radar platform moving or target moving may be happened very quickly. Thus, target with L1=10m, flying with 20m/s cross-radial velocity and with 1km range from radar will have the RCS decorrelation time equal to 10 ms. Since CAMWAR radar frame time is planning to be 10 ms, the most real targets would be decorrelated from frame to frame due to the movement of the radar platform or moving of the target.

However, for slow moving target relatively to the radar platform, the aspect angle diversity will not work. In this case, frequency diversity as another method of the target RCS decorrelation can be used. To make the technic effective and decorrelate different CPI cycles, frequency shift (ΔF) should be higher than c/2L2, where L2 is target depth as viewed along radar line of sight. Thus, for L=3m, ΔF should be at least 50 MHz.

**3.5** **Doppler beam sharpening (DBS)**

The DBS allows significant improvement in azimuth resolution by splitting the antenna beam in several Doppler beams. The method is applicable for side-looking directions on the moving platform and present one of the simplest forms of SAR (synthetic aperture radar) algorithm. The azimuth resolution with DBS is improved with synthetic aperture increase, which is proportional to the dwell time available, the radar velocity, and sine of the angle between radar platform velocity vector and radar beam. To be practical, the DBS mode for CAMWAR required increasing of the CPI time from nominal 1ms to about 10ms (as max refresh/frame time for the radar). For the 10ms CPI and 50 m/s radar platform velocity the synthetic aperture length is equal to 0.5 m, or about 4 times longer than virtual aperture of the CAMWAR radar. So, the DBS azimuth resolution will be in four times narrow than nominal 2 degree, or 0.5 degree if the radar beam directed perpendicular to the velocity vector.

To illustrate the DBS effect, we can show the radar image of the scene model with different beam direction relatively to the platform velocity vector. For example, if the beam to velocity angle equal to 0⁰ (forward looking) has no DBS improvement and azimuth resolution ∆ϕ=2⁰, for the 90⁰ beam direction the DBS provide ∆ϕ=0.5⁰, and in somewhere in the middle 30⁰ the DBS gives ∆ϕ=1⁰ resolution.

**3.6** **Analog and digital scan**

To minimize radar straddling loss and image degradation angular step size for analog and digital scan should be approximately equal to half of the radar beamwidth. Since nominal CAMWAR beamwidth and in azimuth and elevation is 2⁰ and 4⁰ accordingly, the angular step during the scan should be 1⁰ in azimuth and 2⁰ in elevation. The single radar panel should provide 60⁰ in azimuth and 30⁰ in elevation. So, 61 azimuth and 16 elevation beams result in total beam number equaled to 976.

**3.7** **Monopulse operation**

Angular accuracy of the target position determination is not limited by the radar angular resolution. Digital beamforming mode of the CAMWAR radar allow amplitude comparison monopulse application in the azimuth direction. When the discrete target has been detected, the algorithm determines two antenna positions shifted in about one beamwidth and located on the different side of the target. Target angular shift from central position may be determined with following expression:

Where is radar azimuth beamwidth (2⁰ nominally), A1 and A2 are amplitude values measured on the two beam positions.

1. **Radar image model**
   1. **Radar image mode selection**

By having environment scene model with ground and road and other features on the ground surface and helicopter and drone flying on the air, we want to build radar image of the scene and superimpose it on the original model image to compare them. We consider two methods for the radar image building:

1. A plan position indicator (PPI) radar image mode, which show range versus azimuth angle RCS distribution in polar coordinates. Magnitude of the radar returns are shown with the brightness variation. Height (above some reference level) may be illustrated with different colors, or numerical symbology. The PPI image provide top view of the scene with good 2-D (x and y coordinates) resolution, but with poor height (z-coordinate) representation.
2. 3-D perspective view from the radar position point of view. The perspective view image is convenient for pilot or UAV operator, because it reproduces natural human view. However, it has poor resolution in the range direction, especially for low grazing angles. With absence of optical image details, it can provide wrong representation of the flying objects. If terrain surface may be assumed as completely flat, the 3-D perspective view image can be considered as, so called, C-scope radar image.

We are going to provide both PPI and 3-D perspective view radar image modes for better illustration of the CAMWAR capabilities.

* 1. **3-D terrain map algorithm**

To build 3-D terrain image based on radar data, we need to determine height above the terrain (HAT) of the radar position. Additional radar altimeter can be used for it, but the altimeter data may be distorted with some objects under the aircraft, such as trees, buildings, or ravines. Also, the terrain elevation changes due to hills or dips on the radar view cannot be resolved by using the altimeter. Our approach is based on using CAMWAR radar data to measure the HAT for any radar beam which illuminated the terrain. So, in contrast of altimeter, which measure the radar altitude under the aircraft, CAMWAR HAT algorithm will determine radar elevation above terrain area illuminated by specific radar beam. Since, multiple radar beams illuminate different terrain areas, we can obtain 3-D map of the terrain in the radar view. HAT values for several adjacent azimuth beams may be averaged, by using sliding window algorithm. It would improve the HAT accuracy at expense of the azimuth resolution of the terrain map.

In the CAMWAR preliminary design elevation FOV will be varied from 0⁰ to -30⁰, and elevation beamwidth will be about 4⁰. Since, the accurate HAT determination is possible when the grazing angle exceeds the elevation beamwidth in two-three times, the HAT determination will be limited for the elevation angular range from -10⁰ to -30⁰. For elevation angles higher than -10⁰ we will apply the same HAT numbers as were determined for previous (lower) elevation position.

Thus, for each radar beam positions in azimuth direction and each elevation position in between -10⁰ to -30⁰, the all over-the-threshold radar returns are identified, counted, and the range to each of the is determined. Then, the average range to terrain value for specific radar beam, with ϕ and angular numbers, is calculated as follows:

where N is number of the over-the-threshold range bins, and is the range to each of them.

For real radar system, the beam grazing angle should be corrected by using radar platform pitch, roll, and yaw values, or mechanical stabilization mechanism should be applied to put radar in nominal position. However, for the Phase I feasibility study we can avoid the details, which will be accurately considered during Phase II of the project. So, we will assume the radar platform is adjusted to horizontal plane, and the grazing angle is equal to -. In the case, the radar height above terrain area illuminated by the radar is calculated with following expression:

The terrain area related with the single beam elevation value is extended from min to max over-the-threshold ranges in the range direction. The width of the single beam illumination terrain patch is equal to R×∆ϕ.

Since, the single beam value may be to noisy, sliding window averaging algorithm in azimuth direction may be applied to reduce the noise. Also, all values for all applicable azimuth and elevation angles may be averaged to obtain reference terrain level. Since the adjacent radar beams have partially overlapped each other, the terrain elevation number should be averaged in the overlapped areas to get more accurate results. To eliminate sharp boundary between the different terrain patches, some filtering algorithm (TBD) may be applied to get smooth terrain profile.

* 1. **Elevated target positioning on the 3-D image**

To provide proper range and elevation information for elevated (flying) target on the 3-D image, pin-type symbology may be used. The vertical oriented pin is connected to the ground point under the target. Height of the pin is proportional the target over-the-ground altitude.