Synthetic Aperture Radar Point Target Response

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1987

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Table 1: SAR Parameters

Item	Parameter	Value	Units
1	Carrier Frequency	1275	MHz
2	Pulse Chirp Rate	0.5621	MHz/uS
3	Pulse Duration	33.8	uS
4	Pulse Bandwidth	19.0	MHz
5	Center Frequency (IF)	11.38	MHz
6	Pulse Repetition Rate	1645.0	Hz
7	Sampling Rate	45.03	MHz
8	Doppler Frequency	1150.0	Hz
9	Doppler Rate of Change	501.27	Hz
10	Platform Velocity	7.0	Km/s
11	Integration Time	2.0	s
12	Azimuth Sample Time	0.0	s
13	tc	1.0	s
14	Point Range, rp	840.0	kM
15	Point Azimuth tp in index units	1000	index

1 Introduction

We will present the algorithms and simulation results for a point target in SAR. The target simulations will be performed following the procedure developed by McDonough, et. al. (1985) [1] for the typical SEASAT-SAR geometry Figure 1 and parameters given in Table 1. A technique by Fitch [2] will also be used to avoid a Hilbert transform.

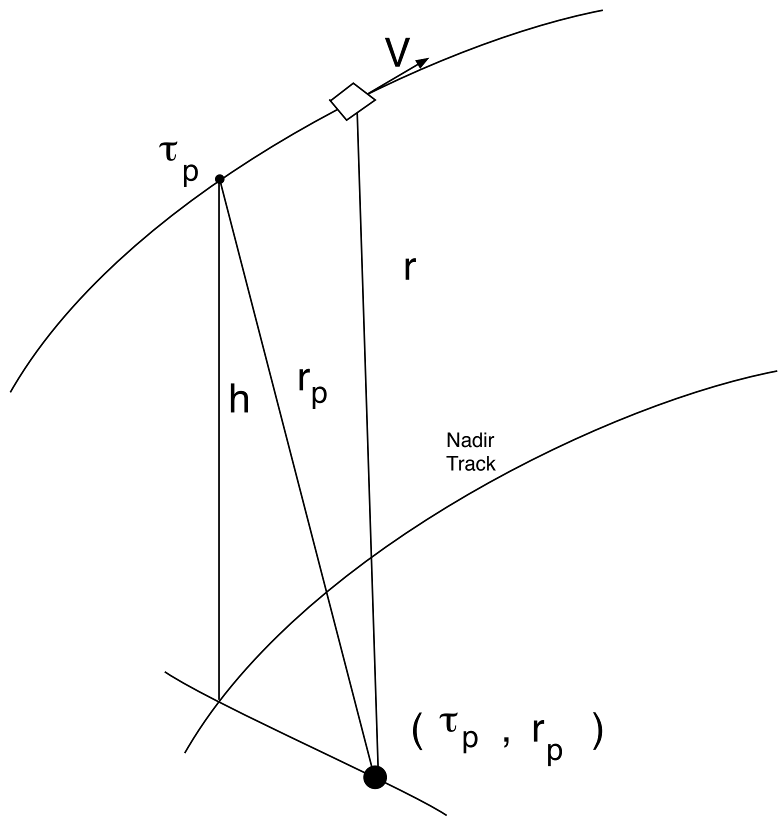

Figure 1: SAR Geometry

2 Point Target Response

Consider a point target arbitrarily placed at position (r_p, τ_p). The radar will fly at some height h, and velocity v. The slant range to the target changes as a function of viewing position as shown by

$$r(t,\tau) = r_p + \frac{v^2}{2r_p}(\tau_c + \tau_p - \tau)^2 \tag{1}$$

where τ is the time variable in the azimuth direction, τ_c coincides with the mid point of the integration time, and τ_p is the azimuthal time location of the point target relative to τ_c. To derive 1 , we note that

$$r^2(t,\tau) = r_p^2 + (v \times (\tau_c + \tau_p - \tau))^2 \tag{2}$$

Then using a Taylor series expansion,

$$r(t,\tau) = r_p + \frac{v^2}{2r_p}(\tau_c + \tau_p - \tau)^2 - \frac{v^4}{2r_p^3}(\tau_c + \tau_p - \tau)^4 + ... \quad (3)$$

Note that $\frac{v\times(\tau_c+\tau_p-\tau)}{r_P} \ll 1$ so we get 1 .

Equation 1 shows that the range history of the target during the integration time for forming an aperture is described by a parabola. For example, if we consider τ_p to coincide with τ_c, then the slant range will be a maximum when the target first enters the beam at $\tau = 0$. It will then reach a minimum when $\tau = \tau_c$, and will again increase to some maximum as the target exits the beam. Now, if the τ_p is not identically located at τ_c, then the beginning and ending slant ranges will not be equal. The difference in the two range positions is known as range walk, and together with the parabolic curvature introduced into the range, the problem is known as range migration.

To obtain high resolution in the range direction, the radar transmits an FM chirped pulse of the form,

$$s(t) = \cos 2\pi(f_0 t + \pi K_r t^2) \quad |t| \leq \Delta t/2 \quad (4)$$

where $s(t)$ is the transmitted signal, f_0 is the carrier frequency of the radar, K_r is the chirp rate and Δt is the pulse width.

Each pulse has a duration of 33.8 μ sec and a chirp rate of 0.5621 MHz/μsec or a pulse bandwidth B_r of 19 MHz which results in a slant range resolution $\delta r = \frac{c}{2} B_r \sin\theta$ of 25 meters.

Figure 2 shows plots of the time domain and frequency domain signal for the radar FM chirped pulse for range.

The received pulse $g(t)$ will be delayed by the round trip time of $2\frac{r(\tau)}{c}$, or,

$$g(t) = \cos\left[(2\pi f_0(t - 2r(\tau)/c) + \pi K_r\left(t - 2r(\tau)/c\right)^2\right] \quad |t - 2r(\tau)/c| \leq \Delta t/2 \quad (5)$$

where $r(\tau)$ is the slant range from the radar at time τ, to the target at position (r_p, τ_p), and c is the speed of light. To minimize the required sampling rate, the signal is then mixed with a local oscillator at the carrier frequency 1275 MHz and down-converted to some intermediate frequency of f_1= 11.38 MHz resulting in,

$$g(t) = \cos\left[(2\pi f_1 t - 2r(\tau)/\lambda) + \pi K_r\left(t - 2r(\tau)/c\right)^2\right] \quad (6)$$

Range Compression

To get any useful information regarding the position of the target, the down-converted received signal can be correlated with a reference function. Thus, when the two signals are coincident at some time and have the same shape the output of the correlation is at a maximum. The correlation is performed as the convolution of $g'(t)$ and the replica $s'(-t)$ as,

$$s'(-t)*g'(t) = \Delta t/2Re\left[\sin\left(\pi B_r\left(t-2r(\tau)/c\right)\right)/(\pi B_r\left(t-2r(\tau)/c\right) \times e^{-j4\pi r(\tau)/\lambda}e^{2pif_1 t}\right] \quad |t-2r(\tau)/c| \le \Delta t \tag{7}$$

where B_r is the bandwidth.

Hence, the time domain convolution in the above expression results in the desired range compressed signal. Now, the reference function for the pulse compression has $U = \tau f_s$ or $33.8\ \mu sec \times 45.03\ MHz = 1530$ points. Thus the time domain correlation will require on the order of $U \times U$ or 2×10^6 multiplications. The number of operations, however, can be significantly reduced to $2U \log U$ or 9.7×10^3 if the time domain convolution is performed as multiplication in the frequency domain. The range compression in the frequency domain is obtained from:

1. Take the DFFT $(g'(t))$ to get $G'(f)$ of length N.
2. Take the DFFT $(s'(t))$ to get $S'(f)$ of length N.
3. Truncate the spectrums to half of the original lengths.
4. Range compressed $= FFT^{-1}\left(G'(f)S'(f)\right)$ of length $\frac{N}{2}$.
5. (r_0) position of point target $= \max(|FFT^{-1}\left(G'(f)S'(f)\right)|)$.

At the end of operation 4 we are left with the right hand side of Equation 7. Step number 3 is necessary since the azimuth compression requires a complex sequence for correlation. This important approach for real to complex conversion using FFTs was described by Fitch in 1988 [2] and it bypasses the need for a Hilbert transform. Basically, the complex sequence has a real part equal to samples of the real signal taken at half the original rate and a spectrum equal to the first half of the original real sequence spectrum. The real to complex conversion is accomplished by using the first half of the spectral coefficients.

The result of the matched filter for range compression is illustrated in the plot in Figure 3.

The range compression operation begins by fixing an arbitrary reference point within the matrix with a known $r(t_{ref}, \tau_{ref})$ and computing its impulse response $g(t)$ using 6. Then, the response $g(t)$ to the fixed value of τ, which is the azimuthal position of $r(t,\tau)$ of 1. The time extents of both $s(t)$ and $g(t)$ are 33.8 μsec and the signals are sampled at f_s or 45.03 MHz. Each pulse is then compressed using a 2048 point FFT according to the procedure described above.

The result of compressing a single pulse is shown in Figure 3. It basically demonstrates the result of the correlation output from Equation 7 showing an envelope of $\frac{\sin x}{x}$ which is maximized when $t = 2r_P/c$, where r_p is the range to the point target. Hence, the range location, r, of the point target has been recovered. Figure 4 illustrates the FM Chirped Pulse and the Compression and Resolution Related to Bandwidth. To show that the range compression is indeed a $\frac{\sin(x)}{x}$ function, Figure 5 shows the range compression of Figure 3 zoomed in.

The range compression process is repeated by moving in the azimuthal direction, fixing the slant range to the point target $r(\tau)$ and transmitting pulses at the PRF rate. For this particular simulation, using an integration time of 2 seconds and a PRF of 1645, a total of 3290 pulses were transmitted.

As the range returns are received a matrix is formed as shown in Figure 6. An illustration of the SAR image prior to range compression and azimuth compression for a point target is shown in Figure 7.

If we consider a number of successive echoes, due to the large change in the range from the satellite to the target during integration time T_i, the range compressed point response will be a parabolic curve as shown by Equation 1 and :

$$\frac{Z^2}{r_0 c} - \frac{\tau}{2} < Y < \frac{Z^2}{r_0 c} + \frac{\tau}{2} \tag{8}$$

and

$$-\frac{vT_i}{2} < Z < \frac{vT_i}{2} \tag{9}$$

where Y is the start of each pulse, $Z = v\tau$, and τ' is the pulse duration.

Azimuth Compression

Now, the complex exponential term $e^{-4\pi r(\tau)\lambda}$ appearing in Equation 7, represents the azimuth phase history which is encoded in the range compressed signal. If $r(\tau)$ is expanded about τ_c,

$$r(\tau) = r(\tau_c) + \dot{r}(\tau_c)(\tau - \tau_c) + \frac{1}{2}\ddot{r}(\tau_c)(\tau - \tau_c)^2 + ... \tag{10}$$

where

$$f_{DC} = -\frac{2\dot{r}}{\lambda} \tag{11}$$

is the Doppler frequency and,

$$K_{az} = -\frac{2\ddot{r}}{\lambda} \tag{12}$$

is the rate of change of Doppler frequency.

$\dot{r}$ and $\ddot{r}$ are the velocity and acceleration vectors respectively.

Re-writting $r(\tau)$ in terms of f_{DC} and K_{az} we get:

$$g(\tau) = e^{-j4\pi r(\tau)/\lambda} = e^{-j4\pi r_c/\lambda} e^{j2\pi f_{DC}(\tau-\tau_c)+j\pi K_{az}(\tau-\tau_c)^2} \quad |\tau - \tau_c| \leq \Delta\tau/2 \ \mathit{and} \ 0 \ \mathit{elsewhere} \tag{13}$$

The matched filter for the azimuth compression will have an impulse response of the form:

$$h(\tau) = e^{j2\pi(f_{DC}\tau - 0.5K_{az}\tau^2)} \quad |\tau| \leq \Delta\tau/2 \tag{14}$$

Figure 8 shows a plot of the Azimuth complex matched filter $h(\tau)$.

For the azimuth compression an operation similar to the range compression is required. The range compressed lines are read back into memory from external disk storage, and the data are corner turned such that consecutive azimuth cells are aligned for a given range line. In actuality, at this stage a range walk and curvature correction is required since the range data are collected along a parabolic curve in the azimuth direction. Each range compressed line will then have a $g(t)$ which will then be convolved with $h(\tau)$ to get:

$$b(\tau) = g(\tau) * h(\tau) = e^{j2\pi f_{DC}\tau)} \times e^{-j2\pi(2r_c/\lambda + f_{DC}\tau_c)} \times \Delta\tau\left(\pi B_D(\tau - \tau_c)\right)/\left(\pi B_D(\tau - \tau_c)\right) \quad |\tau - \tau_c| \leq \Delta\tau/2 \tag{15}$$

where $B_D = 2f_{DC}$. The matched filter response $h(\tau)$, is generated with a τ spacing of $\frac{1}{PRF}$ and f_{DC}= 1150 Hz and K_{az}= 501.3 Hz. Once again because of computational efficiency the above convolution is performed in the frequency domain:

1. Take the $DFFT(g(\tau))$ to get $G(f)$.
2. Take the $DFFT(h(\tau))$ to get $H(f)$.
3. Azimuth compressed $b(\tau) = FFT^{-1}\left(G(f)H(f)\right)$
4. τ position of point target= $max\left(|b(\tau)|\right)$

We note that since both $g(\tau)$ and $h(\tau)$ are complex, the original length of the sequence for the FFT's were used. The above process is repeated until each of the range compressed lines are compressed in the azimuth. The output of the correlator $\frac{\sin \pi B_D(\tau - \tau_c)}{\pi B_D(\tau - \tau_c}$ is a maximum when $\tau = \tau_c$, or when the azimuth position of the point target is aligned with the mid point of the beam.

The SAR image for a poiint targets are shown in Figures 9, and 10.

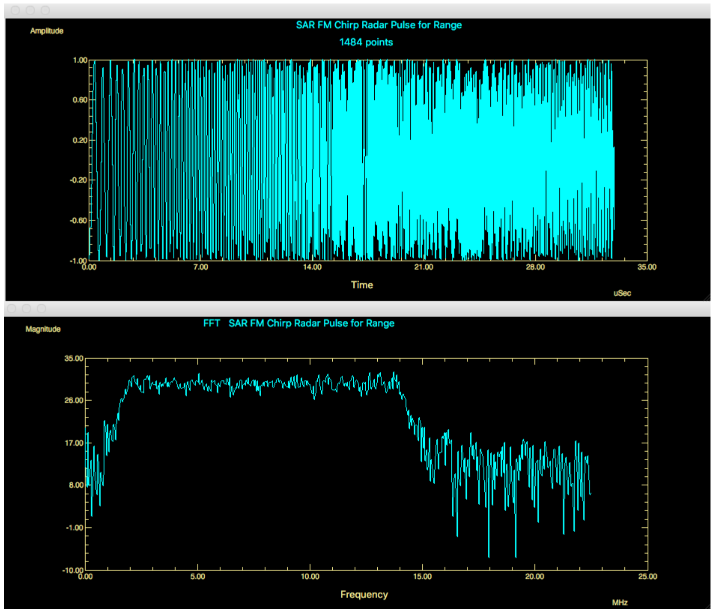

Figure 2: SAR Range FM Chirp Radar Signal

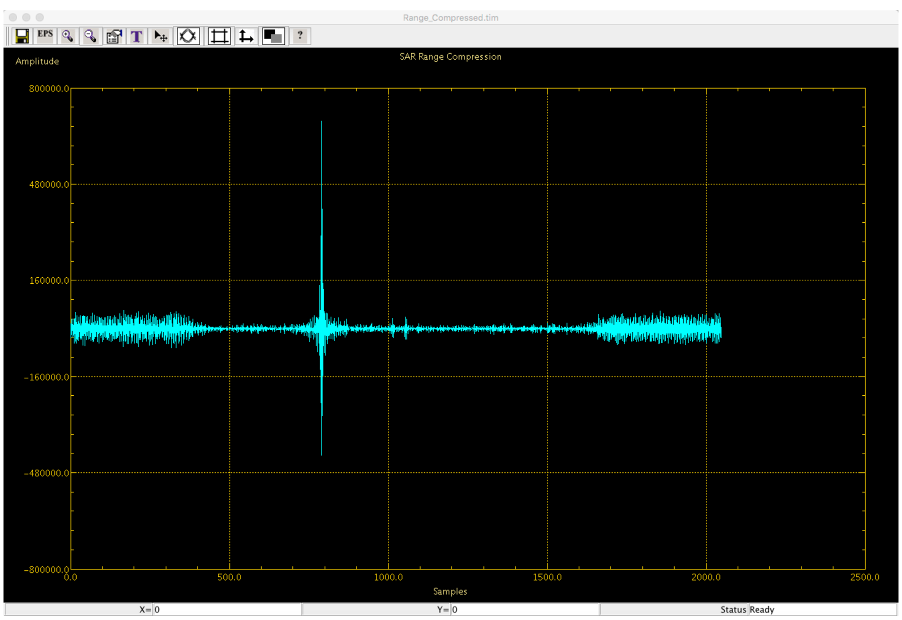

Figure 3: SAR Image Range Compression

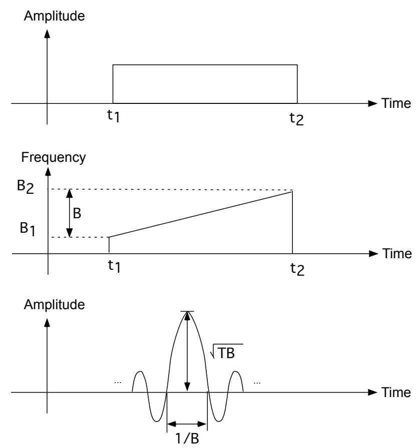

Figure 4: SAR Image Range FM Chirped Radar and Compression

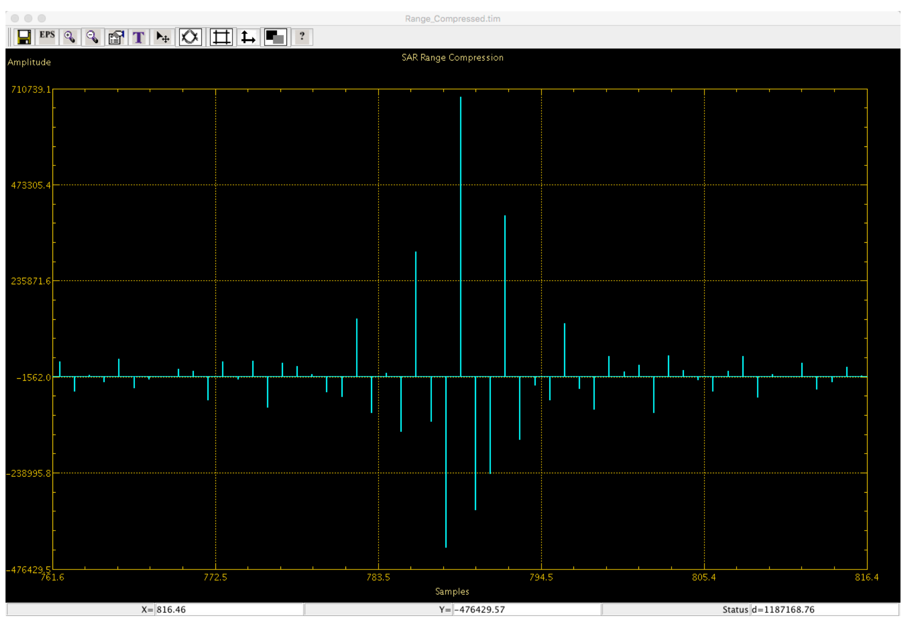

Figure 5: SAR Image Range Compression Zoomed Discrete Showing Sin(x)/x Response

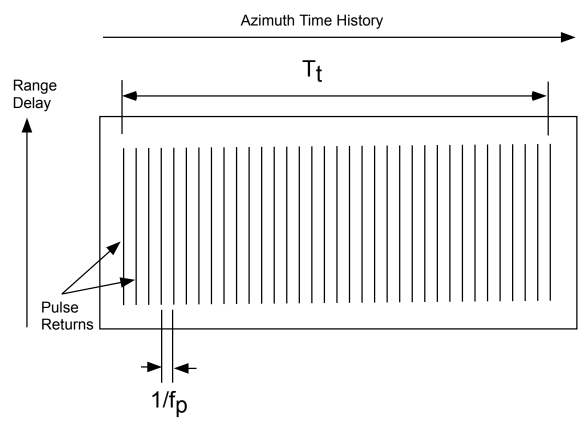

Figure 6: SAR Record Radar Returns

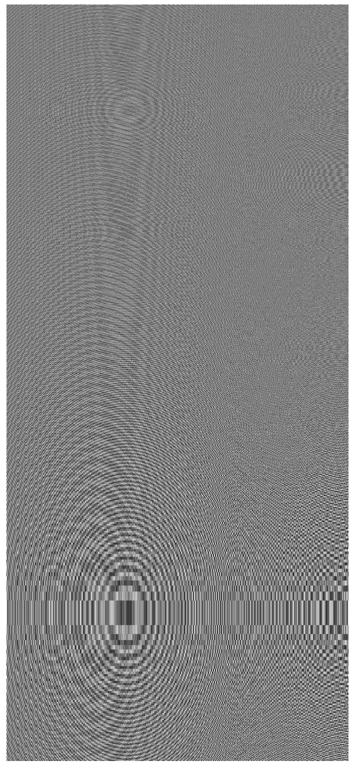

Figure 7: SAR Image of Point Target

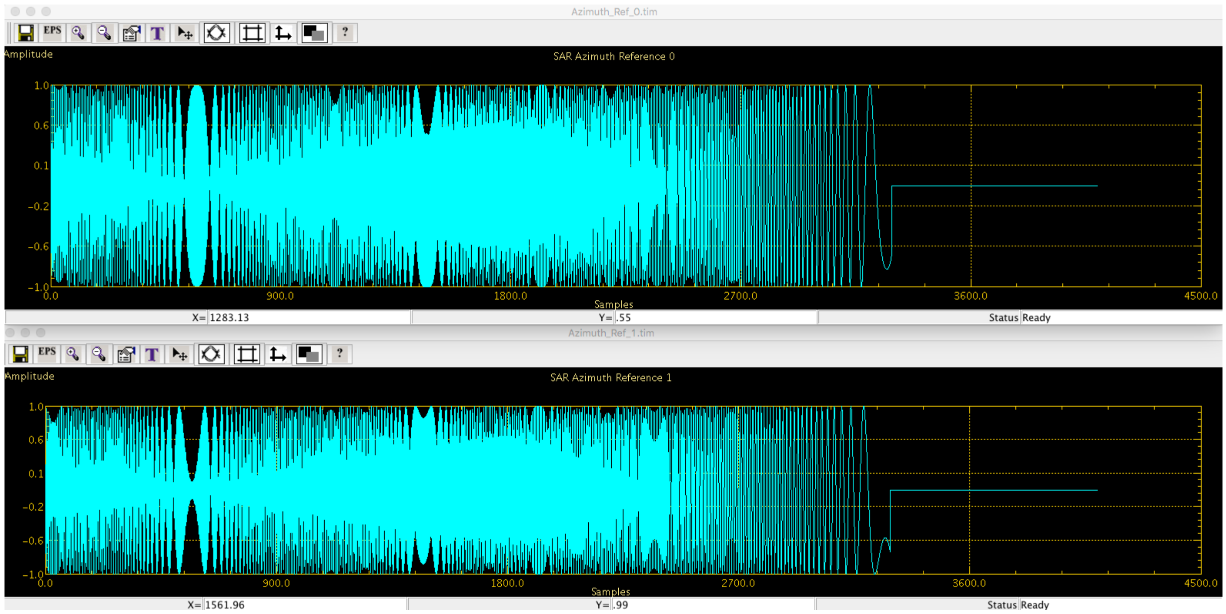

Figure 8: SAR Azimuth Range Reference (Complex)

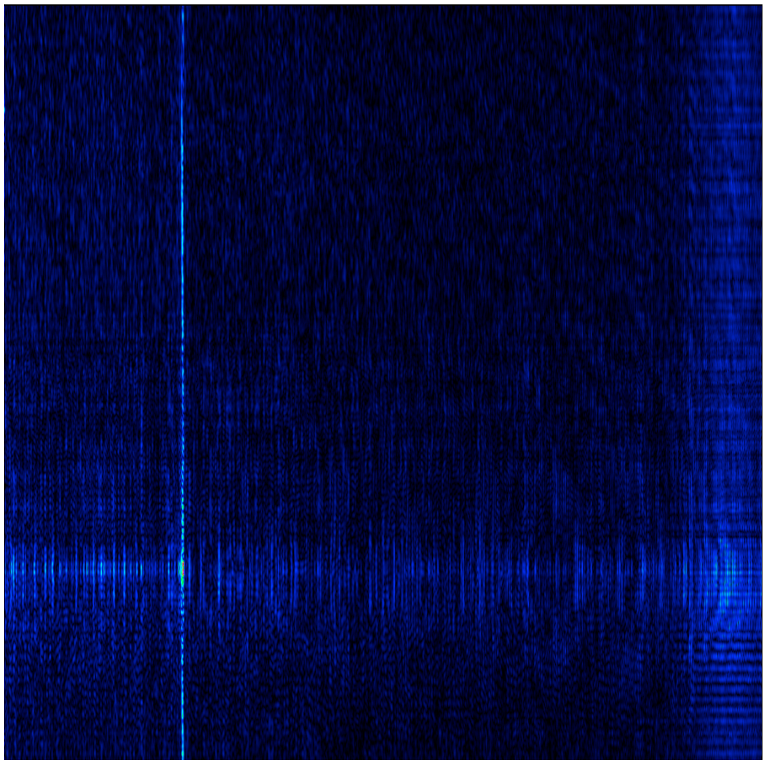

Figure 9: SAR Image Formation Point Target Range 840.8 kM Azimuth Index 200

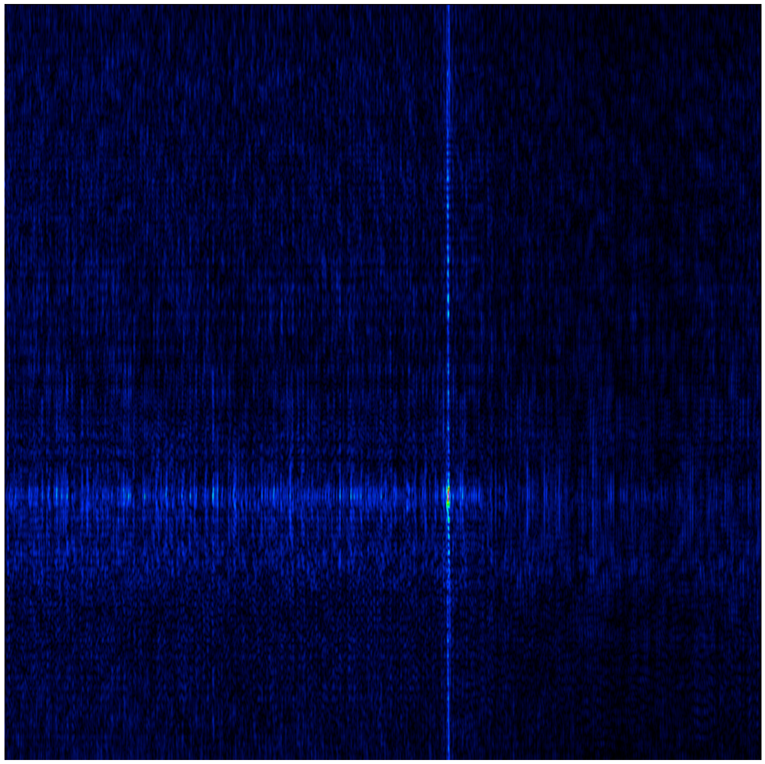

Figure 10: SAR Image Formation Point Target Range 842 kM Azimuth Index 300

Auto-Focusing

The fundamental parameters in SAR target response are the Doppler frequency and the rate of change of the frequency. These parameters are solely dependent on the rate of change of the relative motion characteristics between the SAR sensor and the position of the target. Therefore, a precise knowledge of the spacecraft state vector is necessary in order to determine these parameters. In situations where a precise satellite tracking and ephemeris are not given and the Doppler spectrum and frequency sweep rate are not known apriori, these parameters must be derived from the radar data. Estimating the Doppler parameters is the topic of autofocus and clutter-locking. This adds to the system complexity, and a controller must be designed to not only generate the reference functions for the azimuth, but also to provide a feedback loop to refine and readjust the Doppler parameters.

SAR Block Diagram Simulation

Complete C code for SAR signal processing is available for the Capsim Block Diagram Simulation and Modeling Environment. Visit the following site to obtain the SAR project, including documentation:
http://www.ccdsp.org

3 References

1- McDonough R.N., et. al., Image formation from spaceborne synthetic aperture radar signals. 1985 APL Technical Digest Vol. 6, No. 4 pp 300-312

2- Fitch, J.P. , Synthetic Aperture Radar. 1988 Springer-Verlag New York Berlin Heidelbergh.

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