COMPUTER SIMULATION OF SYNTHETIC APERTURE RADAR

Adam E. Robertson
Brigham Young University, MERS Laboratory
459 CB, Provo, UT 84602
801-378-4884, FAX: 801-378-6586, adam@byu.edu

Abstract — A computer simulation of SAR data is discussed. A method is outlined for simulating a point target that models SAR data under moderate motion of the radar platform and a wide range of incidence angles. A simple Interferometric SAR simulator is also discussed. The usefulness of the simulations is in the ability to test new algorithms in a controlled environment. The simulator allows for several degrees of freedom in the complexity of the simulation.

INTRODUCTION

Brigham Young University has developed several SAR systems, including YSAR[1] and YINSAR[2] . YSAR, a 2GHz SAR, was flown in several locations in Utah and at significant archaeological sites in Israel. YINSAR, a 9.9 GHz interferometric SAR, will be used for numerous applications requiring high resolution digital elevation maps. Both systems are flown on a small aircraft at low altitudes. In the course of the development of these systems simulation has become necessary for studies in motion compensation and interferometry. The requirements for an accurate simulator are:

1) Accurately account for a wide range of incidence angles.
2) Simulate the turbulence induced motion incurred in a small aircraft.
3) Account for the antenna pattern in range and azimuth.
4) Model the scattering (phase, electromagnetic interaction with the surface, probabilistic nature of a distributed scene, etc.)
5) Simulate the effects of terrain height profile.
6) Generate interferometric image pairs.
7) Reasonable computational demands.

The point target simulator discussed in this paper satisfies 1-4 and 7. The interferometric simulator accounts for 5-7. Modeling the scattering mechanisms required for a distributed scene is under investigation, and not accounted for in the current model.

SIMULATING A POINT TARGET

The inputs and outputs of the simulator are illustrated in Figure 1. Dotted lines indicate optional files. The inputs to the simulator are provided in three files. The first file contains the parameters of the SAR system, such as transmit frequency, power, chirp duration and bandwidth, sampling rates, number of points to collect, and several nominal default values: platform velocity and altitude, antenna geometry, and 3dB beam-width. The second file provides the motion of the radar platform; roll, pitch, yaw, position and velocity of the aircraft as a function of time. The last input file contains the antenna pattern. If there is no input file for the platform motion or the antenna pattern, the simulator defaults to linear motion and a uniformly illuminated aperture respectively, where the default values are defined in the SAR parameter file.

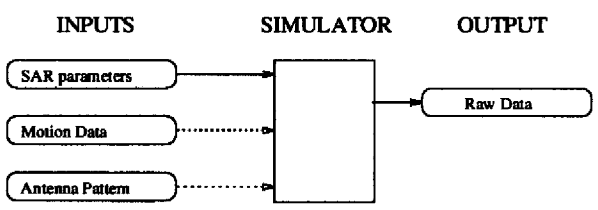

Figure 1: Simulator Inputs and Outputs

The point target simulator is designed to provide a realistic simulation. For example, power fall off as a function of range and the incidence angle dependence of σ^o can be simulated.

ALGORITHM FOR A POINT TARGET

An algorithm for simulating raw data is illustrated by Figure 2. Dashed lines indicate steps in the algorithm that are optional, while solid lines indicate required steps.

For each azimuth line the position of the aircraft will determine if the point target is in the antenna beam. Role, pitch and yaw determine the area illuminated by the antennas. The geometry of the antennas relative to the aircraft comes from the SAR

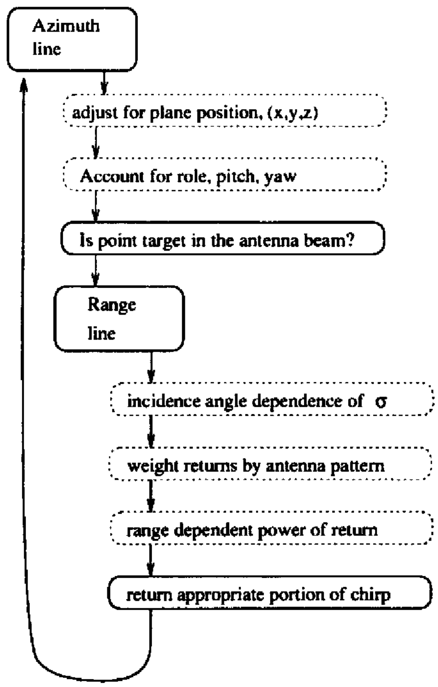

Figure 2: SAR simulator flow diagram

parameter file. The entire antenna pattern can be accounted for, or some thresh hold, such as the 3dB point, can be used to determine the return from the target. For most purposes the 3dB beam-width is sufficient, but the effects of side lobes can be examined by using the entire antenna pattern. For each range line the point response of the chirp is determined from the geometry of the plane and the target. The incident angle (α) dependence of σ^o can be accounted for,

$$\sigma^o(\alpha) \propto \frac{\sin^n(\alpha)}{\cos^u(\alpha)} \qquad (1)$$

$$-1 < n < 3$$

$$1 < u < 5$$

where n and u are dependent on the scene of interest[3] . The magnitude of the return is weighted according to the antenna pattern. Antenna patterns can be simulated using FIR filter design methods[4] for given antenna specifications. Due to its flexibility, Kaiser window design with filter lengths and β values to achieve antenna 3dB beam widths and side lobe levels similar to YINSAR are used in all examples in this paper . The power in the return is dependent on the range to the target,

$$P_R = \frac{P_T G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \qquad (2)$$

Where G is the gain of the antenna, P_T is the power transmitted, and R is the range to the target. Finally the appropriate time dependent return from the point target is calculated based on the speed of propagation of the radar chirp, range to the target, and the shape of the chirp.

The initial implementation of the algorithm is written in MATLAB for rapid development. Implementation of the algorithm in C will result in improvements in the speed of the simulation, and is planned for the realization of the final tool.

Converting the raw data produced by the simulator to a SAR image is performed by matched filters in the range and azimuth direction. All the information needed for range and azimuth compression is located in the SAR parameter file. The matched filter in range is merely the transmitted chirp, which is, in the case of YSAR and YINSAR, a Linear Frequency Modulated (LFM) chirp,

$$LFM(t) = \exp(\beta t^2) \qquad 0 < t < \tau \qquad (3)$$

Where β is the chirp rate and τ is the chirp duration.

Azimuth compression is slightly more complicated. The point target response in the azimuth direction has a quadratic phase that is dependent on the distance from the radar platform to the target, thus the appropriate matched filter is range dependent and must be recomputed for each range line. A matched filter for the azimuth chirp is given as:

$$h(t) = \exp\left(\frac{-j2\pi v^2 t^2}{R_o \lambda}\right) \qquad (4)$$

Where R_o is the nominal distance to the target, and v is the velocity of the aircraft. From eqn 3 and 4 it can be seen that the range matched filter is largely insensitive to motion of the radar platform if τ is small and the delay between transmit and receive is short compared to the motion of the aircraft. On the other hand the azimuth matched filter is dependent on the nominal range to the target and target and the velocity of the platform, both of which are strongly effected by motion. Figure 3 illustrates simple range Doppler SAR signal processing. Fourier transform techniques allow for the efficient implementation of autocorrelation in the frequency domain.

POINT TARGET EXAMPLES

A point target simulation with and without simulated motion is illustrated in Figures 4 - 6 in a noiseless environment with a uniform aperture illumination as generated by the point target simulator. Figure 4 demonstrate the raw radar return from a point

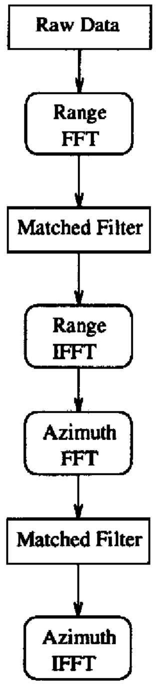

Figure 3: Range and Azimuth Compression

target . It can be seen from the image that range migration is accurately modeled by the simulator. 10% more FLOPS (Floating Point Operations) are required to simulate a point target with motion over the FLOPS required to simulate a point target without motion.

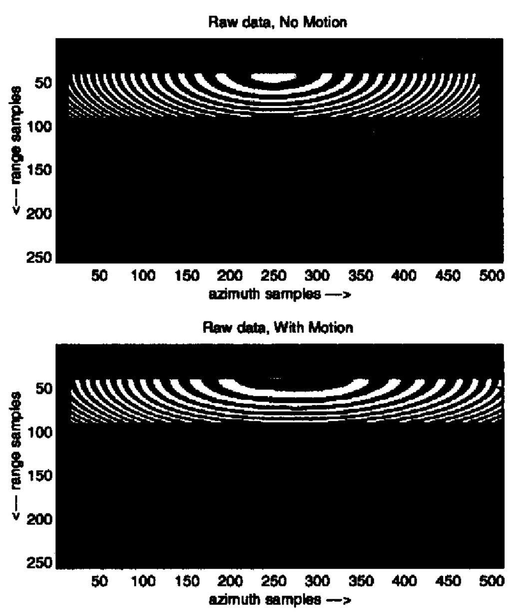

Figure 4: Raw data from a point target return

Figure 5 is a range compressed version of Figure 4. The simulated motion of the radar platform is slow in comparison the the duration of a given range sample, thus the motion of the aircraft is not noticeable in the range compressed data. This observation illustrates the usefulness of a SAR simulator in gaining intuition about the underlying radar system. By noting that range compression is insensitive to the motion induced by a small aircraft, motion compensation techniques can be significantly simplified.

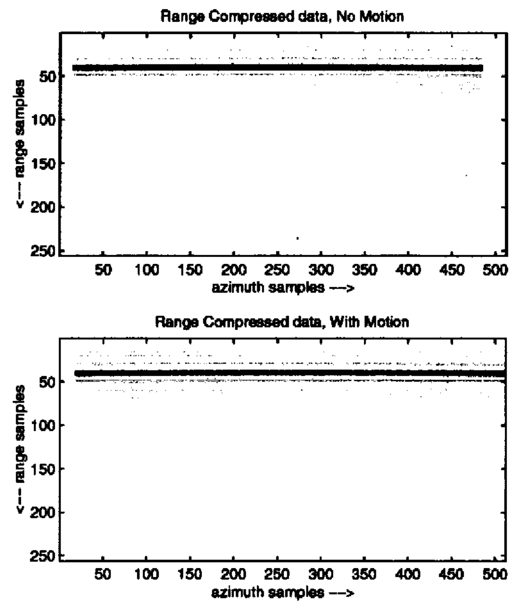

Figure 5: Range Compressed point target

Figure 6 is an azimuth compressed version of Figure 5. The effect of motion on the point target is severe. This is because the motion of the aircraft is large in comparison with a wavelength and rapid in comparison with the total time the target is illuminated. For the no-motion case, the single point target compressed to a sinc function in range and azimuth, the expected result of a matched filter in range and azimuth.

SIMULATED MOTION

The simulated motion used to generate Figures 4 - 6 is illustrated in Figures 8 - 10 for a PRF (Pulse Repetition Frequency) of 1 kHz. The motion simulator generates vectors corresponding to the role, pitch, yaw, position and velocity of the aircraft by the use of random variables. The simulated motion does not necessarily model something an aircraft could actually do, (i.e. an accurate model for actual aircraft motion was not used), but is a rough guess based on

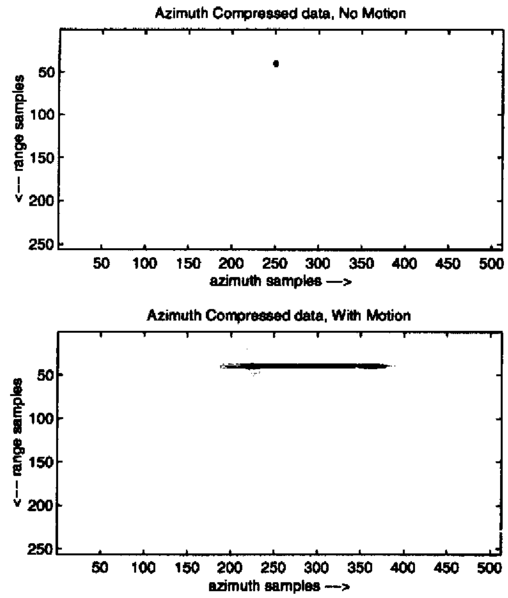

Figure 6: Range and Azimuth Compressed point target

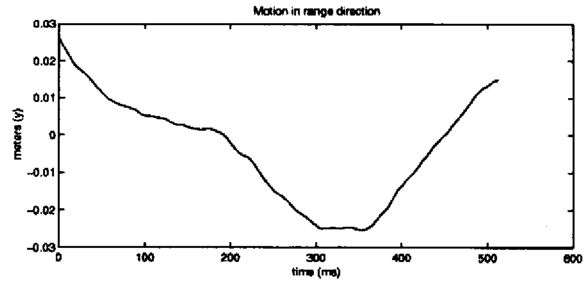

Figure 8: Motion in Range

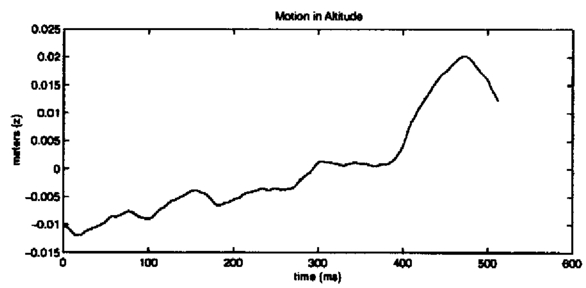

Figure 9: Motion in Altitude

the motion expected in a small aircraft. The geometry used for the simulation is illustrated in Figure 7.

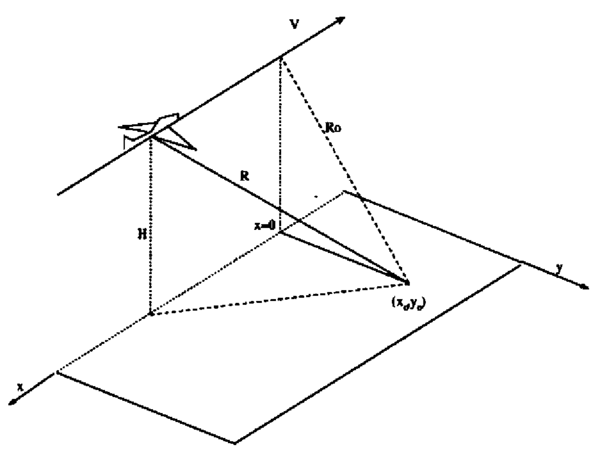

Figure 7: SAR Simulator Geometry

Figure 8 plots the aircraft motion in range, y (m), as a function of time. Note that the motion in Figure 8 is large compared to a wavelength ($\lambda = .03$ m). Figure 9 plots the aircraft motion in altitude, z (m), and Figure 10 is the instantaneous velocity of the aircraft.

The computational load for simulating the platform motion, simulating raw data, implementing a range matched filter, and implementing an azimuth matched filter for a 256 × 512 pixel image is demonstrated in Table 1. All units are in Mega FLOPS. Typical SAR images generated by BYU SARs are on the order of $2^{10} \times 2^{13}$ pixels.

Table 1: Computational Load

Function	Mega FLOPS
Motion Data Simulation	1.22
Raw Data Simulation	0.85
Range Matched Filter	13.28
Azimuth Matched Filter	242.35

Figure 11 demonstrates a set of 12 point targets placed equidistant apart. The large range of incidence angles used in a low altitude SAR like YSAR or YINSAR causes near range targets to appear closer together than they are, a projection of the ground truth domain onto the SAR image domain.

INTERFEROGRAM SIMULATION

An accurate computer simulation of a distributed target as required for interferometry is non-trivial. The correlation between baselines, an accurate scattering model, knowledge of the SAR transfer function, and accurate probability distribution functions

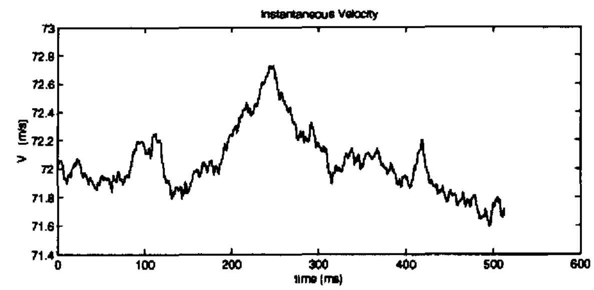

Figure 10: Velocity

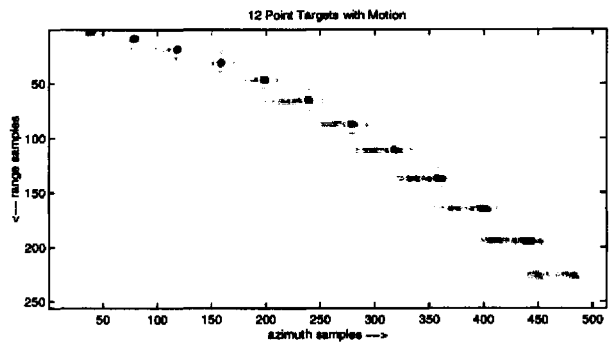

Figure 11: 12 point targets

must be used to properly generate the phase return from a distributed target[5] . However, simple models that account only for the height of the terrain are simple to implement and useful for testing phase unwrapping algorithms on controlled geometries and simulated noise conditions. This is easily implemented by transforming the ground height profile to the SAR image domain. As an example, consider Figure 12 a simulated ground geometry.

An interferometric pair was generated at a nominal altitude of 300 m with a vertical offset of 2 m between the pair using the system parameters of IFSAR. Figure 12 is the ground truth height profile. In Figures 12 - 14 the images are wrapped in 2π to effectively illustrate the phase patterns. Increasing height is from black to white. The nominal, (flat earth) phase difference between the two received radar images, Figure 13, is subtracted from the the interferogram before phase unwrapping. Both direct phase unwrapping and Unweighted Least Squares[6] phase unwrapping result in the reconstruction of the height profile. The unwrapped interferogram, Figure 14, is re-wrapped for comparison to Figure 12.

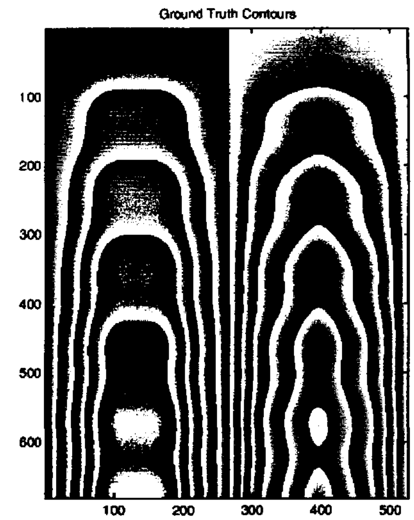

Figure 12: Ground Truth

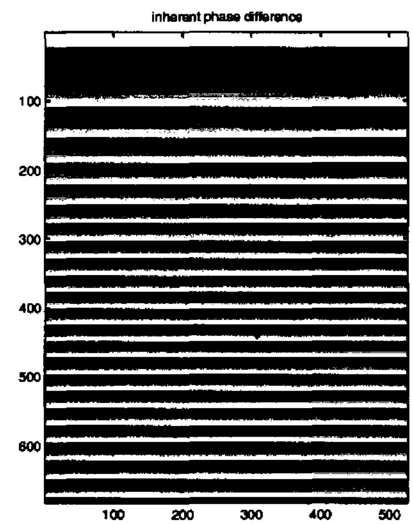

Figure 13: Inherent Phase Difference

FUTURE WORK

There several effects that the simulations do not account for. The most significant is an accurate model of the scattering from a distributed scene. The electromagnetic and probabilistic models needed are outlined by Franceschettti[7] and Bamler[8] . Fourier methods that can improve the computational efficiency of a simulator have also been developed[9] . The ray tracing needed to simulate the effects of shadowing is also an issue for future work. Additionally, for interferometric applications the decorrelation that occurs between antenna pairs must be modeled. A recent publications address interfer-

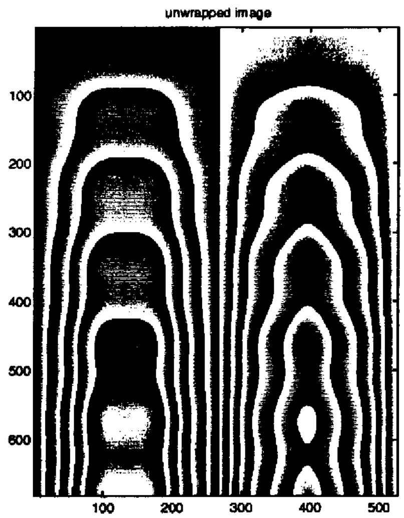

Figure 14: Unwrapped phase in SAR image domain

ometric raw data simulation[5] based on the ground laying work of Rodriguez[10].

CONCLUSION

The simulations meet most of the specified requirements. Arbitrary incidence angle, platform motion, and interferograms are modeled. The simulator allows the researcher to evaluate the effects of various compression algorithms, motion of the radar platform, antenna pattern's and geometry, ground images and reflectivities, phase unwrapping, etc. independent of one another or combined together.

REFERENCES

[1] D. G. Thompson, D. V. Arnold, D. G. Long, G. F. Miner, and T. W. Karlinsey. Ysar: A compact, low-cost synthetic aperture radar. In Proceedings of the 1996 International Geoscience and Remote Sensing Symposium, pages 1892–1894, Lincoln, Nebraska, May 1996.

[2] Douglas G. Thompson, James S.Bates, David V. Arnold, David G. Long, and Adam E. Robertson. Yinsar: A compact, low-cost interferometric synthetic aperture radar. In Proceedings of the 1998 International Geoscience and Remote Sensing Symposium, Seattle, Aug 1998.

[3] Nadav Levanon. Radar Principles. John Wiley & Sons, New York, 1988.

[4] Alan V. Oppenheim and Ronald W. Schafer. Discrete-Time Signal Processing, chapter 7.4. Prentice Hall, 1989.

[5] Giorgio Franceschetti, Antonio Iodice, Maurizio Migliaccio, and Daniele Riccio. A novel across-track sar interferometry simulator. IEEE Transactions on Geoscience and Remote Sensing, 1998.

[6] Dennis C. Ghiglia and Louis A. Romero. Robust two-dimensional weighted and unweighted phase unwrapping that uses fast transforms and iterative methods. Journal of the Optical Society of America A, 1994.

[7] Giorgio Franceschetti, Maurizio Migliaccio, Daniele Riccio, and Gilda Schirinzi. Saras: A synthetic aperture radar (sar) raw signal simulator. IEEE Transactions on Geoscience and Remote Sensing, 1992.

[8] Dieter Just and Richard Bamler. Phase statistics of interferograms with applications to synthetic aperature radar. Applied Optics, 1994.

[9] Giorgio Franceschetti and Gilda Schirinzi. A sar processor based on two-dimensional fft codes. IEEE Tranactions on Aerospace and Electronic Systems, 1990.

[10] E. Rodriguez and J. M. Martin. Theory and design of interferometric synthetic aperture radars. IEEE Proceedings, 1992.