A Simulation Study of SAR Processing for Forward Looking Synthetic Aperture Radar (SAR)

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Abstract
This paper highlights the key differences in signal properties between Forward and Broad-side looking SAR. A comparison of available SAR processing algorithms and their efficacy for processing forward squinted data is presented. Simulation results using traditional Range Migration Algorithm (RMA) shows focused point targets for squint angles up to 50°. The algorithm was modified, with which fully focused point targets were obtained even up to 20° as required for forward looking SAR.

Key Words: *Range, Azimuth, Doppler, Squint Angle, Range Cell Migration (RCM)*

I INTRODUCTION

Synthetic Aperture Radar (SAR) generates a high resolution two dimensional radar image of a terrain by processing the Range-Doppler features of each scatterer on the terrain. It's all weather, long range and day/night capability gives a convincing edge over optical and infra-red sensors making it one of the most important tool for remote sensing application followed by a wide range of military applications such as reconnaissance and surveillance, precision targeting, navigation and guidance, foliage and ground penetration. The system has been successfully deployed in large number of satellites, fighter aircrafts and UAV's.

Traditional SAR radars are side looking where the radar antenna is positioned broadside to platform motion which results in limited trajectory options available to image a particular scene. This limitation makes airborne systems such as UAV's to follow fixed and known trajectories which increase the platform's vulnerability to hostile action.

Modern SAR radars are consistently thriving towards achieving higher spatial resolution and near forward look imaging. A forward looking SAR will have definite advantage over side-looking SAR in terms of long standoff operational range and wide variety of routing options. However there is certain critical signal processing parameters to be met.

In this paper we bring out the signal characteristics of squint mode SAR and the fundamental challenges in processing forward squinted SAR data as compared to traditional side-looking SAR data.

II SIGNAL CHARACTERISTICS OF SQUINT MODE SAR DATA

Synthetic Aperture Radar (SAR) onboard an airborne or space borne vehicle collects backscattered microwave pulses from terrain as the vehicle is moving and processes to form an image as shown in fig.1.

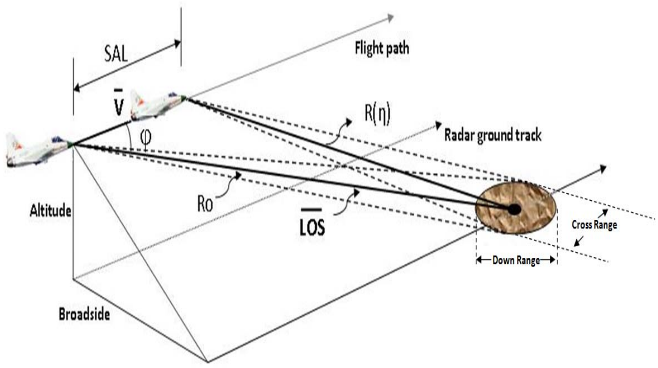


Figure1 Squint mode Imaging Geometry

In general a real-beam radar can provide high resolution along down-range axis and poor cross-range resolution (azimuth),where as SAR can provide high resolution even along azimuth axis. The core concept is that the relative motion between the vehicle and scatters on terrain causes shift in Doppler frequency. These shifts are different for scatters offset along azimuth axis. Thus scatters at same down-range can be resolved in azimuth on basis of their Doppler shift return.

Fig.1 shows the squint mode imaging geometry where the platform is flying with velocity V along the flight path. R_0 is the initial slant range to scene centre on ground at the start of imaging. $R(\eta)$ is the instantaneous slant range to point target as a function of azimuth time η. The line joining Antenna Phase Centre and point target is termed as Line of Sight (LOS). Squint angle(φ) is defined as angle between Line Of Sight (LOS) vector and Velocity vector (V).

1 SAR Echo Model

SAR radar collects series of pulses and stores as 2D matrix represented by two time domain axes namely fast time along down-range axis and slow time along azimuth axis. This section brings out the mathematical description of the echo model.

In general the transmitted signal $S_{pul}(t)$ is a linear frequency modulated (LFM) waveform where the instantaneous frequency varies linearly with fast time t.

$$s_{pul}(t) = A_t rect(\frac{t}{T_p}).\cos(2\pi(f_c t + \frac{\gamma}{2}t^2) \quad (1)$$

Where γ is LFM chirp rate, T_p is pulse width, f_c is centre frequency, A_t is transmitted amplitude.

The received signal $S_r(t)$ is a replica of the transmitted signal but with a time delay and reduced amplitude which is proportional to target radar cross section (RCS), antenna gain and range attenuation.The received echo from a point target is

$$s_r(t) = A_r.rect(\frac{t}{T_p} - \frac{2R_0}{c}).\cos(2\pi(f_c(t - \frac{2R_0}{c}) + \frac{\gamma}{2}(t - \frac{2R_0}{c})^2) \quad (2)$$

Where A_r is received amplitude from a point target and R_0 is Range to the target at start of imaging.

As the platform moves forward, the Range to target R(η) varies as function of azimuth time η. Also the signal strength of return from scatter depends on azimuth beam pattern w_a of the antenna. The received echoes can thus be represented by a two dimensional signal

$$s_r(t,\eta) = A_r.w_a(\eta).rect(\frac{t}{T_p} - \frac{2R(\eta)}{c}).\cos(2\pi(f_c(t - \frac{2R(\eta)}{c}) + \frac{\gamma}{2}(t - \frac{2R(\eta)}{c})^2 \quad (3)$$

The received signals $s_r(t, \eta)$ is converted to base band and modulated to generate complex I and Q data. Hence the final SAR echo data is a complex two dimensional signal

$$s_0(t,\eta) = A_r.w_a(\eta).rect(\frac{t}{T_p} - \frac{2R(\eta)}{c}).e^{(-i.4\pi.f_c\frac{R(\eta)}{c})}.e^{i.\pi.\gamma(t - \frac{2R(\eta)}{c})^2} \quad (4)$$

Equation (4) is the standard echo model for SAR processing. The last exponential component in the equation shows that the phase variation along range time axis is quadratic leading to linear frequency modulation (LFM) along this axis. Hence high-resolution in the range direction can be achieved by a LFM based matched filter.

The last but one exponential component defines the SAR signal characteristics along azimuth time axis. Frequency variation along this axis which is also termed as Doppler frequency variation depends on Slant range R(η). In order to achieve high resolution along this axis proper understanding of Doppler parameters is must for selecting the right matched filter.

2 Understanding Slant Range Equation R(η)

The slant range distance between radar and point target $R(\eta,R_0)$ can be derived using simple triangle equation as

$$R(\eta,R_0) = \sqrt{R_0^2 + (V.\eta)^2 - 2R_0.V.\eta.\cos\varphi} \quad (5)$$

Where R_0 is slant range at the start of imaging (t = 0), V is velocity of the SAR platform , φ is angle between velocity vector and Line of Site (LOS) vector ,η is azimuth time along the radar flight path as shown in fig.1.

To aid further analysis, the expression (5) is expanded using Taylor's series.

$$R(\eta,R_0) \approx R_0 + \frac{dR}{d\eta}\eta + \frac{1}{2!}\frac{d^2R}{d\eta^2}\eta^2 + \frac{1}{3!}\frac{d^3R}{d\eta^3}\eta^3 + ...$$

$$\approx R_0 + (\frac{2V}{\lambda}.\cos\varphi)\eta + \frac{1}{2!}(-\frac{2V^2}{\lambda R_0}.\sin^2\varphi)\eta^2 + \frac{1}{3!}(-\frac{6V^3.\sin^2\varphi.\cos\varphi}{\lambda R_0^2})\eta^3 + ... \quad (6)$$

Equation (6) can further be represented in terms of Doppler parameters

$$R(\eta,R_0) \approx R_0 - \frac{\lambda}{2}f_{DC}\eta - \frac{\lambda}{4}f_{DR}\eta^2 - \frac{\lambda}{12}f'_{DR}\eta^3 - ... \quad (7)$$

Where f_{DC} is Doppler Centroid frequency, f_{DR} is Azimuth frequency chirp rate, f'_{DR} is rate of change of Azimuth frequency chirp rate.

Equation (6) reveals that squint angle plays a major role in received SAR echo signal properties.

3 Side looking SAR Signal Properties

Side looking SAR radars have antenna placed perpendicular to velocity vector i.e φ = 90º.Substituting this value in eq. 6 & eq.7 we get

$$f_{DC} = 0, f_{DR} = -2V^2/(\lambda.R_0) \text{ and } f'_{DR} = 0$$

Neglecting higher order terms the Range equation becomes

$$R(\eta, R_0) \approx R_0 - \frac{\lambda}{4}f_{DR}\eta^2 \quad (8)$$

The following are the observations in signal properties:

i. The range equation has quadratic term that causes echoes from successive pulses to occur at different ranges, leading to a phenomenon known as range curvature as shown in fig.2

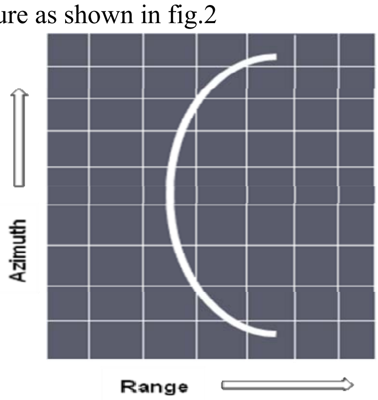


Figure 2 Range Curvature

ii. The phase variation along azimuth axis is also quadratic in nature leading to linear frequency modulation along azimuth direction. This helps in using a LFM based pulse compression technique as azimuth matched filter similar to that in range direction.
iii. Doppler centroid is zero, which makes estimation process simpler.

4 Squint Mode SAR Signal Properties

For this mode φ ≠ 90º and for forward looking case it is typically 10º to 30º. Substituting this value in eq. 6 & eq.7 we get f_{DC}, f_{DR} and $f'_{DR} \neq 0$ which leads to slant range equation

$$R(\eta,R_0) \approx R_0 - \frac{\lambda}{2}f_{DC}\eta - \frac{\lambda}{4}f_{DR}\eta^2 - \frac{\lambda}{12}f'_{DR}\eta^3 - ... \quad (9)$$

The following are the observations in signal properties:

i. Apart from quadratic term, the range equation has linear, cubic and higher order terms. The linear component causes the echo from successive pulses to appear in different range bins leading to a phenomenon known as range walk. Squint-mode SAR has a combination effect of range curvature and range walk which is termed as Range Cell Migration (RCM) as shown in fig.3

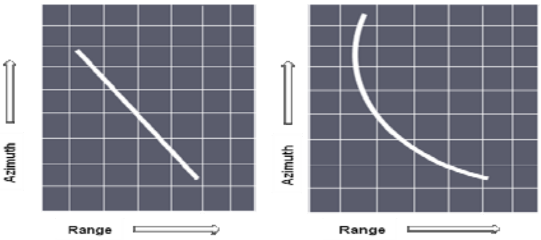


Figure 3 (a) Range Walk (b) Range Cell Migration

ii. Cubic and higher order terms in range equation causes non-linear frequency modulation along azimuth. This non-linearity leads to defocusing if a LFM pulse compression technique is used. Thus making Azimuth matched filter design complicated.
iii. Estimation of Doppler history becomes critical as Doppler centroid is non zero.

Based on this section it can be concluded that Squint Mode SAR need additional processing for correcting Range Cell Migration (RCM), estimation of Doppler centroid and specialised Azimuth filter as compared to side looking SAR. The complexity increase as the squint angle becomes narrower close to forward looking SAR. Hence it becomes important to select the right SAR processing algorithm.

III SELECTION OF PROCESSING ALGORITHM FOR FORWARD LOOKING SAR

Raw SAR echo data is transformed into high resolution Image using a SAR processing algorithm. There are many traditional algorithms available in literature [1],[2],[3]. In this paper we compare four most popular algorithms that utilise frequency domain computations namely:

a) Range Doppler Algorithm (RDA)
b) Chirp Scaling Algorithm (CSA)
c) Polar Format Algorithm (PFA)
d) Range Migration Algorithm (RMA)

There are other time domain algorithms too, however due to computation load especially for airborne platforms they have not been considered for further study. The basic difference is the operational domain in which they work, processing modes, RCM corrections.

Range Doppler Algorithm (RDA) [2] is one of the first algorithms developed for processing strip map SAR data and is still the most popular algorithm for its simplicity of block processing using one dimensional operations.Chirp Scaling Algorithm (CSA)[2] was developed specifically to eliminate the time domain interpolator used for RCM correction in RDA algorithm

Both RDA and CSA approximate range equation (Eq.6) as quadratic by ignoring cubic and higher order terms which is popularly known as Fresnel approximation. This assumption is valid for short dwells, small beam widths and squint angle close to broadside. Hence these algorithms cannot be used for forward squinted data as the range equation is hyperbolic.

Polar Format Algorithm [1] is one of the most popular algorithm developed for spotlight mode SAR. The algorithm collects successive pulses in polar format instead of rectangular and performs a polar-to-rectangular re-sampling before 2D FFT processing, which is time consuming. Also PFA assumes the received wave fronts as planar instead of spherical. This assumption is termed as Fraunhofer approximation due to which PFA can focus only limited scene size. This assumption is valid for smaller beamwidths and longer dwells.

Range migration algorithm [1],[3] originated from wave propagation theory commonly used in seismic processing. This algorithm is free of above mentioned approximations that gives it inherent ability to process data acquired over wide azimuth apertures and squint angles. It performs its focusing operations in 2-D frequency domain that removes the range-azimuth coupling, corrects RCM correction using simpler signal processing functions. Hence this algorithm has been selected for further study.

IV CORE CONCEPT OF RANGE MIGRATION ALGORITHM (RMA)

Any point target at a spatial location Xc,Yc can be represented in 2D-spatial frequency domain as

$$F(kx,ky) = e^{(j*kx*Xc + j*ky*Yc)} \qquad (10)$$

where kx, ky are spatial frequencies of point targets along x, y direction respectively. A 2D IFFT of eq.10 gives impulse response at location Xc,Yc.

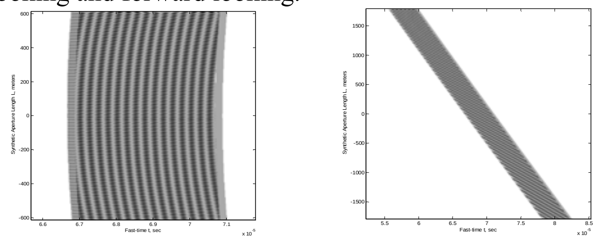
The whole idea behind RMA algorithm is to allocate individual independent spatial frequencies kx, ky to each point targets, by removing the range-azimuth coupling that arise due to imaging geometry.

Following are the steps involved in RMA algorithm [1] with their mathematical interpretation:

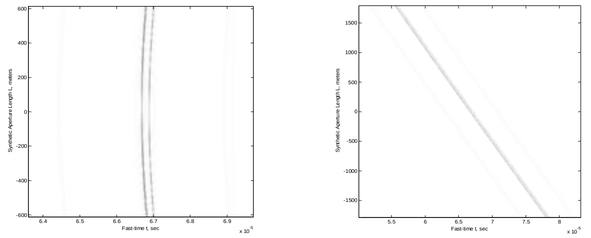
i. The raw I/Q pulses are compressed along fast time axis.
ii. A 2D FFT is performed to transform the SAR signal data into the 2D spatial frequency domain.
iii. The SAR signal data is now multiplied with a 2D reference filter. This filter is computed for a particular range, usually the mid swath. After this step, Range cell migration (RCM) of target at the reference range is completely compensated, while targets other than that range are only partially compensated. Also it allocates individual azimuth frequency to each point target.
iv. The data is remapped in range frequency axis using Stolt interpolation[1] which corrects the residual RCM and allocates instantaneous range frequency to each point target. One can view the reference filter multiply as bulk focusing and the stolt interpolation as differential focusing.
v. Each scatterer in the SAR signal data is now been allocated individual range and azimuth frequencies in both directions. Hence a 2D IFFT gives focused targets.

V SIMULATION RESULTS OF SAR PROCESSING USING TRADITIONAL RANGE MIGRATION ALGORITHM (RMA)

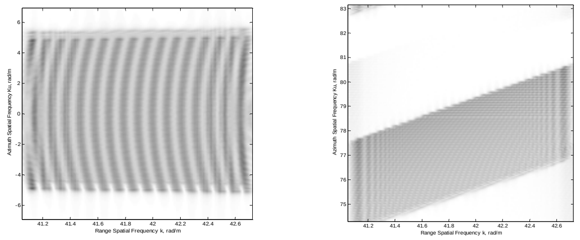
Spotlight SAR simulator has been developed using which simulations were carried out for a series of squint angles, however results of two cases namely side looking (φ = 90°) and forward looking (φ = 20°) is being presented.SAR echo data for stationary 3 point targets was generated and processed using traditional RMA algorithm[1]. Fig. 4 shows the raw data as it looks for side looking and forward looking.



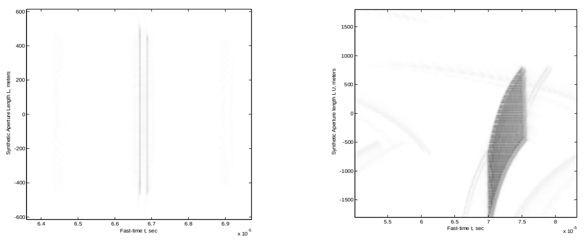
(a) Side Looking (φ =90°) (b) Forward Looking (φ = 20°)
Figure 4 Simulated Raw I & Q Data for different Squint angles (φ)



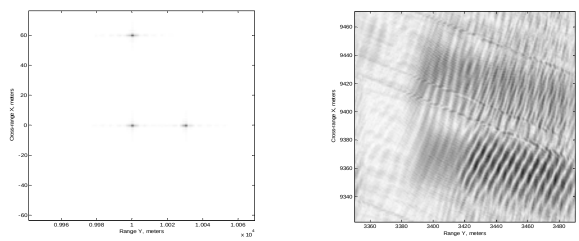
(a) Side Looking (φ = 90°) (b) Forward Looking (φ = 20°)
Figure 5 Range Compressed results for different Squint angles (φ)



(a) Side Looking (φ = 90°) (b) Forward Looking (φ = 20°)
Figure 6 2-D Spectrum for different Squint angles (φ)



(a) Side Looking (φ = 90°) (b) Forward Looking (φ = 20°)
Figure 7 RCM correction for different Squint angles (φ)



(a) Side Looking (φ = 90°) (b) Forward Looking (φ = 20°)
Figure 8 Final processed output for different Squint angles (φ)

Fig. 5 shows the data compressed along range axis using LFM matched filter where it is evident that range curvature is dominant in side looking case while range walk is dominant in forward looking case. Fig. 6 shows the 2D spectrum data where the azimuth spectrum has zero Doppler centroid in side looking case while it is non-baseband for forward looking case. Fig.7 shows results after reference filter multiply and Stolt interpolation where RCM is completely compensated for side looking and not for forward looking. Fig. 8 presents the final processed output which shows that the traditional RMA fails to process forward looking data (φ =20°).

VI MODIFIED RANGE MIGRATION ALGORITHM (M-RMA)

It is evident from previous results that traditional Range Migration algorithm doesn't work beyond certain squint angles.There are many research papers [4],[5],[6] which deal about improving RMA results for squinted data. One such paper [4] proposed a method where a modified reference signal is used to transform a squint-mode data to a broadside-mode data. This is based on coordinate transformation and extended Taylor approximation. Moreover, to compensate curvature errors, the proposed method is extended on the basis of the subarea technique.The maximum squint angle achived was 25°.Other papers[5],[6] tried to focus on modifing stolt mapping step which led to improvements up to 50°.

After analysing the results obtained at each step of tradiational RMA for various squint angles we came to conclusion that the problem must be addressed even before taking data to 2D-frequency domain.Fig.9 depicts the modified RMA algorithm for forward squint.

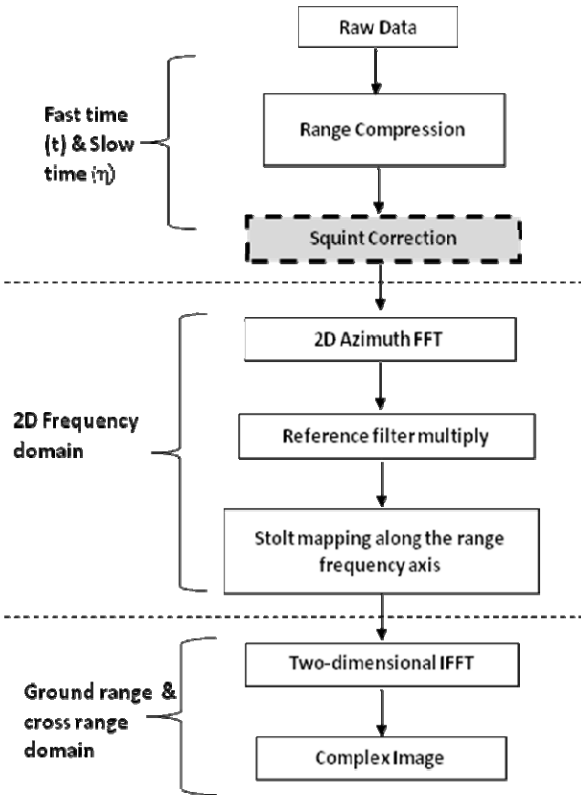
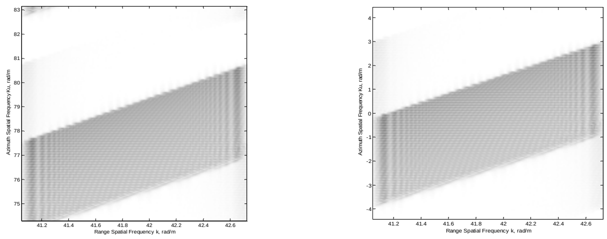


Figure 9 Block Diagram of Modified-RMA

As we move towards forward squint the azimuth spectra becomes more and more non-base band.This is due to fact that Doppler Centorid dominates the Doppler spread at such squint angles.In general the Pulse Repetetion Frequency (PRF) is taken greater than Doppler spread over entire SAL.Hence the data for forward squint becomes doppler aliased leading to foldover of azimuth frequencies which doesn't allow RMA to allocate individual range-azimuth frequencies to each scatterer.

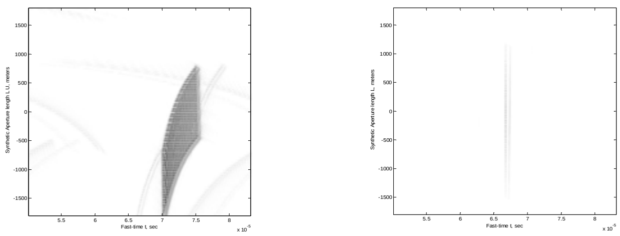
The modified algorithm carries out additional operation termed as squint correction, as highlighted in fig.9 which in principle down converts the doppler spread to base band,removes the doppler aliasing and corrects for uncompenstaed phase errors.

The simulation was repeated with modifed algorithm and following are the comparision results for traditional v/s modified RMA for forward looking SAR (squint angle, φ = 20°)



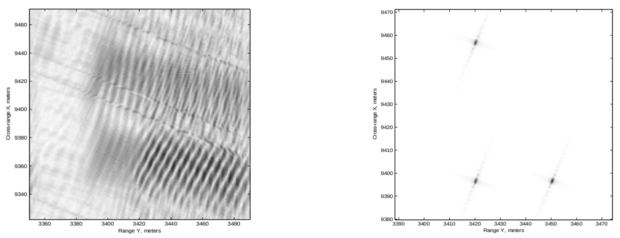
(a) Traditional RMA (b) Modified RMA

Figure 10 2D spectrum for Forward Looking (φ = 20°)



(a) Traditional RMA (b) Modified RMA

Figure 11 RCM correction for Forward Looking (φ = 20°)



(a) Traditional RMA (b) Modified RMA

Figure 12 Final processed output for Forward Looking (φ = 20°)

Fig .10 shows the 2D spectrum data where it is evident that modified RMA algorithm brings the azimuth spectra to base band. Fig.11. shows that compared to traditional algorithm, the modified RMA does complete RCM correction.Fig.12 compares the final output of traditional and modfied RMA algorithm, which shows that modified algorithm provides fully focussed point targets for forward looking squint angle (φ =20°).

CONCLUSION

Complexities involved in processing forward looking SAR data are brought out in detail. Range Migration Algorithm is found to be best suited algorithm for this data as it is free of approximations made by other algorithms. Simulation results with modified RMA algorithm shows promising results up to squint angle of 20°,thus meeting requirements of a forward looking SAR. This work will be futher compounded with studies of forward looking SAR traversing a non-linear motion.

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Santosh Kumar Kheer obtained his B. E. in Electrical and Electronics Engineering from Andhra University in 2005. He joined BrahMos Aerospace as System Engineer the same year, wherein he worked in the areas of electrical integration and testing of missile electronics. He was posted to Electronics and Radar Development Establishment (LRDE) from 2007-2010 for design and development of a novel forward looking SAR based Imaging radar. During this period he has done extensive research on SAR processing algorithms. Currently he is serving as Deputy General Manager (DGM) at BrahMos Aerospace, Hyderabad. His areas of interest are Synthetic Aperture Radar System design, SAR Signal Processing, monopulse tracking radars, system integration, testing and evaluation.

Dr A Vengadarajan obtained his B. E. in Electronics and Communication Engineering from Madurai Kamaraj University in 1985. He joined DRDO in the same year and was posted to Centre for AirBorne Systems (CABS) wherein he worked in the area of system analysis of airborne radars and in the design and development of ultra low side lobe antenna array using slotted waveguide antennas and microstrip antennas. During his tenure in CABS he obtained his M.Tech. and PhD degrees in Microwave Engineering from IIT, Kharagpur. He started working in Synthetic Aperture Radar from 1999 onwards and was transferred to Electronics and Radar Development Establishment (LRDE) in 2006. He functioned as Project Director for Primary Radar development for AEW&C till 2007 and then for Synthetic Aperture Radar for UAV till 2011. During this period he was also in charge of SAR developments for various other requirements. Currently he is serving as Director, System Analysis, Quality and Reliability (SQR) at Office of DG-ECS located at DARE Campus in Bangalore. His areas of interest are Synthetic Aperture Radar and Space Time Adaptive Processing and other Advanced Signal Processing for Ground based and Airborne Radars.