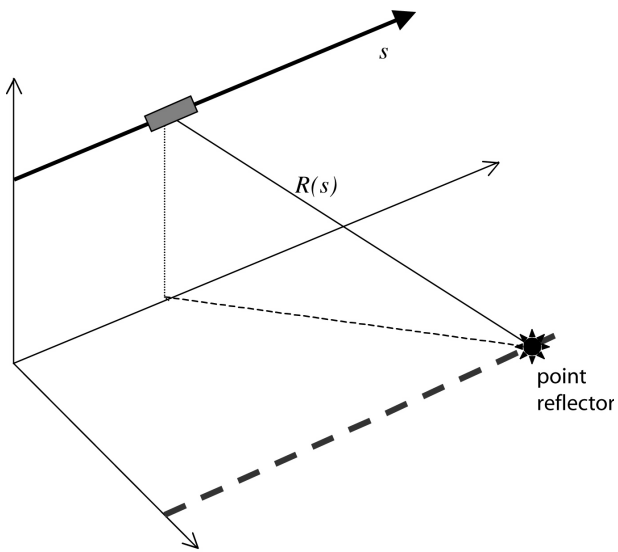


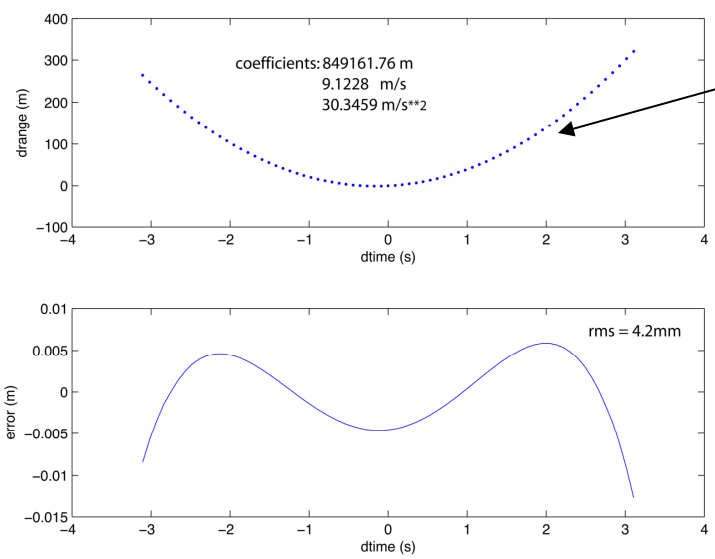
phase history of point reflector

$$C(s) = \exp\left\{ i \frac{4\pi}{\lambda} \left[R(s) \right] \right\}$$

parabolic approximation to range history

$$R(s) = R_o + \dot{R}_o (s - s_o) + \frac{\ddot{R}_o}{2} (s - s_o)^2 + \ldots$$

$$f_{DC} = \frac{-2\dot{R}}{\lambda} \qquad f_R = \frac{2\ddot{R}}{\lambda}$$



Least-squares fit of range history for each point in DEM provides both the accurate position in range azimuth $\left[R_o, s_o \right]$ space and the Dopper centroid and rate parameters needed to focus the image. This analysis only needs to be applied to the master image.

http://topex.ucsd.edu/gmtsar

Scripps Institution of Oceanography Technical Report

GMTSAR: An InSAR Processing System Based on Generic Mapping Tools

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May 1, 2011

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2. Software
    - 2.1 Standard products
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Appendix B. SAR Image Formation

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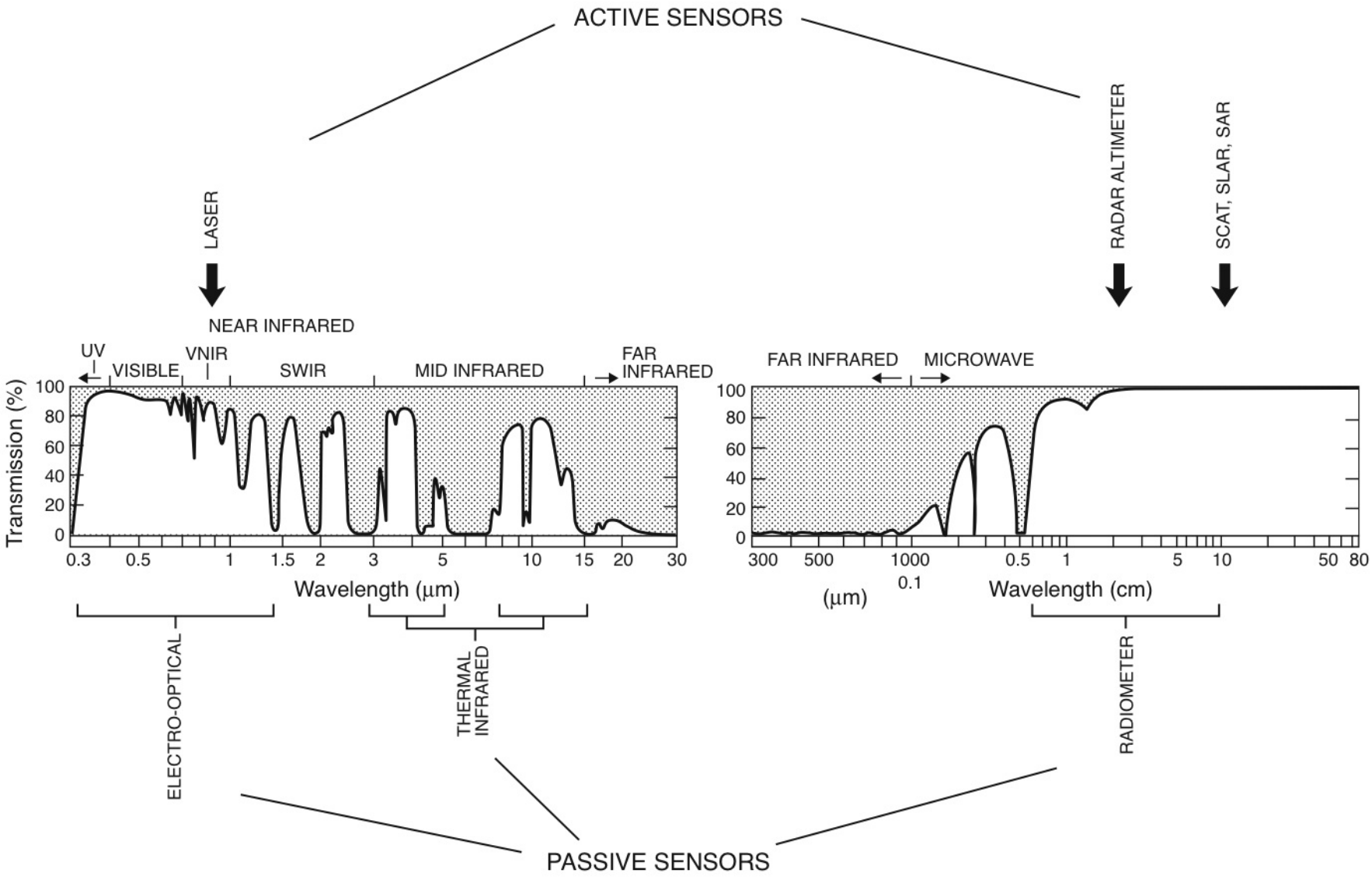
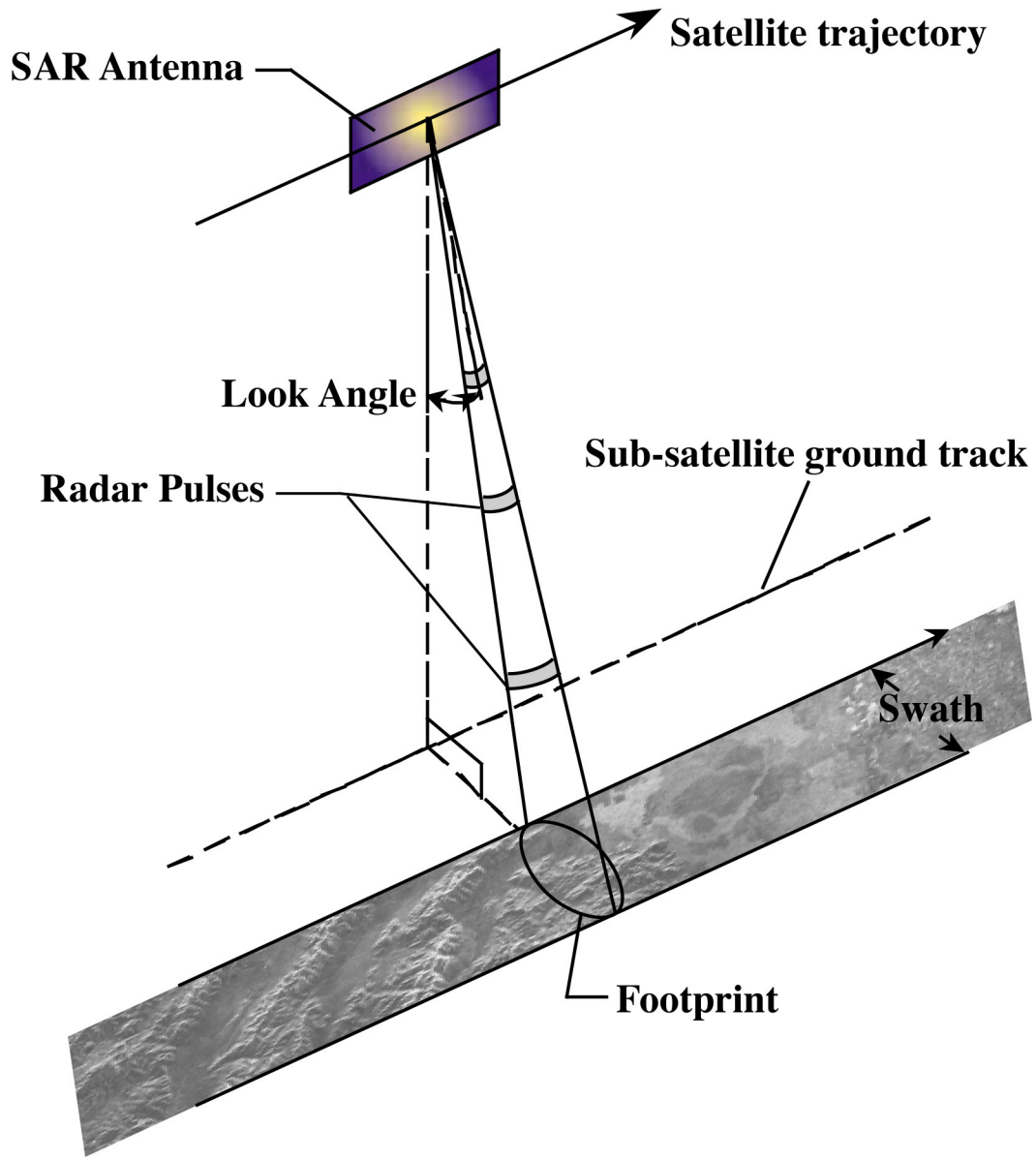
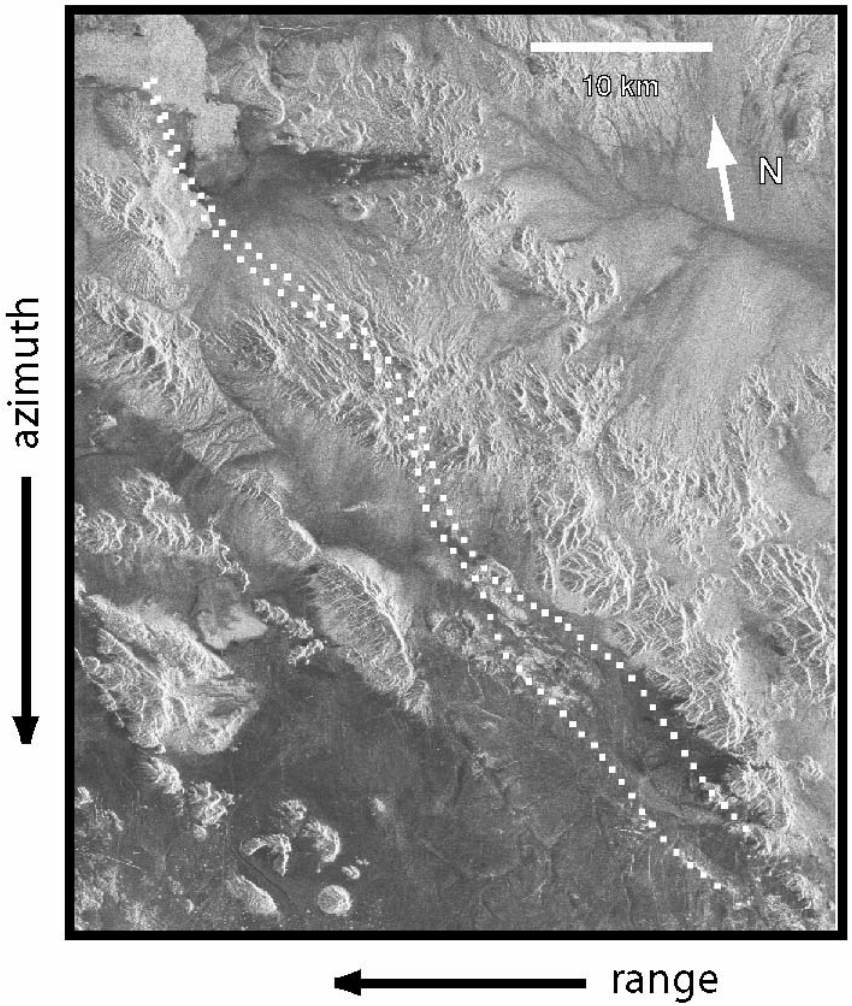
Appendix F. Installation of GMTSAR


ACTIVE SENSORS
LASER
RADAR ALTIMETER
SCAT, SLAR, SAR
NEAR INFRARED
UV
VISIBLE
VNIR
SWIR
MID INFRARED
FAR INFRARED
Transmission (%)
100
80
60
40
20
0
0.3
0.5
1
1.5
2
3
5
10
15
20
30
Wavelength (μm)
FAR INFRARED
MICROWAVE
300
500
1000
0.1
(μm)
0.5
1
5
10
50
80
Wavelength (cm)
ELECTRO-OPTICAL
THERMAL INFRARED
RADIOMETER
PASSIVE SENSORS

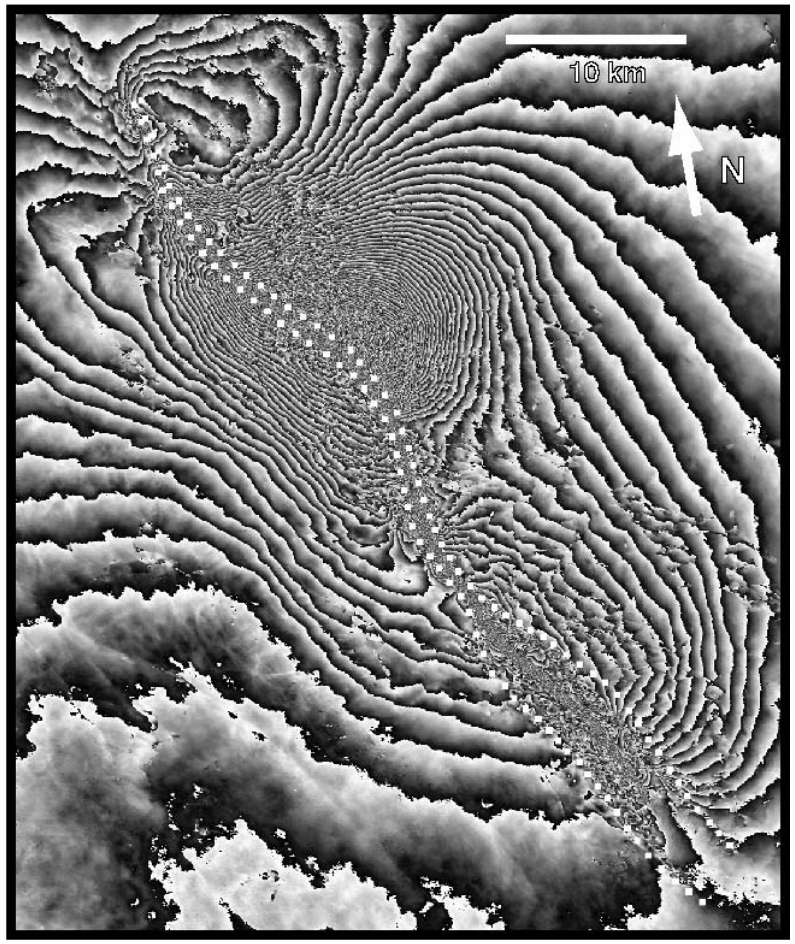

Satellite trajectory
SAR Antenna
Look Angle
Sub-satellite ground track
Radar Pulses
Swath
Footprint

amplitude and phase

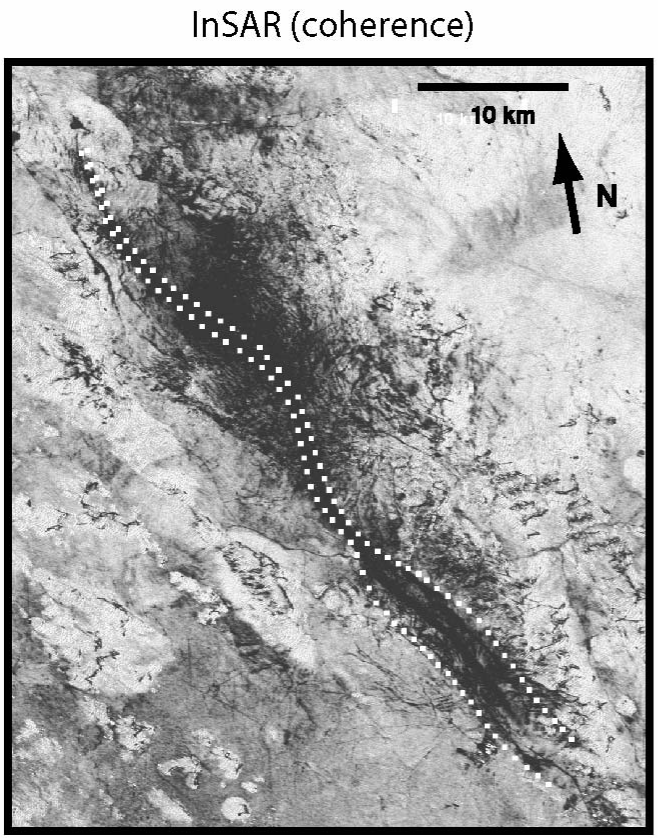
step 1 - SAR (amplitude)

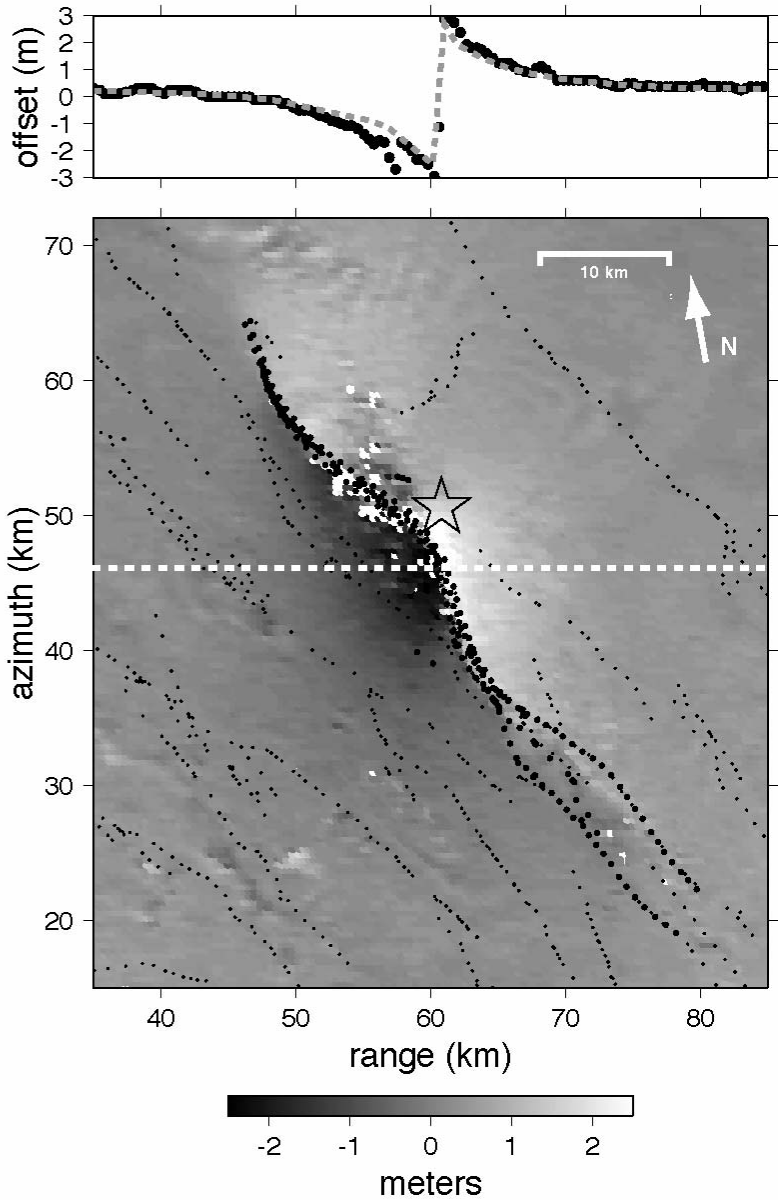


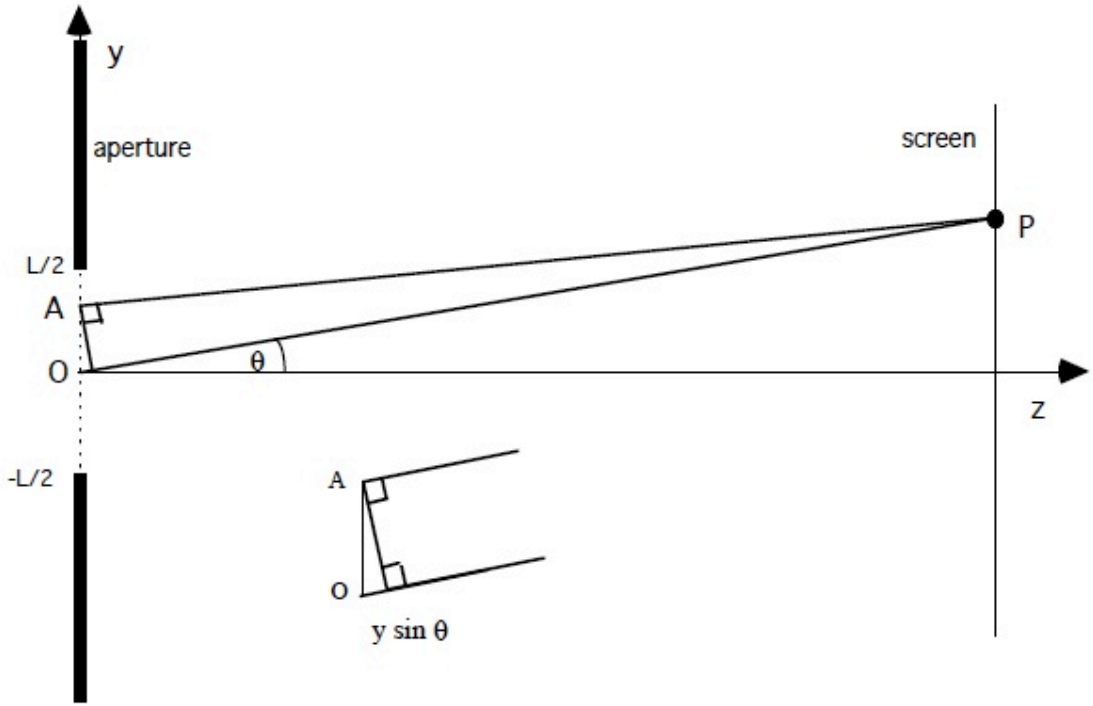
step 2 - InSAR (phase difference)



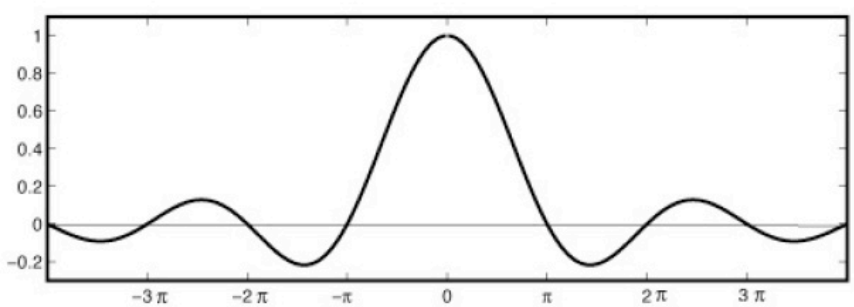
coherence and pixel matching





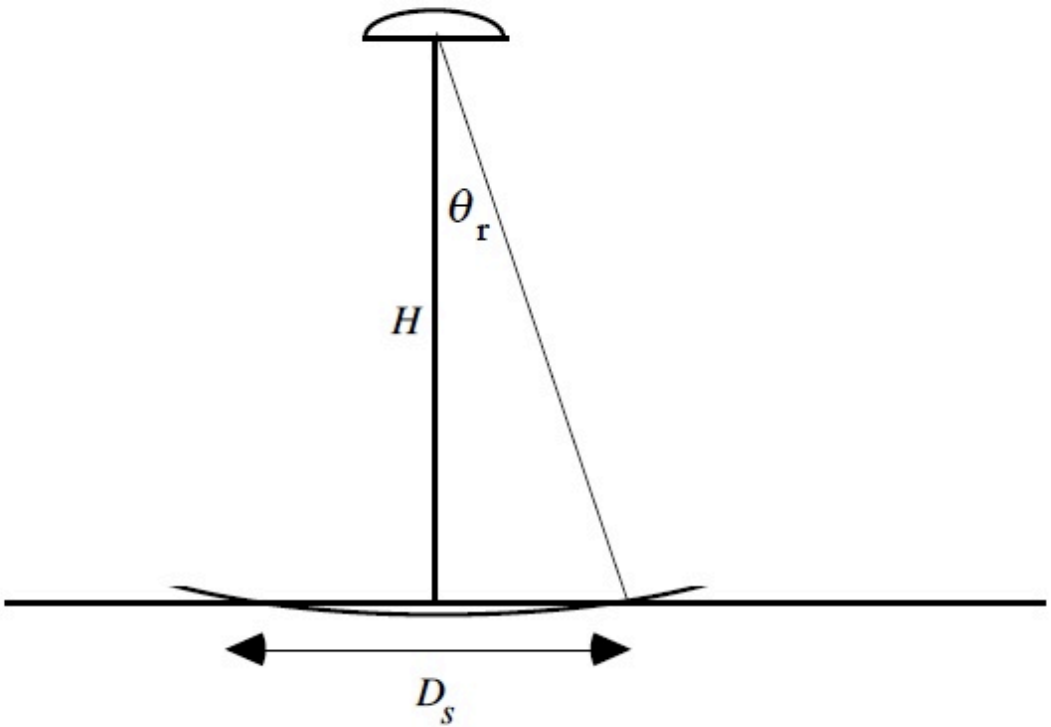


The illumination pattern on the screen is shown in the following diagram.



The first zero crossing, or angular resolution θ_r of the sinc function occurs when the argument is π so $\boxed{\sin\theta_r = \frac{\lambda}{L}}$ and for small angles $\theta_r \cong \lambda / L$ and $\tan\theta_r \cong \sin\theta_r$. Note that

resolution: optical vs. microwave



$$D_s = 2H\sin\theta_r = 2H\frac{\lambda}{L}$$

$$H = 800km.$$

$$Optical:$$

$$L = 1m$$

$$\lambda = 0.5\mu m$$

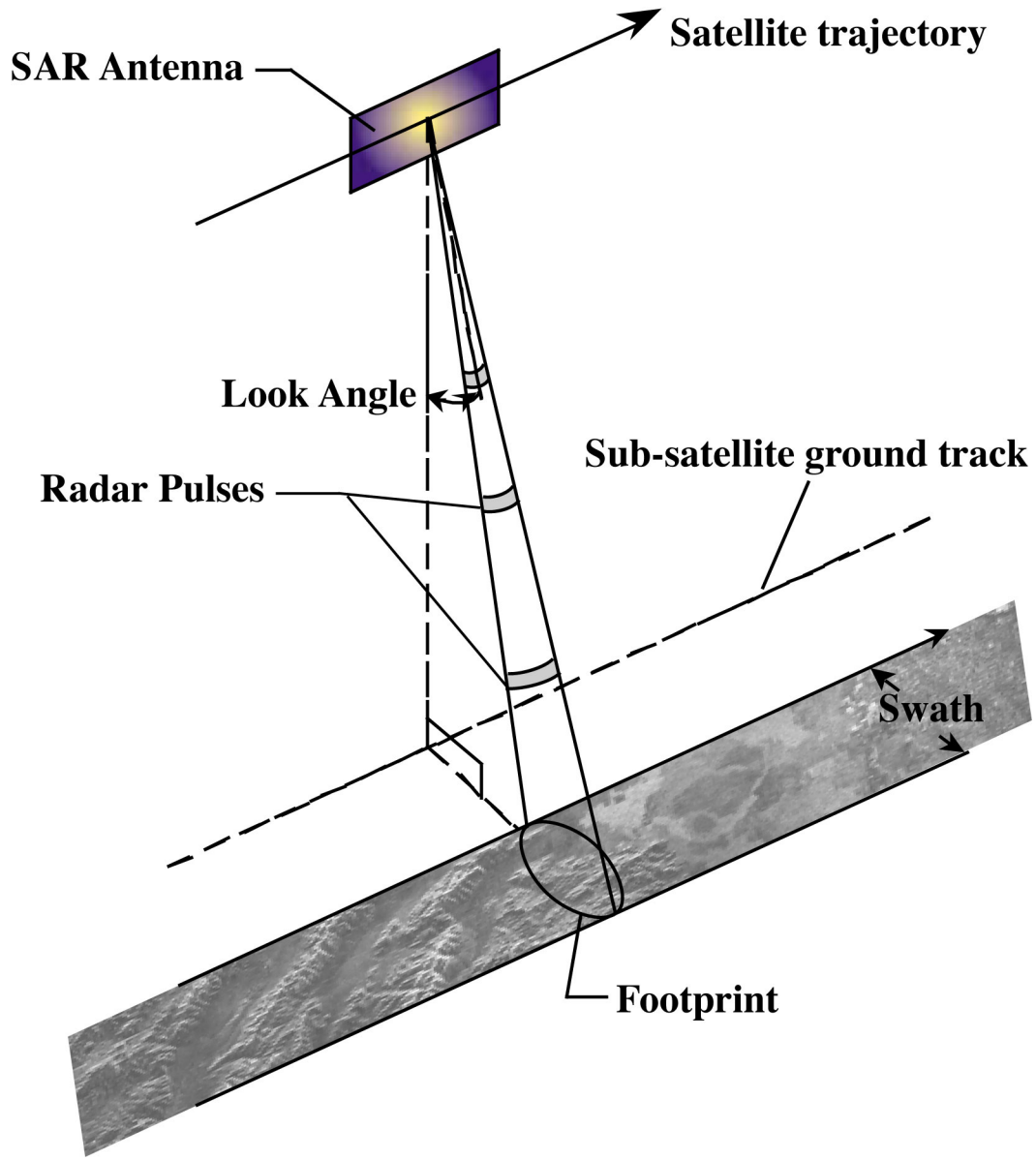
$$D_s = 0.8m$$

$$Microwave:$$

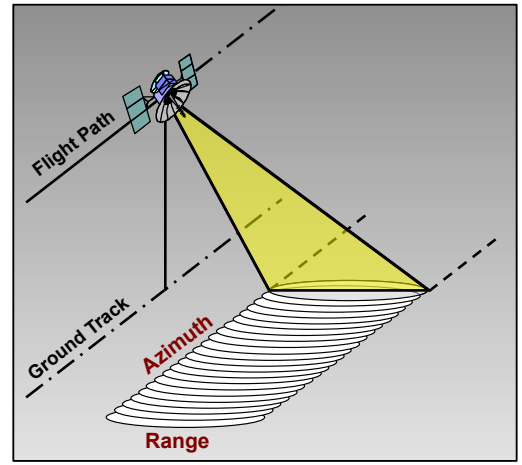
$$L = 10m$$

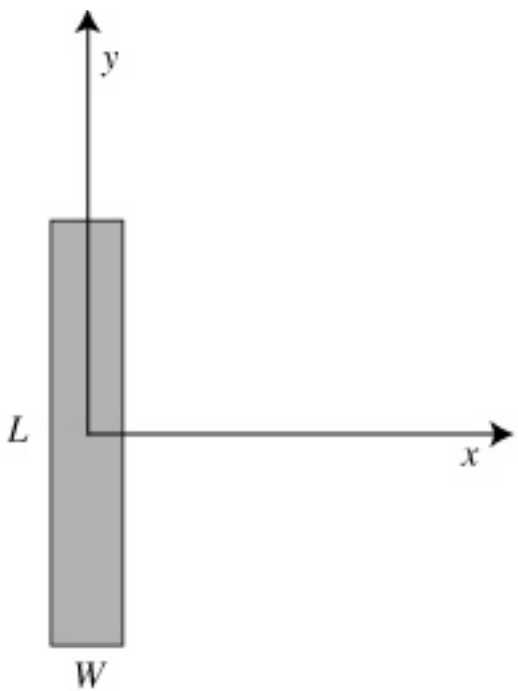
$$\lambda = 0.23m$$

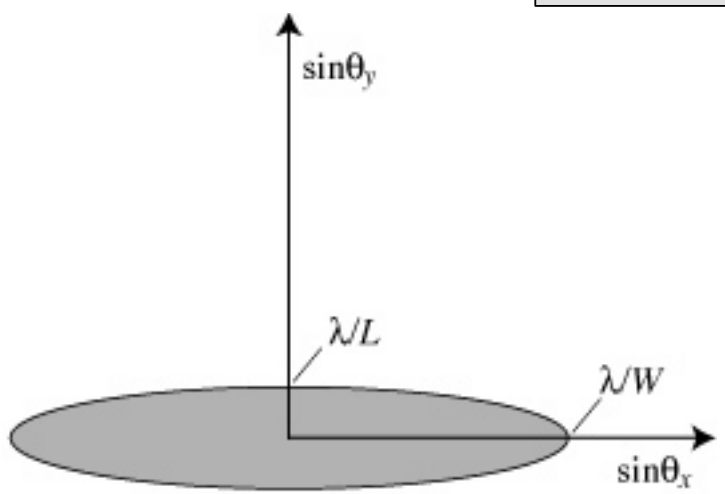
$$D_s = 46{,}000m!!!!!!$$


Satellite trajectory
SAR Antenna
Look Angle
Sub-satellite ground track
Radar Pulses
Swath
Footprint

2-D Aperture

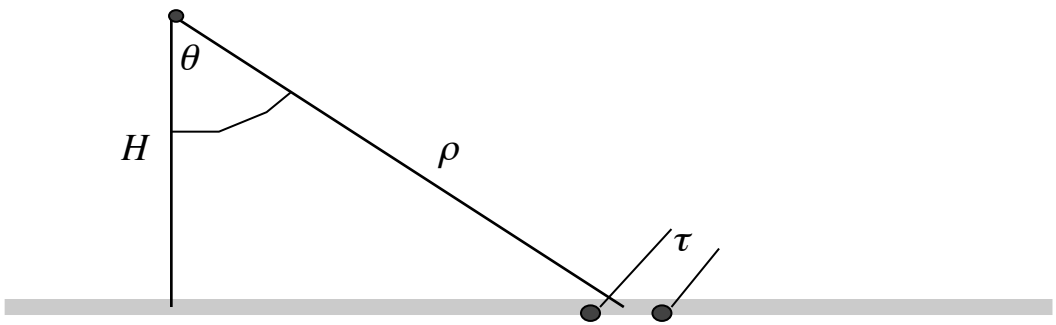






$$P(\theta_x,\theta_y) = \int_{-L/2}^{L/2}\int_{-W/2}^{W/2} A(x,y)\exp\left[i\frac{2\pi}{\lambda}\left(x\sin\theta_x + y\sin\theta_y\right)\right]dxdy \quad \longrightarrow \quad P(\theta_x,\theta_y) = LW\ \mathrm{sinc}\left(\frac{\pi W\sin\theta_x}{\lambda}\right)\ \mathrm{sinc}\left(\frac{\pi L\sin\theta_y}{\lambda}\right)$$

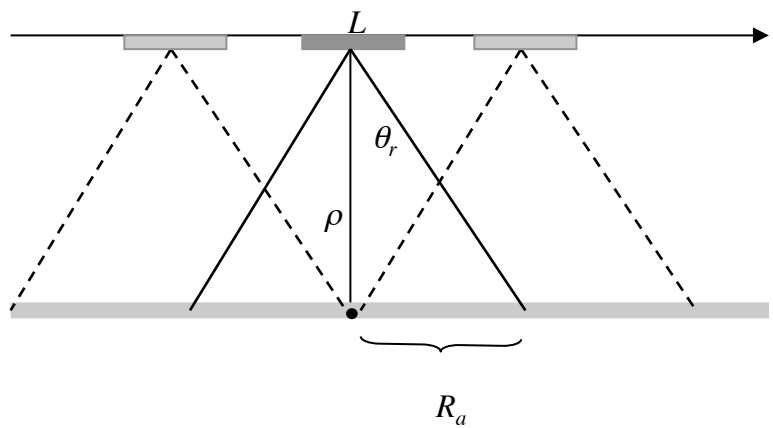
range resolution



θ - look angle
H - spacecraft height
τ - pulse length
C - speed of light (sound)

$$R_r = \frac{C\tau}{2\sin\theta}$$

azimuth resolution



L - length of radar antenna
ρ - nominal slant range $H/\cos\theta$
λ − wavelength of radar

unfocussed

$$R_a = \rho \sin\theta_r = \rho\lambda / L$$

focussed

$$R_a^{'} = \frac{\lambda H}{2R_a \cos\theta} = \frac{L}{2}$$

PRF - upper bound

The PRF cannot be too large or the return pulses from the near range and far range will overlap in time as shown in Figure A9.

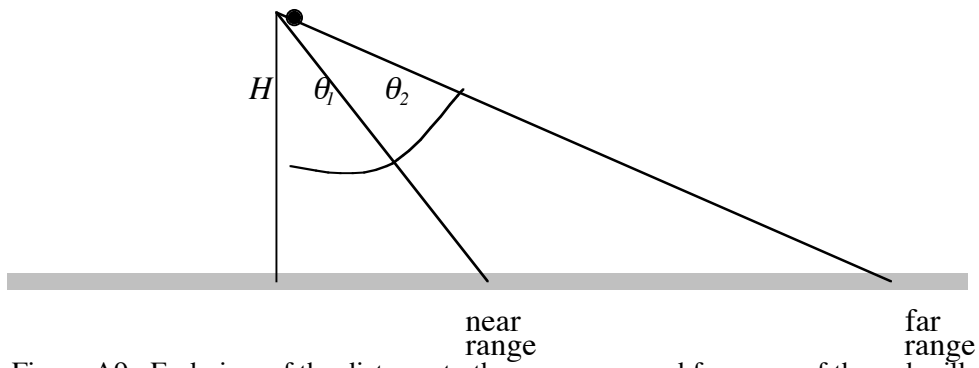


Figure A9. End view of the distance to the near range and far range of the radar illumination pattern.

$$PRF < \frac{1}{t_2 - t_1}$$

$$t_1 = \frac{2H}{C\cos\theta_1} \qquad t_2 = \frac{2H}{C\cos\theta_2}$$

$$\Delta t = \frac{2H}{C}\left(\sec\theta_2 - \sec\theta_1\right) \tag{A12}$$

$$\frac{2V}{L} < PRF < \frac{C}{2H}\left(\sec\theta_2 - \sec\theta_1\right)^{-1}$$

For ERS the look angles to the rear range and far range are 18˚ and 24˚, respectively. Thus the maximum PRF is 4777 Hz. The actual PRF of 1680 is safely below this value.

Problems

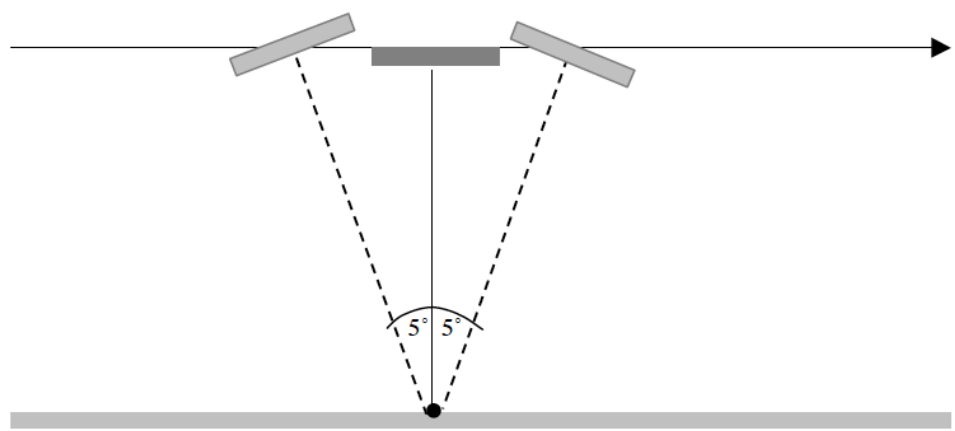
1) What is the illumination pattern for an aperture with a sign reversal at its center? What is $P(0)$? Is the function real or imaginary? Is the function symmetric or asymmetric?

The aperture is

$$A(y) = \begin{cases} 0 & |y| > \frac{L}{2} \\ 1 & 0 < y \le \frac{L}{2} \\ -1 & -\frac{L}{2} \le y < 0 \end{cases}$$

A13

3) What is the theoretical azimuth resolution of a spotlight-mode SAR that can illuminate the target over a 10° angle as shown in the diagram below.



5) What is the ground-range resolution of side-looking radar with a pulse length of 6×10^{-8} s and a look angle of 45°?

7) (a) What is the period for a satellite in a circular orbit about the moon where the radius of the orbit is 1.9×10^{6} m? The mass of the moon is 7.34×10^{22} kg.

(b) You are developing a SAR mission for the moon. The length of your SAR antenna is 10 m. What minimum pulse repetition frequency is needed to form a complete aperture? The circumference of the moon is 1.1×10^{7}m. You will need the orbital period from problem (a).

8) Derive equation (A10)

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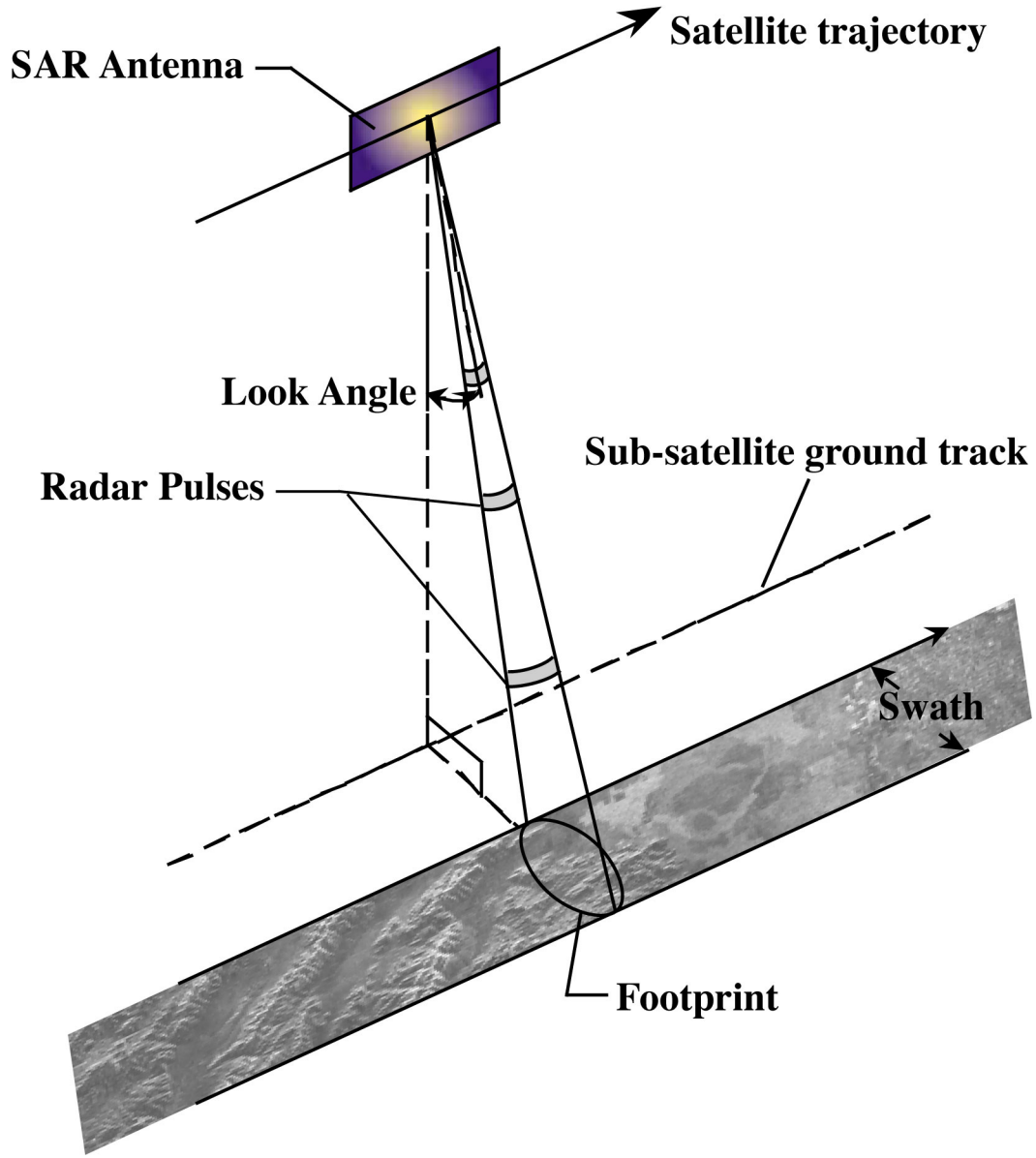
How is the image focused in the computer?



SAR processor

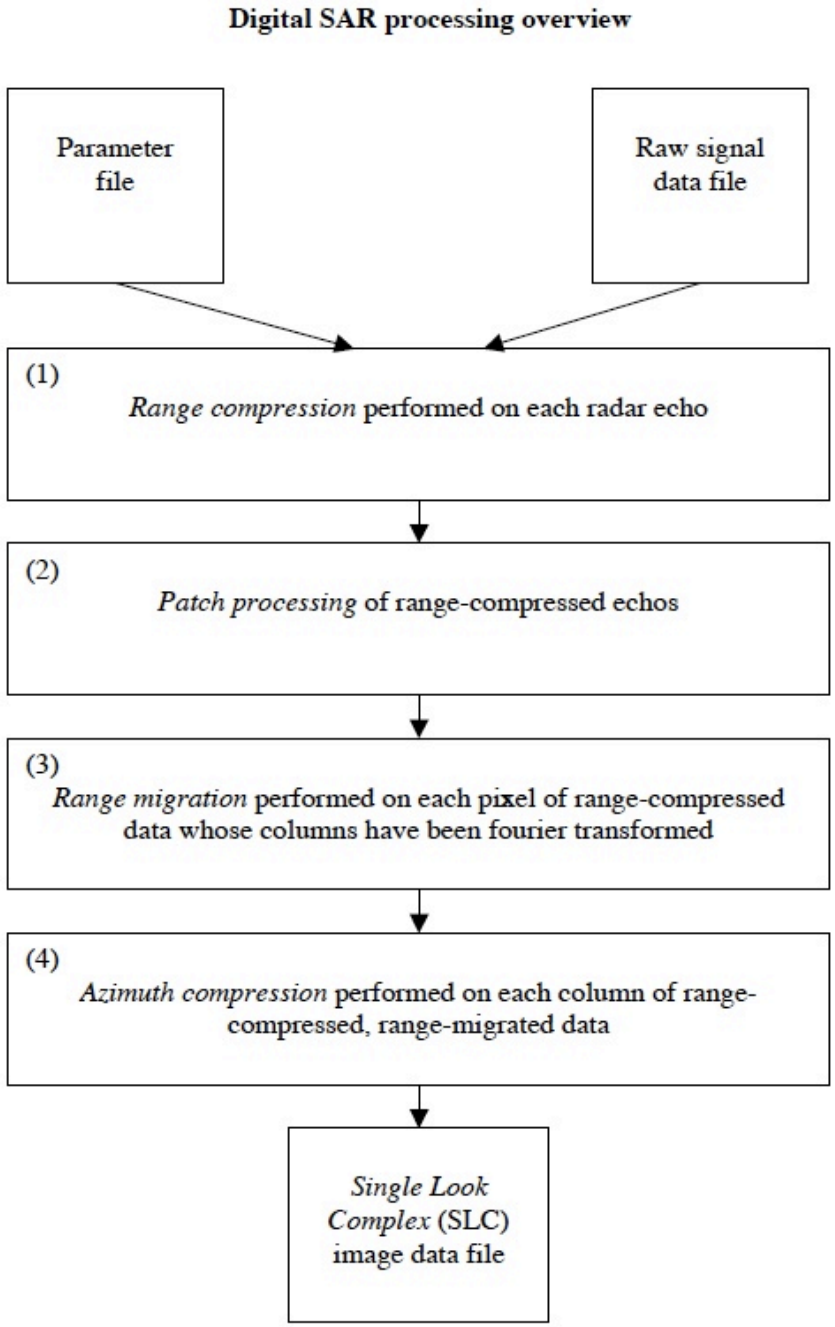
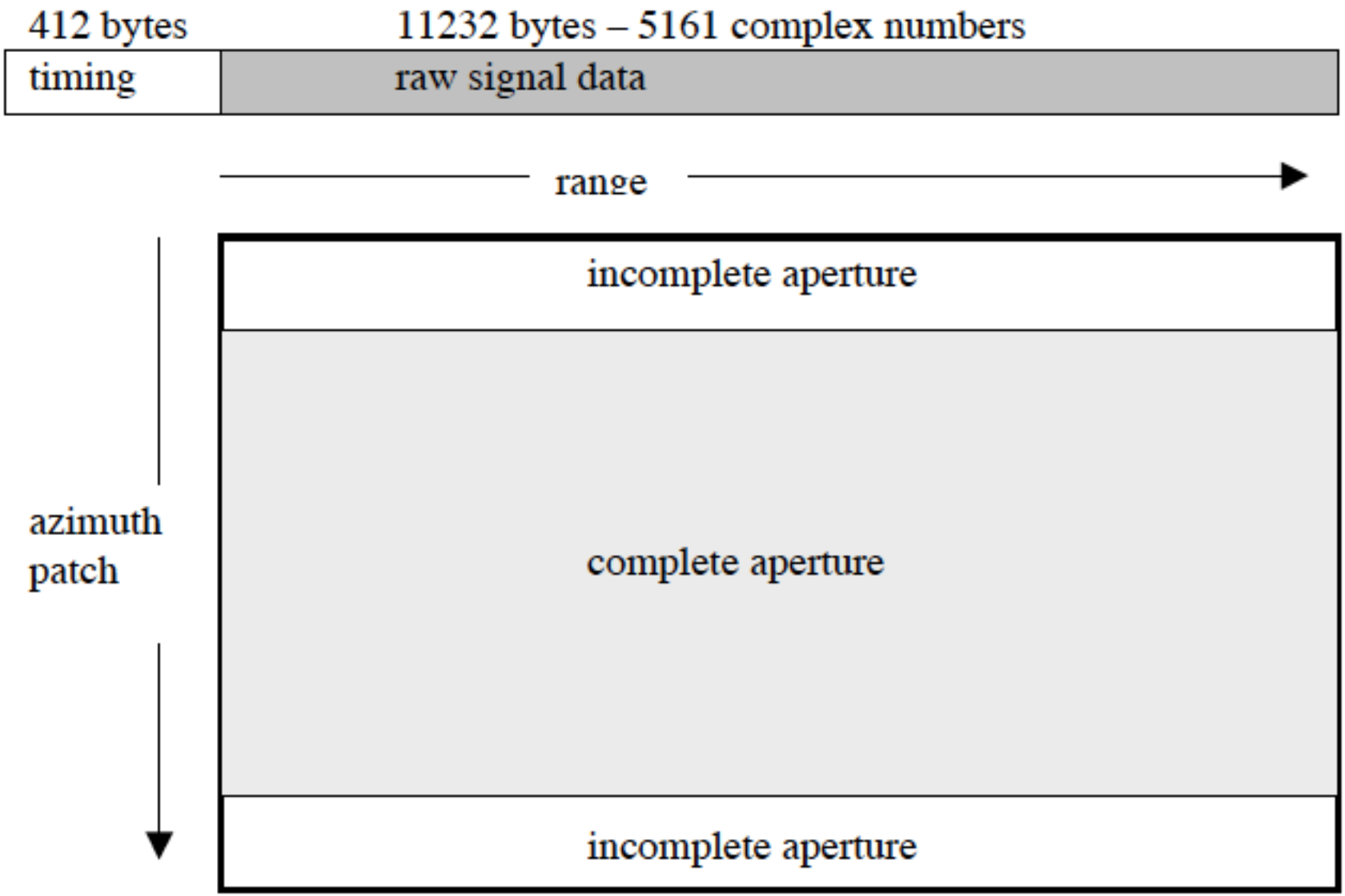
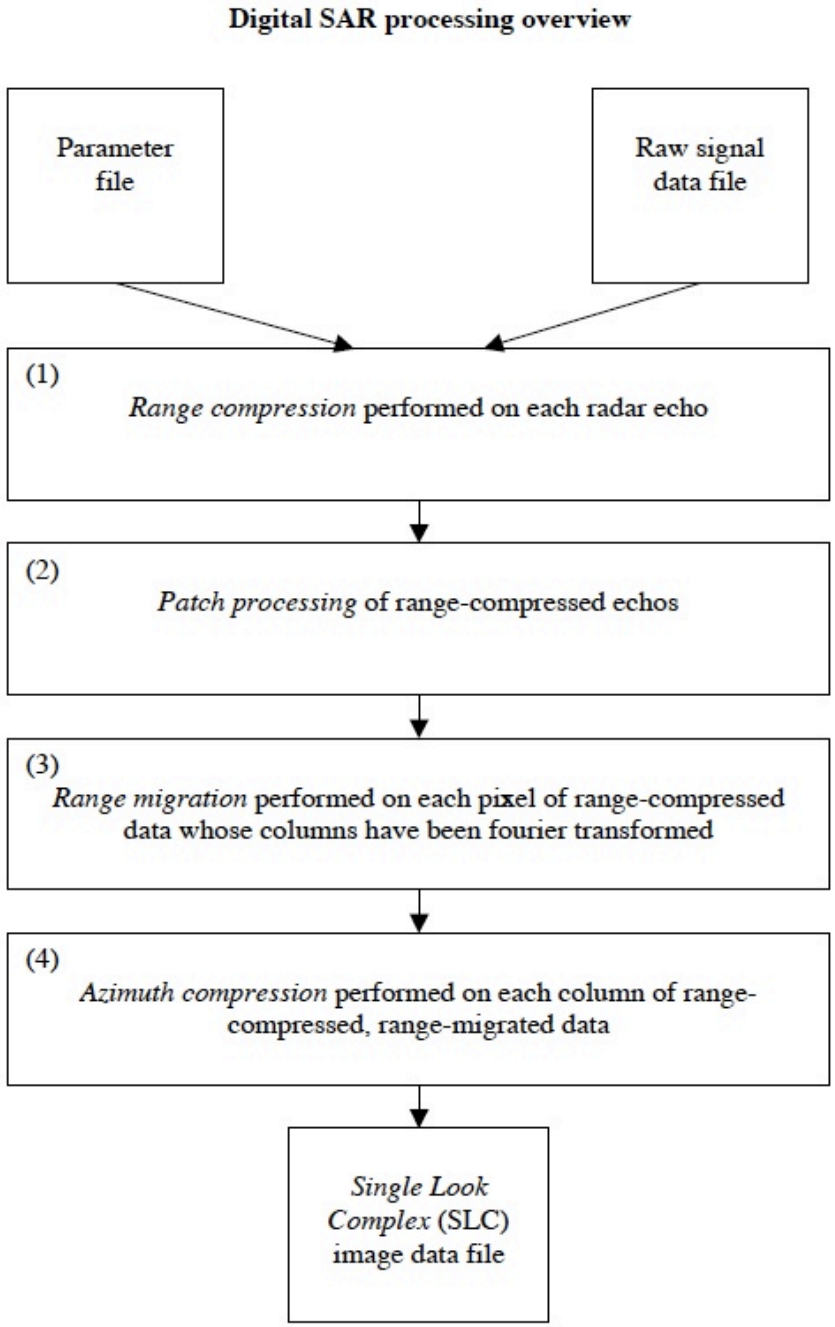


Table B1. Example Parameter (PRM) file (e2_10001_2925.PRM)

file information/format			
input_file	e2_10001_2925.fix	name of raw data file	
SC_identity	2	(1) – ERS-1 or (2) – ERS-2	
bytes_per_line	11644	number of bytes in row of raw data	
first_sample	206	412 bytes of timing information to skip over	
fd1	248.115	Doppler centroid estimated from data	f_{Dc}
I_mean	15.5	mean value of real numbers	
Q_mean	15.5	mean value of imaginary numbers	
icu_start	2576039268.848	spacecraft clock for first sample	
SC_clock_start	1997078.767881851	UTC for first sample YYYDDD.DDDDDDDD	
SC_clock_stop	1997078.768074699	UTC for last sample YYYDDD.DDDDDDDD	
radar characteristics			
PRF	1679.902394	pulse repitition frequency	PRF
rng_samp_rate	1.89625e+07	range sampling rate	f_s
chirp_slope	4.17788e+11	chirp slope	k
pulse_dur	3.712e-05	pulse duration	τ_p
radar_wavelength	0.056666	radar wavelength	λ
orbital information			
near_range	829924.365777	distance to first range bin	R_{near}
earth_radius	6371746.4379	earth radius ~1/2 way into image	R_e
SC_height	787955.52	spacecraft height above the earth_radius	H
SC_vel	7125.0330	effective speed	V
processing information			
num_valid_az	2800	size of patch to process	
num_patches	10	number of patches to process	
first_line	1		
deskew	n	deskew (yes or no)	
st_rng_bin	1	start processing at row number	
num_rng_bins	6144	number of range bins in output file	
chirp_ext	614	extend the chirp to process outside swath	
Flip_iq	n	exchange real and imaginary numbers (yes or no)	
nlooks	1	number of azimuth echoes to average	
image alignment			
rshift	15.1	range shift to align image to master	
ashift	483.2	azimuth shift to align image to master	
stretch_r	.0014569	range stretch versus range	
stretch_a	-.0019436	azimuth stretch versus range	
a_stretch_r	0.0	range stretch versus azimuth	
a_stretch_a	0.0	azimuth stretch versus azimuth	


412 bytes
11232 bytes – 5161 complex numbers
timing
raw signal data
range
azimuth
patch
incomplete aperture
complete aperture
incomplete aperture

SAR processor



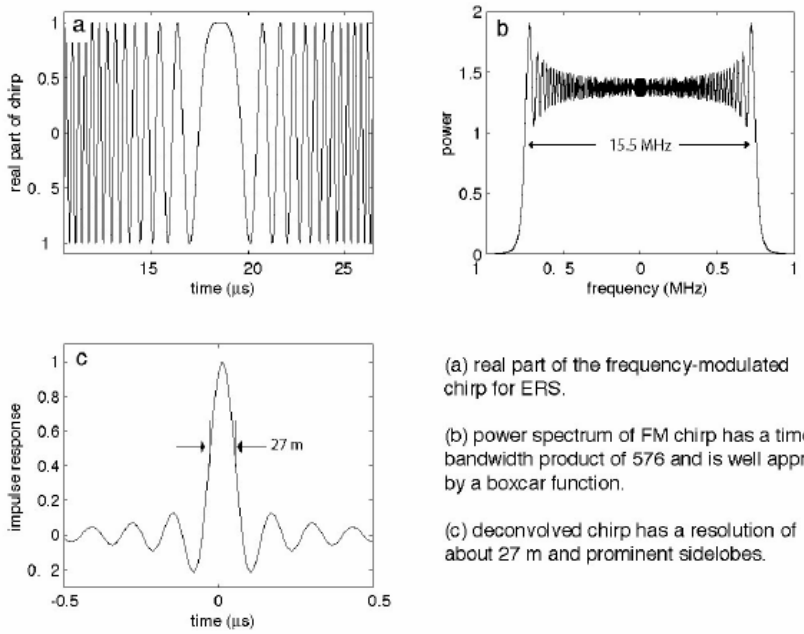
$$s(t) = e^{i\pi k t^2} \qquad |t| < \tau_p/2 .$$

Range Compression

where

k - chirp slope (4.17788 x 10^{11} s^{-2})
τ_p - pulse duration (3.712 x 10^{-5} s or ~11 km long)
f_s - range sampling rate (1.89625 x 10^7 s^{-1}).

An example of a portion of the chirp for the ERS- radar as well as its power spectrum and impulse response is shown below.



(a) real part of the frequency-modulated chirp for ERS.

(b) power spectrum of FM chirp has a time-bandwidth product of 576 and is well approximated by a boxcar function.

(c) deconvolved chirp has a resolution of about 27 m and prominent sidelobes.

Figure B4 Chirp for ERS-1

The bandwidth of the chirp, $B = k\tau_p$, has a value of 15.5 MHz for the ERS radar. A matched filter is used to deconvolve the chirp from the data. In this case, the matched filter is simply the complex conjugate of the chirp or $s^*(t) = e^{-i\pi k t^2}$. The convolution of $s^*(t)$ and $s(t)$ is shown in Figure B4b. The effective range resolution of the radar is about 27 m.

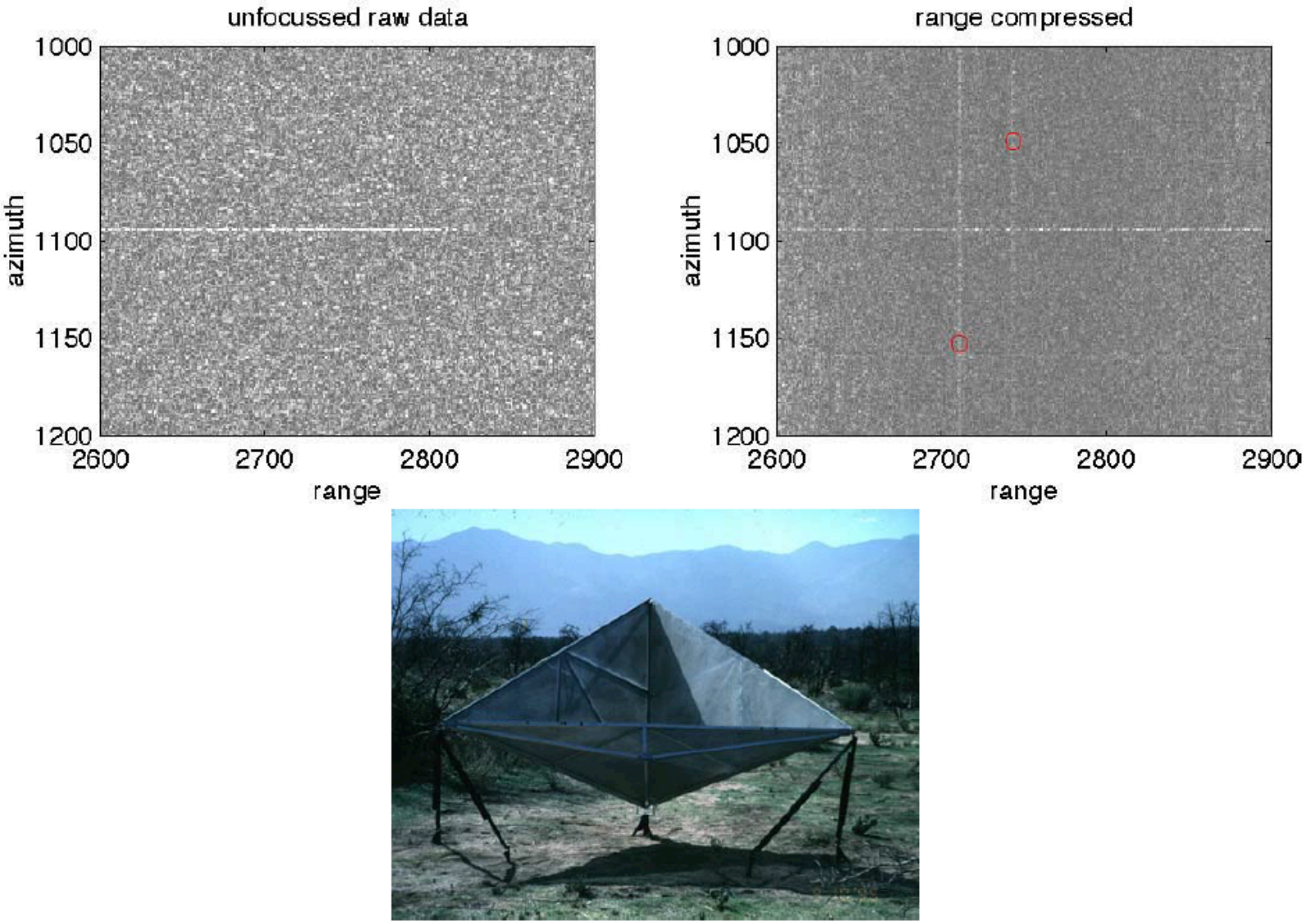


Figure B5. Raw ERS signal data (left) and range compressed data (right) for data over Pinon Flat California where two radar corner reflectors are installed (lower).

Azimuth compression

Azimuth compression or azimuth focusing involves coherent summation of echos at a constant range from the point reflector. The geo metry of the strip-mode acquisition is shown in Figure B6

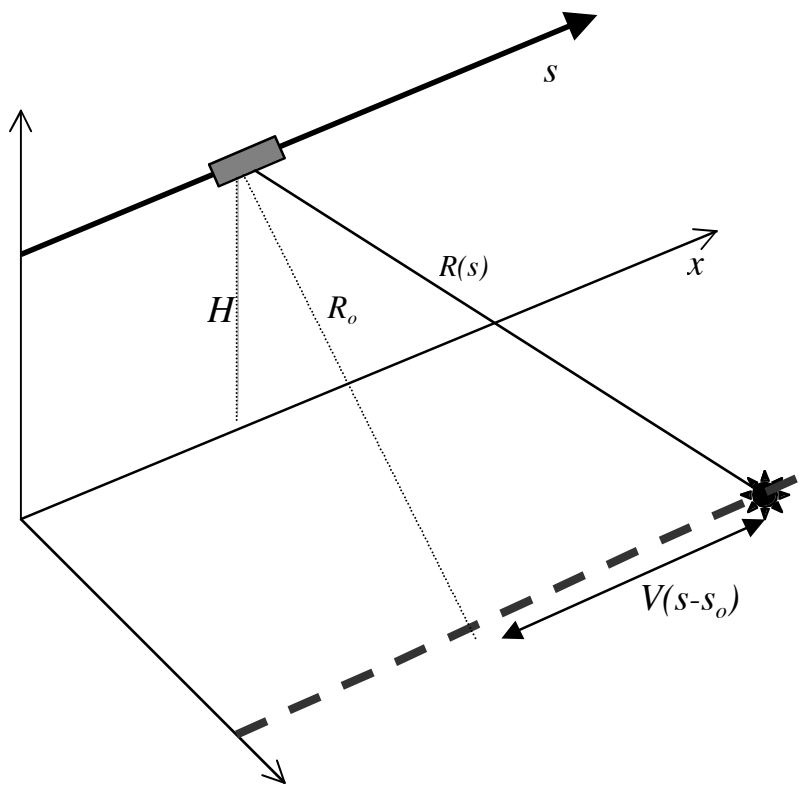


Figure B6. Geometry of radar passing over a point reflector where

V – the effective speed which is about equal to the ground track speed

s – slow time along the satellite track

s_o – time when the center of the radar echo passes over the point reflector

R_o = $R_{near} + n * (C / fs)$ minimum range from the spacecraft to the target

R_{near} – near range to first data sample in the swath

The range to the point reflector evolves with time as

$$R^2(s) = R_o^2 + V^2(s - s_o)^2 .$$

The complex phase of the return echo is

$$C(s) = \exp\left[-i\frac{4\pi}{\lambda}R(s)\right].$$

The range versus slow time is approximately a hyperbola but for mathematical convenience we'll approximate this using a parabola

$$R(s) = R_o + \dot{R}_o(s - s_o) + \frac{\ddot{R}_o}{2}(s - s_o)^2 + \ldots$$

where the dot indicates derivative with respect to slow time, s. *Curlander and McDonough* [1991] discuss the accuracy of this polynomial approximation and it is also discussed below in terms of the ALOS SAR. The approximation is good enough for strip-mode SAR but may be inadequate for the much longer apertures associated with spotlight-mode SAR. Now we can write the phase of the return signal as a function range, range rate, and range acceleration.

$$C(s) = \exp\left\{-i\frac{4\pi}{\lambda}\left[R_o + \dot{R}_o(s - s_o) + \ddot{R}_o(s - s_o)^2/2\right]\right\}$$

It is more common to describe the parameters for focusing the SAR image as the Doppler centroid f_{Dc} and the Doppler frequency rate f_R. The relationships are:

$$f_{Dc} = \frac{-2\dot{R}}{\lambda} \quad \text{and} \quad f_R = \frac{-2\ddot{R}}{\lambda} .$$

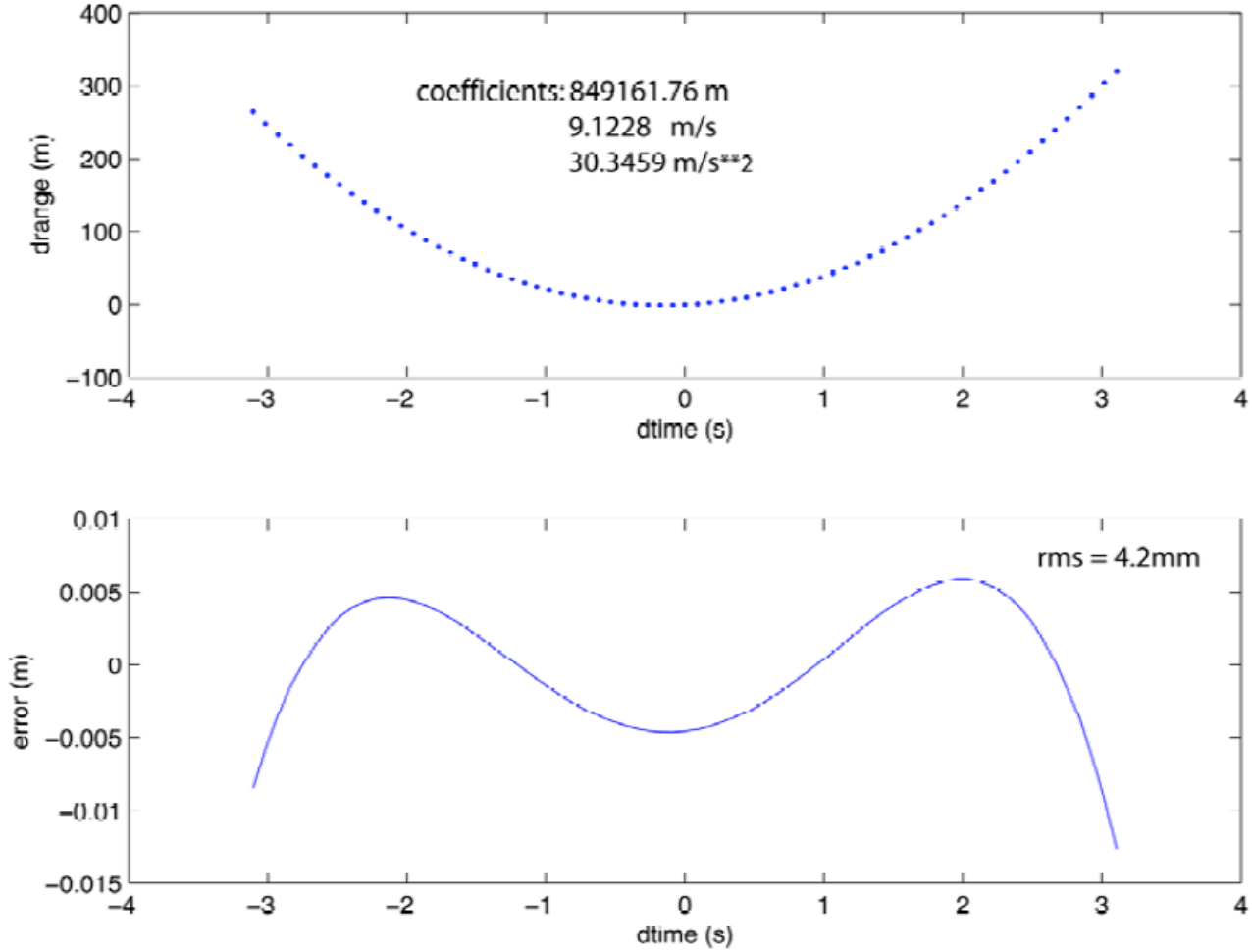


Figure B12. (upper) range versus slow time for ALOS for a 6 second aperture. The actual aperture is 4.2 seconds (Table B3). (lower) deviation from a parabolic fit to this range vs. time function.

Length of synthetic aperture - The length of the synthetic aperture L_a depends on the length of the radar ground footprint in the azimuth direction, which is approximately

$$L_a = R_o \frac{\lambda}{L} \qquad (1$$

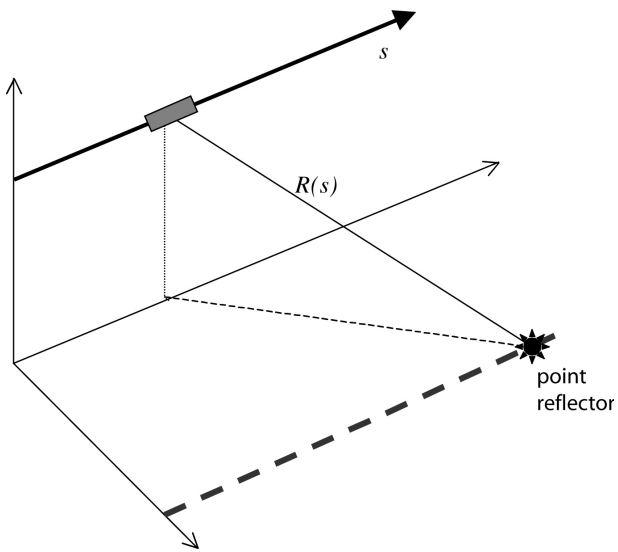
where L is the physical length of the antenna, λ is the wavelength and R_o is the slant range given above. The length of the aperture in terms of radar echos is given by

$$n_a = \frac{L_a \, PRF}{V} \qquad (1$$

This is simply the length of the synthetic aperture divided by the along-track sampling distance. The following table provides these quantities for SARs of interest for interferometry today.

Table B3. Length of synthetic aperture for three satellites.

	V *(m/s)*	λ *(m)*	*PRF (Hz)*	R_o *(km)*	L *(m)*	L_a *(m)*	n_a *theory*	n_a *actual*
ERS-1/2	7125	0.057	1679	~850	10	4850	1142	1164
Envisat	7125	0.057	2067	~1020	10	5830	1690	1740
ALOS	7125	0.236	2159	~1020	9	26,830	8128	9216



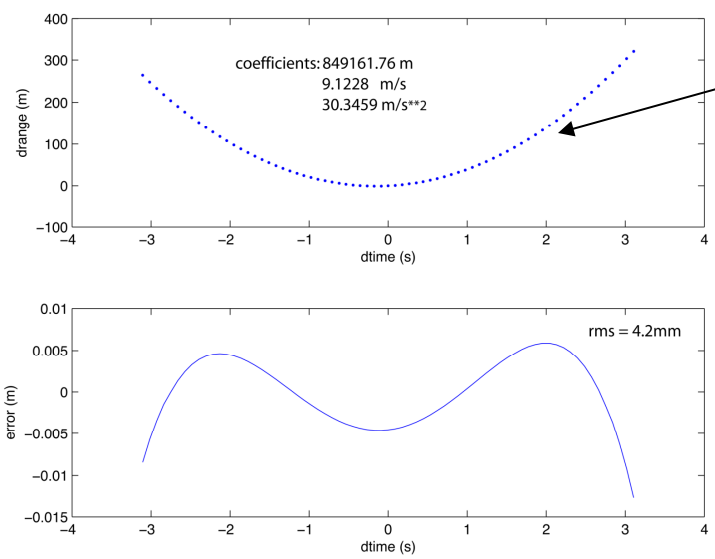
phase history of point reflector

$$C(s) = \exp\left\{ i \frac{4\pi}{\lambda} \left[R(s) \right] \right\}$$

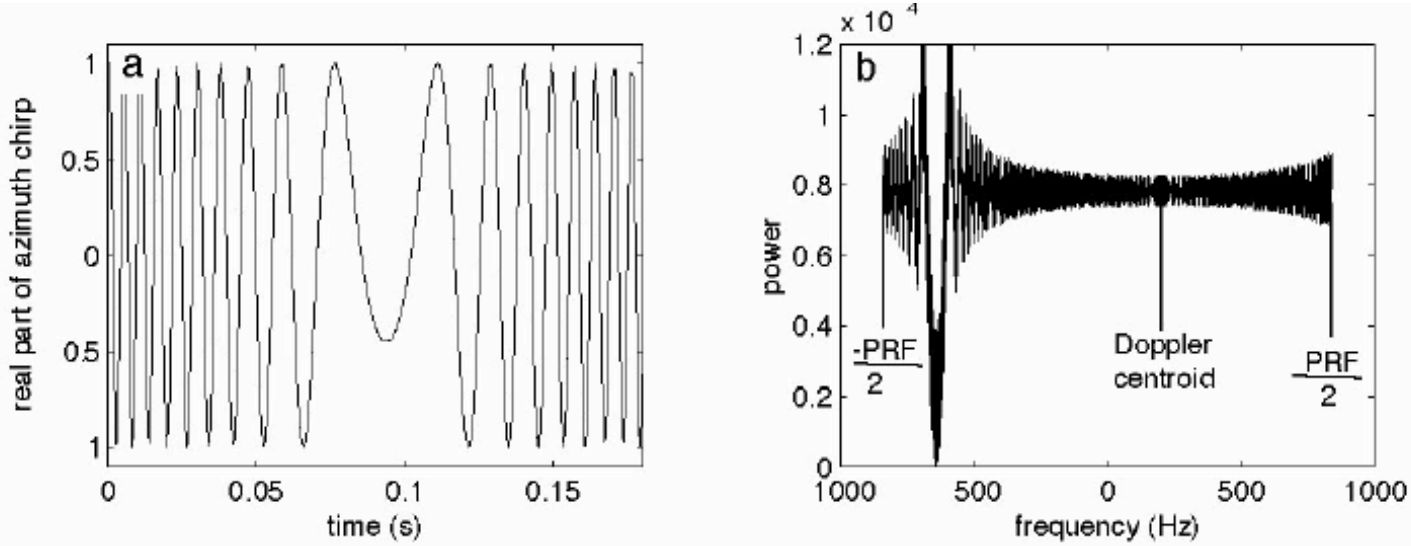
parabolic approximation to range history

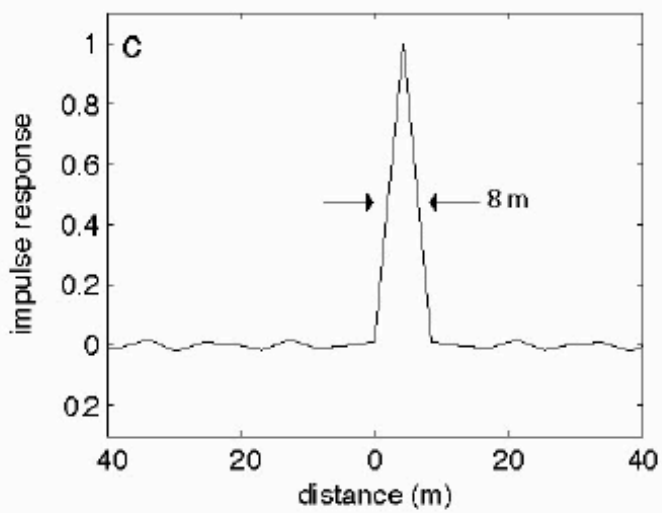
$$R(s) = R_o + \dot{R}_o (s - s_o) + \frac{\ddot{R}_o}{2} (s - s_o)^2 + \ldots$$

$$f_{DC} = \frac{-2\dot{R}}{\lambda} \qquad f_R = \frac{2\ddot{R}}{\lambda}$$



Least-squares fit of range history for each point in DEM provides both the accurate position in range azimuth $\left[R_o, s_o \right]$ space and the Dopper centroid and rate parameters needed to focus the image. This analysis only needs to be applied to the master image.





(a) real part of the azimuth phase function for a doppler centroid of 200 Hz..

(b) power spectrum of the azimuth phase function is nearly a boxcar function that is shifted in frequency by the doppler centroid.

(c) deconvolved azimuth chirp has a resolution of about 8 m.

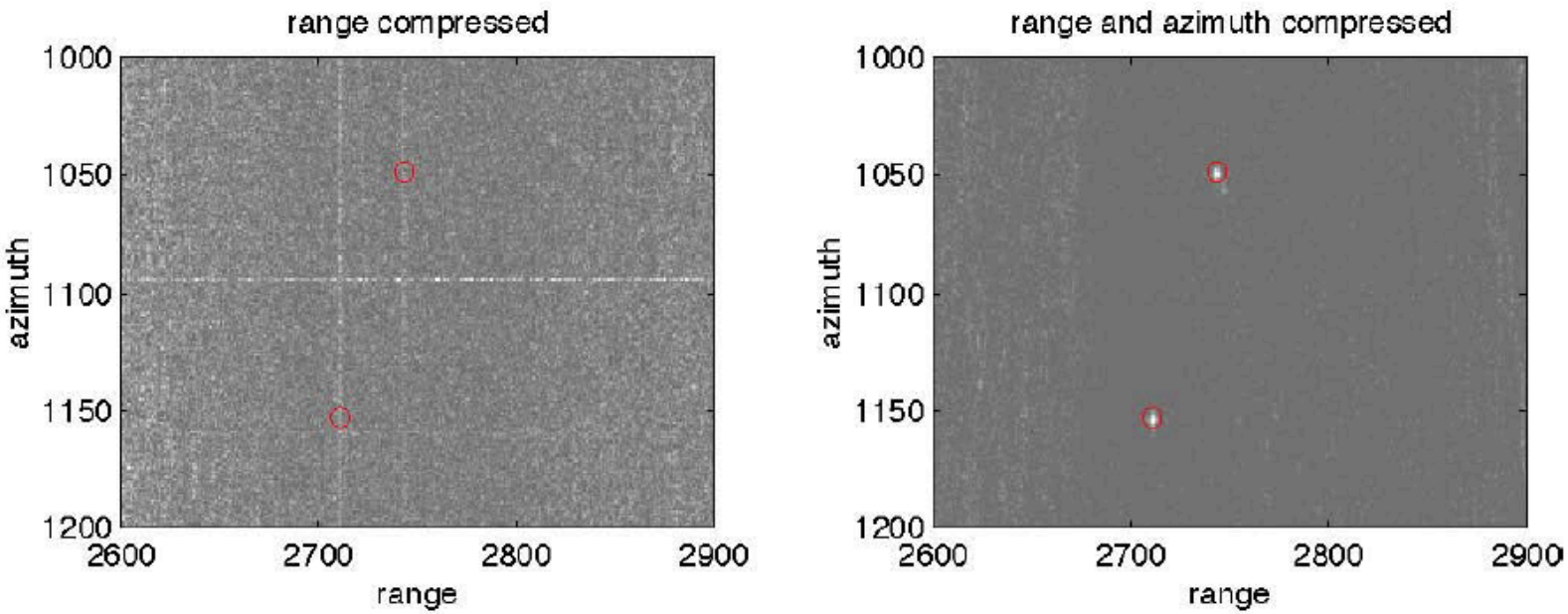


Figure B8. Range compressed (left) and fully focussed image (right). The two bright reflectors are 3-m corner cubes at Pinon Flat observatory. These were deployed in 1996 and therefore provide stable calibration points for ERS-1, ERS-2, Envisat, ALOS and all future satellites.

SAR processor

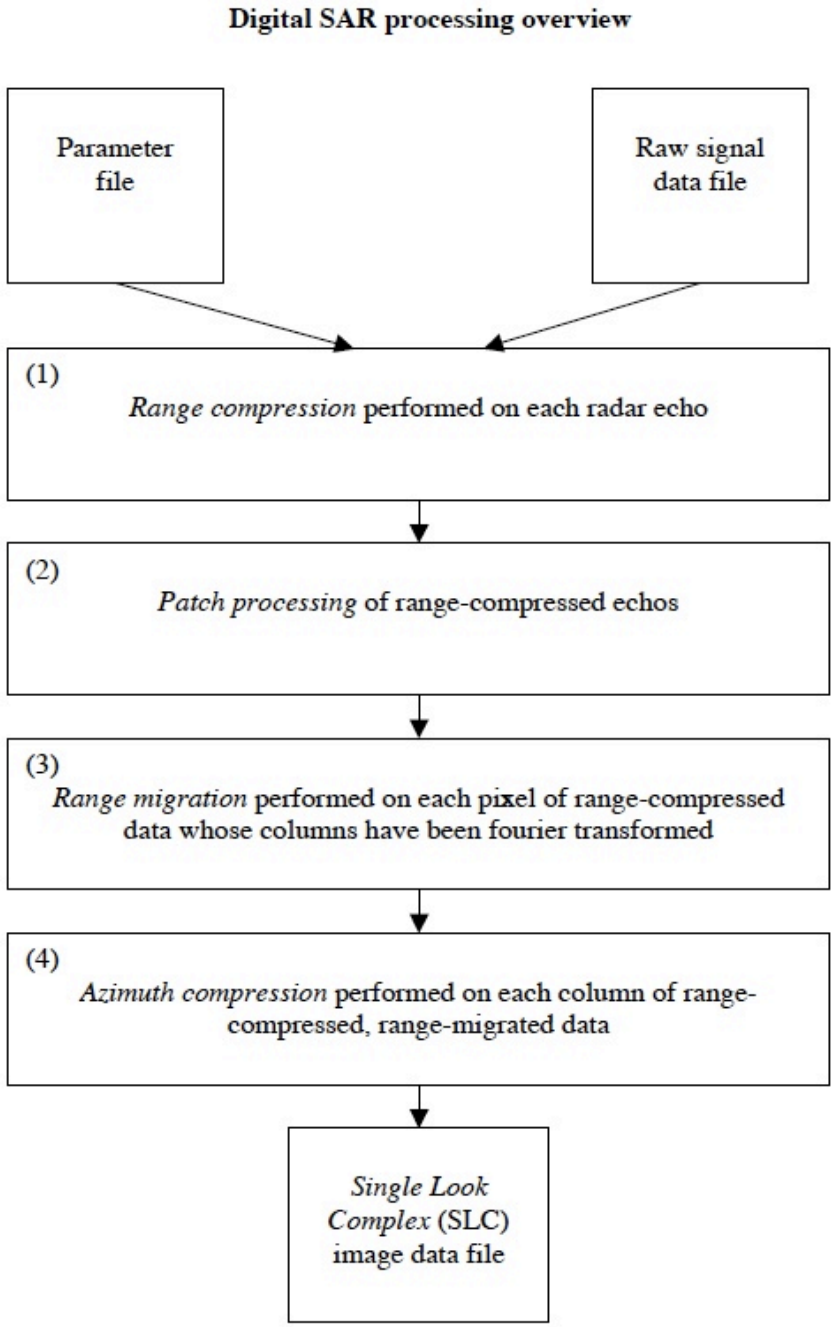
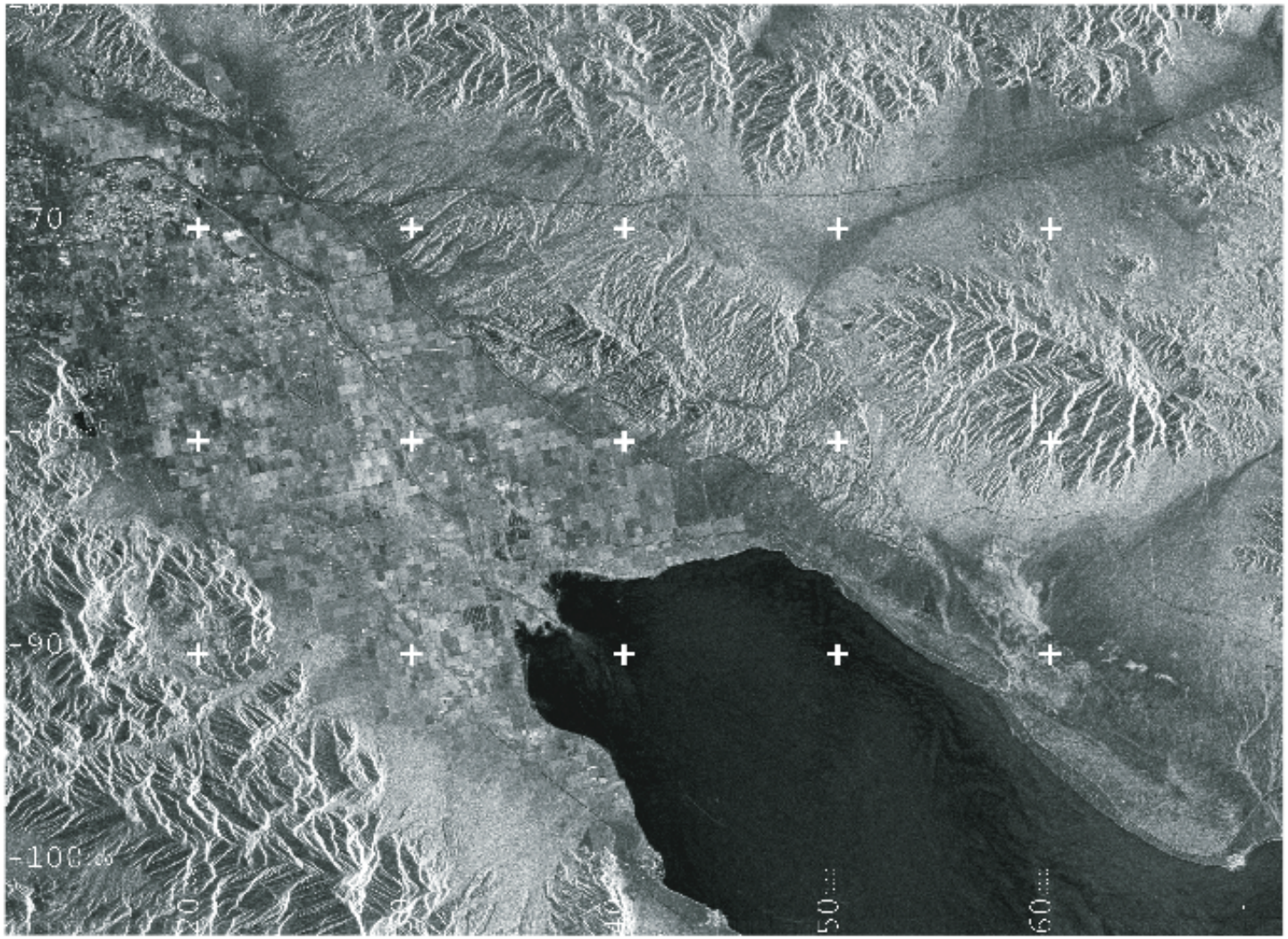


Table B1. Example Parameter (PRM) file (e2_10001_2925.PRM)

file information/format			
input_file	e2_10001_2925.fix	name of raw data file	
SC_identity	2	(1) – ERS-1 or (2) – ERS-2	
bytes_per_line	11644	number of bytes in row of raw data	
first_sample	206	412 bytes of timing information to skip over	
fd1	248.115	Doppler centroid estimated from data	f_{Dc}
I_mean	15.5	mean value of real numbers	
Q_mean	15.5	mean value of imaginary numbers	
icu_start	2576039268.848	spacecraft clock for first sample	
SC_clock_start	1997078.767881851	UTC for first sample YYYDDD.DDDDDDDD	
SC_clock_stop	1997078.768074699	UTC for last sample YYYDDD.DDDDDDDD	
radar characteristics			
PRF	1679.902394	pulse repitition frequency	PRF
rng_samp_rate	1.89625e+07	range sampling rate	f_s
chirp_slope	4.17788e+11	chirp slope	k
pulse_dur	3.712e-05	pulse duration	τ_p
radar_wavelength	0.056666	radar wavelength	λ
orbital information			
near_range	829924.365777	distance to first range bin	R_{near}
earth_radius	6371746.4379	earth radius ~1/2 way into image	R_e
SC_height	787955.52	spacecraft height above the earth_radius	H
SC_vel	7125.0330	effective speed	V
processing information			
num_valid_az	2800	size of patch to process	
num_patches	10	number of patches to process	
first_line	1		
deskew	n	deskew (yes or no)	
st_rng_bin	1	start processing at row number	
num_rng_bins	6144	number of range bins in output file	
chirp_ext	614	extend the chirp to process outside swath	
Flip_iq	n	exchange real and imaginary numbers (yes or no)	
nlooks	1	number of azimuth echoes to average	
image alignment			
rshift	15.1	range shift to align image to master	
ashift	483.2	azimuth shift to align image to master	
stretch_r	.0014569	range stretch versus range	
stretch_a	-.0019436	azimuth stretch versus range	
a_stretch_r	0.0	range stretch versus azimuth	
a_stretch_a	0.0	azimuth stretch versus azimuth	

amplitude image



1) This is an image of radar backscatter from a stack of ERS SAR data. The flight path is top to bottom and the radar looks from the right. The area is the Salton Sea and Cochella Valley, and the tic marks are spaced at 10 km. The satellite is 7159717m from the center of the Earth, the local Earth radius is 6371593 m, and the range to the center of the image is 850148 m. Calculate the look angle to the center of the image. Identify areas of layover. What is the minimum mountain slope in the areas of layover? Why is the Salton Sea dark?

Problems

1) Explain why the raw signal data are provided as complex numbers. Why are the numbers restricted to the range 0-31?

2) Why is the SAR processing done in patches rather than all at once? What is the minimum possible patch size?

3) Most SAR instruments emit a frequency modulated chirp rather than a short pulse. Why? Write a Matlab program to deconvolve the FM chirp for ERS and reproduce the impulse response function shown in Figure B4.

$$C(s) = \exp\left\{-i\frac{4\pi}{\lambda}\left[R_o + \dot{R}_o(s-s_o) + \ddot{R}_o(s-s_o)^2/2\right]\right\}$$

4) Make a plot of the real and imaginary parts of the function given in (B5) for a time interval of -2 to 2 seconds. Use $R_o = 850km$, $\dot{R}_o = 0$, $\ddot{R}_o = \frac{V^2}{R_o}$ where $V = 7125ms^{-1}$.

5) Derive equation (B12)

$$V = \frac{V_s}{\left(1+\frac{H}{R_e}\right)^{1/2}}$$

6) Derive equation (B13). (You may need to look back at Appendix A.)

$$L_a = R_o\frac{\lambda}{L}$$

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Appendix A. Principles of Synthetic Aperture Radar

Appendix B. SAR Image Formation

Appendic C. InSAR

Appendix D. ScanSAR processor and interferometry

Appendix E. Geolocation accuracy for Pinon corner reflectors

Appendix F. Installation of GMTSAR