

Tomographic Processing of Spotlight-Mode SAR

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C O N N E X I O N S

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Chapter 1

Introduction¹

1.1 Introduction

Our project covers an investigation of Synthetic Aperture Radar (SAR) and the Matlab processing of SAR data we received from Ohio State University. The data was generated by a simulation of spotlight-mode SAR, a specific type of SAR which takes advantage of a moving sensor tracking a single ground target. To process this data, we utilize digital signal processing techniques such as interpolation and windowing along with a knowledge of how SAR works.

¹This content is available online at <<http://cnx.org/content/m15658/1.1/>>.

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Chapter 2

Background¹

2.1 Synthetic Aperture Radar: Background

2.1.1 What is Synthetic Aperture Radar?

Synthetic Aperture Radar (SAR) is a microwave imaging system that is used to obtain high resolution pictures of large areas of terrain. The radar can be either airborne or spaceborne. As the platform moves, closely spaced pulses are transmitted and the reflected signals are received and processed using Fourier methods. The processed data resembles data taken with a system that has a very large antenna, thus allowing extremely high resolution.

Synthetic Aperture Radar was first developed in the early 1950's. The earliest type of SAR is called strip-mapping mode SAR. It is primarily used for imaging large areas of terrain, such as the surface of a nearby planet. This mode emits the radar pulses at a constant "look" angle to the surface while traveling along a flight path or orbit. This process creates a strip of mapped ground, and can be repeated along a polar orbit to map the entire surface of a planet.

Spotlight mode SAR is a newer form of SAR and was developed in the early 1980's. It is more widely used today than strip-mapping mode and it is what our project deals with. In spotlight mode, the radar is steered continually as the carrier of the radar flies over a patch of ground. In another word, the "look" angle is constantly adjusted so that a single patch of ground is always illuminated. This method allows for higher resolution in the azimuth "travel" direction of the platform but is not able to image as large of an area as strip-mapping mode.

2.1.2 How Does Imaging Radar Work?

As mentioned earlier, we use the Synthetic Aperture Radar processing technique because of its advantages when it comes to imaging large areas at high resolutions. However, why do we even use radar to image things in the first place?

Radar is used in imaging because of the minimal constraints that it has on time-of-day and atmospheric conditions. The area of imaging does not have to be illuminated by sunlight in order to obtain a picture. This allows for continuous mapping regardless of the position of the sun, which saves time and therefore, money.

Radar also has the ability to penetrate cloud cover because one can choose a wavelength that is not absorbed by water. This fact is what allowed scientists at NASA to provide stunning images of the surface of Venus, which is completely shrouded in cloud-cover.

Imaging radar works by emitting a signal and then recording the strength of the reflected signal (scattering coefficient) for that area. The pulses are emitted at an angle to the surface such that if they strike a smooth,

¹This content is available online at <<http://cnx.org/content/m15667/1.1/>>.

flat surface, very little of the signal will be reflected back towards the antenna which corresponds to a darker spot on our scattering coefficient image.

When the radar pulse strikes uneven surfaces such as urban areas or vegetated areas, the signal gets reflected numerous times and there is an increased likelihood that the radar antenna will eventually receive a large portion of the signal back, corresponding to a whiter spot on your image. Scientists use this fact to determine the extent of flooding in urban areas or to discern how much an oil spill in the ocean has grown.

2.1.3 Synthetic Aperture Radar and Microwave Imaging System

The resolution of an image taken from an imaging system is usually determined by the size of the Aperture (lens for optical systems and antenna for radar). Conventional radar systems use passive methods deployed with optical or short-wave infrared sensor that rely on sunlight reflection. On the other hand, synthetic Aperture Radar uses a microwave imaging system. Two important advantages resulting from using microwave pulses are that cloud cover can be penetrated and the imaging process can be performed at night.

However, antenna size limits one from applying microwave imaging systems. A very large size of antenna is required to obtain satisfactory resolution. Therefore, the size of the antenna makes it impractical for the radar carrier.

Synthetic Aperture Radar solves the problem by “simulating” a large Aperture. The radar sends and receives signals from a relatively small antenna while the platform traveling along a flight path. One can then use the digital signal processing techniques to combine the data into a coherent image. The result is the same as if one has used a very large antenna.

Chapter 3

Projection-Slice Theorem¹

¹This content is available online at <http://cnx.org/content/m15663/1.1/>.

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3.1 Brief Review of Computer-Aided Tomography

Computer-Aided Tomography, or CAT (as in CAT scan) is a technique for remote 2-D and 3-D imaging. By moving a sensor around a target, one can collect sufficient 1-dimensional data to reconstruct the original multidimensional image. This process utilizes an amazing relationship called the Projection-Slice Theorem, which states that each piece of projection data at some angle is the same as the Fourier transform of the multidimensional object at that angle. Using a range of data from a range of angles, one can, given sufficient computation resources, reconstruct the actual image by taking the inverse transform. The Projection-Slice Theorem has found a range of applications in remote sensing, the most famous of which is the 3-D imaging of humans, popularly known as the CAT scan. The focus of this project, Spotlight-Mode Synthetic Aperture Radar, uses the Projection Slice Theorem in a way quite similar to CAT scan technology, except the way radar projections are generated by the image is slightly different from the way CAT scans use X-rays.

3.1.1 Projection-Slice Theorem

Let $g(x,y)$ represent the radar reflection of our image. The two-dimensional Fourier transform of g is defined as

$$G(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x,y) e^{-j(xX+yY)} dx dy$$

Figure 3.1

And

$$g(x,y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(x,y) e^{j(xX+yY)} dXdY$$

Figure 3.2

We can model the reflection behavior of the incident radar by considering the following overhead diagram

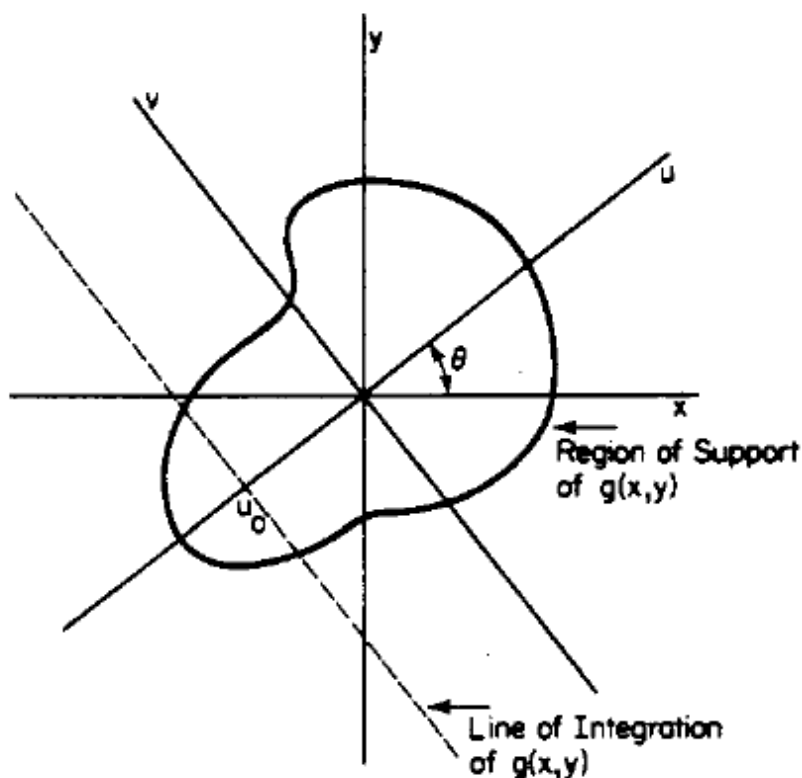


Figure 3.3

The smooth line outlines our image $g(x,y)$, and the horizontal and vertical axes x,y are overlaid. The radar is incident upon the target along the axis of the path \mathbf{u} at an angle θ . For a target which is far away, the radar wave front is approximately flat, and so this means that a reflected beam which has traveled a certain unique distance to and from the sensor comes from a straight path across the image, perpendicular to \mathbf{u} . This path is in the direction of \mathbf{v} and can be represented by a line integral in the direction of \mathbf{v} at position \mathbf{u}_0 . The formula for this is given by

$$p_{\theta}(u) = \int_{-\infty}^{\infty} g(u \cos \theta - v \sin \theta, u \sin \theta + v \cos \theta) dv$$

Figure 3.4

The 1-D Fourier transform of $\mathbf{p}(\mathbf{u})$ is given by

$$P_{\theta}(U) = \int_{-\infty}^{\infty} p_{\theta}(u) e^{-juU} du$$

Figure 3.5

And then, through applying the equation for $\mathbf{p}(\mathbf{u})$ and simplifying, we are left with

$$P_{\theta}(U) = G(U \cos \theta, U \sin \theta)$$

Figure 3.6

This is the Projection Slice Theorem! What this states is that the Fourier transform of a projection taken at an angle theta is **equal to** the 2-D Fourier transform of the image at that same angle theta. To reconstruct the original image, one must merely take the inverse Fourier transform in two dimensions of a set of data $\mathbf{P}(\mathbf{U})$. This is not as easy as it sounds for reasons discussed later. Notice how the Fourier transform of the image \mathbf{G} does not have the usual form, $\mathbf{G}(\mathbf{X}, \mathbf{Y})$. It is instead expressed in polar form, and the variable theta lets us know that we have only a slice of the transform for each $P(U)$.

Chapter 4

Tomographic Processing¹

4.1 Data Processing

In the words of the highly esteemed Rich Baraniuk, the signals received by the radar sensor must be “munjed” upon in order that the user can learn anything useful at all. We flesh-out the basic spotlight-mode SAR derivation from start to finish, noting the places in which we make approximations, all the while aiming at interpreting our bit stream into the meaningful pieces of the Projection-Slice Theorem. Something to note is that this theoretical approach does not include any Doppler shift analysis. Other approaches to synthetic aperture radar heavily rely on phase data collected during a physical flyby of the target, where instrument velocity plays an important role. The mathematics in this section follows as in David Munson’s 1983 paper on “A Tomographic Formulation of Spotlight-Mode Synthetic Aperture Radar.”

4.1.1 The Setup

The way spotlight-mode SAR collects data samples is by gathering image projections from a range of angles. In our case, this range is broken down into a set of equally spaced angles so that essentially we have snapshots at various views around a target. A depiction of what it would look like is given below.

¹This content is available online at <http://cnx.org/content/m15661/1.1/>.

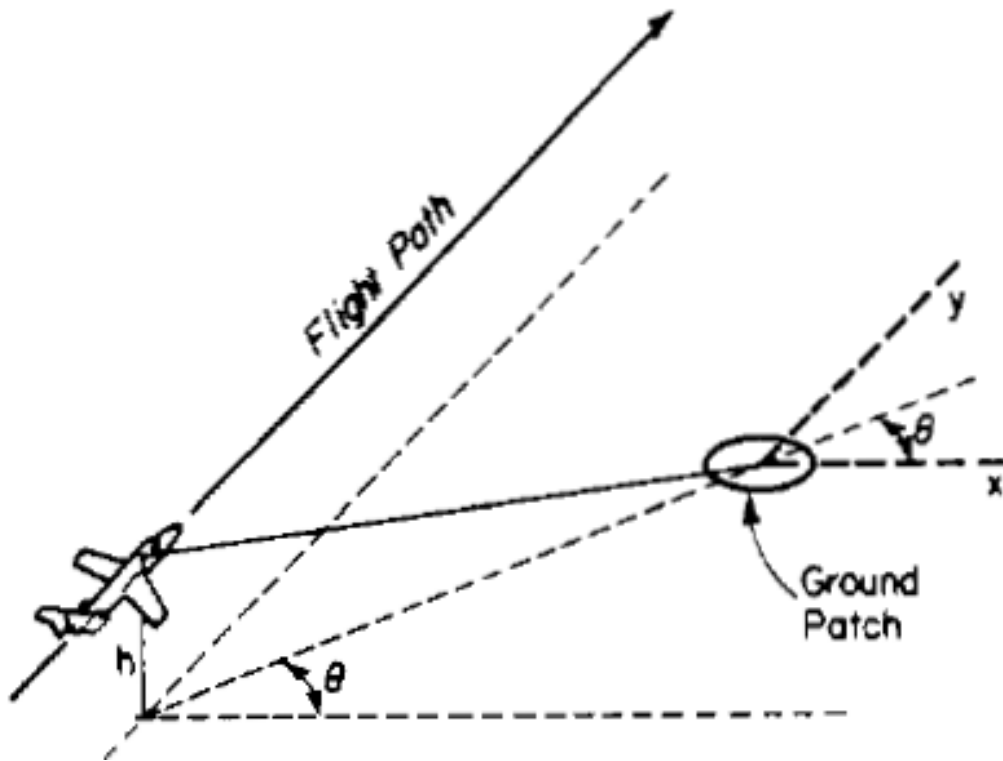


Figure 4.1

This drawing shows how the altitude of the sensor platform might play a role in the angular view of the target. For our derivation, we will ignore this parameter and assume that the radar is somehow incident at ground level, that as the sensor moves closer to the target distances remain undistorted by this variation in 3-dimensions. This ground plane geometry is as shown below.

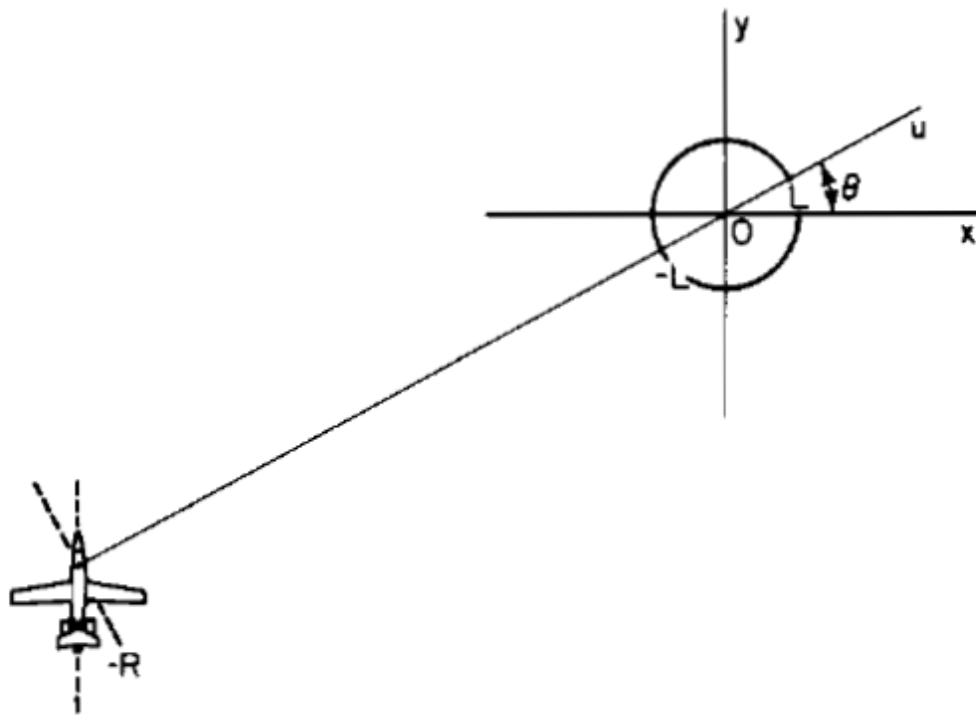


Figure 4.2

Note that the angle **theta** is the same as that in the description of the Projection-Slice Theorem. The distance from the center of the target image is given by the variable **R**, and the radius of a circular target is given by **L**. The radar signal travels along and parallel to path **u**.

4.1.2 Generating the Reflection Signal

At this point we are ready to start generating our signals! Our radar device works in a microwave frequency range designed to penetrate clouds and other obstructions with ease. It emits a linear FM chirp pulse waveform $\text{Re}\{s(t)\}$ where

$$s(t) = \begin{cases} e^{j(\omega_0 t + at^2)}, & |t| \leq \frac{T}{2} \\ 0, & \text{otherwise} \end{cases}$$

Figure 4.3

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