# InSAR Simulations for SWOT and Dual Frequency Processing for Topographic Measurements 

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# INSAR SIMULATIONS FOR SWOT AND DUAL FREQUENCY PROCESSING FOR TOPOGRAPHIC MEASUREMENTS 

A Thesis Presented<br>by<br>GERARD MASALIAS HUGUET

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

February 2019

# INSAR SIMULATIONS FOR SWOT AND DUAL FREQUENCY PROCESSING FOR TOPOGRAPHIC MEASUREMENTS 

A Thesis Presented<br>by<br>GERARD MASALIAS HUGUET

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Paul R. Siqueira, Chair

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Electrical and Computer Engineering

## DEDICATION

To my family

## ACKNOWLEDGMENTS

First of all I would like to thank my advisor, professor Paul Siqueira, for all the help and guidance, and for the opportunity he has given me. Paul, you make of MIRSL such a unique place, you have made me learn in so manys and I will always look up to you. I would like to thank professor Stephen Frasier for taking the time to be in my commitee and also to professor Weibo Gong, your classes are pure inspiration and I am grateful you agreed to be part of my committee.

To all the people who have worked on developing the radars, thank you for doing such a great job and making my life easier. Thanks to the folks who helped every day in the lab, Tom, Max, Dustin, Tracy and Chen. Special thanks to Jan-Willem de Blesser at JPL for always being willing to help and giving me great ideas during my time there.

For those who never missed the opportunity and made my visits so special, thank you Mike and Sheila. Hayk, there has never been a boring day in the office with you, thanks for all you have done. Thank you Gerard, you truly made a difference during my time in Amherst and left memories for the days to come.

Thanks to my parents and sister for always encouraging me. Finally, I do not think words can speak justice as to how much effort you put in, this journey abroad would have been impossible without you and your timeless support, thank you Eulàlia.

# ABSTRACT <br> INSAR SIMULATIONS FOR SWOT AND DUAL FREQUENCY PROCESSING FOR TOPOGRAPHIC MEASUREMENTS 

FEBRUARY 2019<br>GERARD MASALIAS HUGUET<br>B.S., POLYTECHNIC UNIVERSITY OF CATALONIA<br>M.S., UNIVERSITY OF MASSACHUSETTS AMHERST<br>Directed by: Professor Paul R. Siqueira

In Earth remote sensing precise characterization of the backscatter coefficient is important to extract valuable information about the observed target. A system that eliminates platform motion during near-nadir airborne observations is presented in this thesis, showing an improvement on the accuracy of measurements for a Kaband scatterometer previously developed at Microwave Remote Sensing Laboratory (MIRSL). These very same results are used to simulate the reflectivity of such targets as seen from a spaceborne radar and estimate height errors based on mission-specific geometry. Finally, data collected from a dual-frequency airborne interferometer comprised by the Ka-band system and an S-band radar is processed and analyzed to estimate forest heights.

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## CHAPTER 1

## INTRODUCTION

The study of Earth's natural processes has always been of interest, especialy in light of the more recent awareness and concerns for climate change. As more advanced models are required to better understand the complex interactions between the different processes, more sophisticated systems with finer resolution products are needed. Among others, monitoring the water cycle and global carbon budget are key factors whose studies can impact the development of more precise prediction models. This work focuses on radar scatterometry at Ka-band and Interferometric Synthetic Aperture Radar (InSAR) at S- and Ka-bands.

The MIRSL Ka-band scatterometer (KaScat) was developed to support the Surface Water and Ocean Topography (SWOT) mission. SWOT is a joint mission between NASA, CNES and other partners whose goal is to measure ocean height as well as inland water such as river or lakes, to provide a global inventory of fresh water availability [10]. The repeated measurements will also provide monitoring of height variations over time, allowing to estimate river discharges and improving hydrological models. SWOT's main instrument KaRIN is shown in Figure 1.1, it is a Ka-band interferometer taking an unconventional approach to measure water heights by employing interferometry instead of a classic altimeter. KaRIN will provide ocean measurements as dense as 1 x 1 km grids to observe the small-scale events that contribute to the ocean-atmosphere exchange of heat and carbon which are major components in global climate change.

The uncommon KaRIN geometry for SAR, with look angles ranging from 0 to 4 degrees and the lack of data at 35 GHz , required precise characterization of the backscattering coefficients of targets from different nature, especially of river water. A motion compensation system has been developed to isolate the radar antenna from the airplane attitude to provide high fidelity backscattering measurements. Additionally, it provides the ability to steer or scan the antennas to cover KaRIn nominal range of look angles. These data collected by the KaScat are important because they can be used to create a simulator for SWOT data which will test on-board algorithms.

An S-band interferometer was developed at MIRSL [1] as the result of supporting the development of NASA-ISRO Synthetic Aperture Radar (NISAR) mission. NISAR will observe Earth's changes in the ecosystem and measure surface deformation, providing information about natural hazards [8]. A 12-day orbital repeat provides monitoring that will help to track ice masses changes and the resulting sea level raise. Moreover, this mission will determine Earth's biomass contribution to the global carbon budget and disturbances such as wildfires. NISAR main instruments are two SAR's operating at S- and L-bands, allowing for continous measurements regardless of the weather since these bands are not much affected by rain attenuation. In regard to NISAR, MIRSL's S-band instrument is an effort that may be used to characterize backscattering coefficients and investigate interferometry, given that not many SAR systems operate at that frequency. The S-band radar was later merged with the Ka-band radar in interferometer configuration to form KaSI, a dual frequency interferometer described in [2] that employed a time domain SAR processor [9]. This work uses the existing system and processor to produce radar imagery, subsequently estimate forest heights and geolocate the results.


Figure 1.1: Artist concept of KaRIn, the interferometric radar to be used in SWOT mission.

### 1.1 Summary of Chapters

This thesis is structured into three main parts: radar basics, research related to SWOT and scatterometry, and studies related to NISAR and interferometry. Chapter 2 provides an introduction to radars and the mathematical background for their applications in interferometry and SAR. The second part is comprised by Chapters 3 , 4 and 5. Chapter 3 describes an attitude control built for the Ka-band scatterometer, Chapter 4 details the system in more depth and shows the results obtained, and Chapter 5 explains the process to simulate KaRIn reflectivity using airborne data. The last part, Chapter 6, gives a brief overview of the dual-frequency interferometer, shows the results obtained and investigates forest heights based on the differential heights.

## CHAPTER 2

## RADAR BASICS

The classic radar operates by sending out a pulse of energy and then recording its echo. The most basic principle is to use the echo delay to determine the range of the targets. A different kind of radar named Frequency Modulated Continous Waveform (FMCW) is used in this work. The FMCW radar is able to send and receive pulses simultaneously and estimates range through frequency instead of time delay. More sophisticated remote sensing techniques have made possible to extract more information about the target other than the range, such as its shape or height, and can also generate images similarly looking to those captured by optical cameras. The following sections of this chapter review basic concepts and describe algorithms used in radar data processing.

### 2.1 FMCW

FMCW radars send out a frequency modulated (FM) waveform, such modulation can take several different forms but for the most cases it is linearly modulated and this kind will be assumed here. A linear FM signal is often referred to as chirp and its frequency over a time $\tau$ can increase, decrease or do both creating a sawtooth shape. When the frequency increases over time (as in this example), it is called an up-chirp, and the transmitted signal takes the following form:

$$
\begin{equation*}
s_{t}(t)=w(t) \cos (\phi(t)) \tag{2.1}
\end{equation*}
$$

$$
\begin{equation*}
w(t)=\operatorname{rect}\left(\frac{t}{\tau}\right) \tag{2.2}
\end{equation*}
$$

where the phase $\phi(t)$ of the waveform is modulated and increases as

$$
\begin{equation*}
f(t)=\frac{1}{2 \pi} \frac{d \phi(t)}{d t}=f_{0}+k_{s} t \tag{2.3}
\end{equation*}
$$

where, $f_{0}$ is the starting frequency of the chirp and $k_{s}$ the chirp slope. To calculate the slope one needs to specify initial and final frequencies, $f_{0}$ and $f_{1}$, such that

$$
\begin{equation*}
k_{s}=\frac{f_{1}-f_{0}}{\tau}=\frac{B W}{\tau} \tag{2.4}
\end{equation*}
$$

with $B W$ being the bandwidth of the radar system. Having defined frequency as a function of time, $f(t)$, one must integrate to obtain the phase, $\phi(t)$, as in

$$
\begin{equation*}
\phi(t)=\int_{0}^{t} 2 \pi\left(f_{0}+k_{s} t\right) d t=\phi_{0}+2 \pi\left(f_{0} t+\frac{k_{s}}{2} t^{2}\right) \tag{2.5}
\end{equation*}
$$

Hence, the transmitted up-chirp, can be written as

$$
\begin{equation*}
s_{t}(t)=w(t) \cos \left(\phi_{0}+2 \pi\left(f_{0} t+\frac{k_{s}}{2} t^{2}\right)\right) . \tag{2.6}
\end{equation*}
$$

The above signal is transmitted and travels until it hits a target that will reflect some of the energy back to the radar. The amount of energy reflected will vary depending on the physical properties of the targets themselves, their distribution and incidence angle of the electromagnetic wave. In general a radar illuminates an area conatining several targets that interact wich each other and scatter off the signal back to the antenna. For the sake describing the FMCW operation a single scatter point is assumed, with reflectivity $\sigma$ at distance $R$ :

$$
\begin{equation*}
g_{r}(t)=\sigma \delta\left(t-t_{d}\right) \tag{2.7}
\end{equation*}
$$

where $t_{d}=\frac{2 R}{c}$ is the time delay, being $c$ the speed of light. In this case, the reflectivity coefficient $\sigma$ is commonly referred to as the Radar Cross Section (RCS) which models the amount of power scattered back to the radar. When multiple scatters are present, usually the same backscatter coefficient is assumed for all and the illuminated region is intergrated to account for all the contributions. Commonly, the total area observed is approximated via the antenna beamwidth. The signal received at the radar antenna is a delayed and scaled version of the transmitted waveform and can be modeled by

$$
\begin{gather*}
s_{r}(t)=s_{t}(t) * g_{r}(t)  \tag{2.8}\\
s_{r}(t)=w(t) \cos \left(\phi_{0}+2 \pi\left(f_{0} t+\frac{k_{s}}{2} t^{2}\right)\right) * \sigma \delta\left(t-t_{d}\right), \tag{2.9}
\end{gather*}
$$

and

$$
\begin{equation*}
s_{r}(t)=G w\left(t-t_{d}\right) \sigma \cos \left(\phi_{0}+2 \pi\left(f_{0}\left(t-t_{d}\right)+\frac{k_{s}}{2}\left(t-t_{d}\right)^{2}\right)\right) . \tag{2.10}
\end{equation*}
$$

An additional constant $G$ has been added to account for multiple amplitude gains like path loss or antenna patterns.

### 2.1.1 Pulse Compression

Most FMCW radars perform the pulse compresion operation in real time, in the RF hardware, before digitizing. In order to achieve this, the received signal is mixed with a replica of the transmitted and only the baseband signal is kept. Effectively this is done by

$$
\begin{gather*}
s_{c}(t)=\left.\left(s_{r}(t) \cdot s_{t}(t)\right)\right|_{L P F}  \tag{2.11}\\
s_{c}(t)=G w\left(t-t_{d}\right) \sigma \cos \left(\phi_{0}+2 \pi\left(f_{0}\left(t-t_{d}\right)+\frac{k_{s}}{2}\left(t-t_{d}\right)^{2}\right)\right)  \tag{2.12}\\
\left.\cdot w(t) \cos \left(\phi_{0}+2 \pi\left(f_{0} t+\frac{k_{s}}{2} t^{2}\right)\right)\right|_{L P F}
\end{gather*}
$$

The result of the mixing and low pass filter operations is a cosine whose frequency is the difference of frequencies between the transmitted and received signal. Therefore, simplifying (2.12)

$$
\begin{equation*}
s_{c}(t)=\frac{G}{2} w(t) \sigma \cos \left(2 \pi\left(f_{0} t_{d}-\frac{k_{s}}{2} t_{d}^{2}+t k_{s} t_{d}\right)\right) \tag{2.13}
\end{equation*}
$$

and taking the derivative of the phase of $s_{c}(t)$ yields

$$
\begin{equation*}
f_{c}(t)=\frac{1}{2 \pi} \frac{d}{d t}\left(2 \pi\left(f_{0} t_{d}-\frac{k_{s}}{2} t_{d}^{2}+t k_{s} t_{d}\right)\right)=k_{s} t_{d}=f_{b} \tag{2.14}
\end{equation*}
$$

where it can be observed that the range roundtrip delay is proportional to the instantaneous frequency. Therefore, the range could be measured as a frequency shift, also known as the beat frequency. A Fourier transform operation will finalize the range compression and will readily provide the desired mapping between range and frequency by

$$
\begin{equation*}
f_{c}(r)=k_{s} t_{d}=k_{s} \frac{2 r}{c} \tag{2.15}
\end{equation*}
$$

Classical radars that do not employ pulse compression have their range resoluion limited by the pulse length, as $\delta_{r}=\frac{c \tau}{2}$. If pulse compression is performed, then the improved resolution becomes $\delta_{r}=c / 2 B W$.

### 2.2 Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) is the combination of data collection and signal processing used to generate radar imagery. Such a tecnique requires motion of the sensor which can be achieved by airborne or spaceborne means. In general the radars point perpendicular to the direction of travel, often referred to as cross-track or range, and the flight track is commonly named along-track or azimuth. To generate high resolution images the data is compresed in range and azimuth directions. There are several methods available in the literature [3] [4] to perform azimuth compression


Figure 2.1: Geometry of a side-looking radar for stripmap SAR
either in frequency- or time-domain. This work focuses on airborne radars with the azimuth compression done in time-domain using the backprojection algorithm that will be further described in this section. The main reason of using a time-domain processor is to compensate for the non-linear motion of the airplane at the expense of higher computational time.

An airborne radar with a side-looking geometry measures the range from the antenna to a ground target, $p$, as in Figure 2.1a. In the cross-track direction, this is referred to as slant range, which has the form $r=\sqrt{x^{2}+y^{2}+z^{2}}$. The resolution in the slant range direction is dictated by the system bandwith if pulse compression is employed as described in Section 2.1.1. Note that this is not the true ground resolution, in order to determine the resolution in the ground range, one needs to project the radar ray which results in

$$
\begin{equation*}
\delta_{r g n d}=\frac{c}{2 B W \sin \left(\theta_{l}\right)}, \tag{2.16}
\end{equation*}
$$

where $\theta_{l}$ is the look angle shown in Figure 2.1a.
The radar antenna illuminates a certain area on the ground, as illustrated in Figure 2.1a and labeled as footprint. The area size will depend mostly on the flight
altitude and antenna beamwidth, and the location of the illuminated targets will vary depending on the aircraft attitude. When the radar sends out pulses, due to the footprint, different radar pulses in time will illuminate the same targets on the ground. A SAR uses the information of all of the pulses that contain the same target. Because the airplane is moving while sending pulses, an aperture larger than the physical size of the antenna (see Figure 2.1b) is synthesized, which results in a resolution improvement compared to the real antenna aperture. This method of synthetizing an aperture is called stripmap mode. The classical result of performing this operation gives a maximum resolution equal to one half of the physical length of the antenna

$$
\begin{equation*}
\delta_{a z}=\frac{L_{a n t}}{2} . \tag{2.17}
\end{equation*}
$$

To exploit such a technique, it is clear now the need to calculate the "edges" of the fooprint, whose span is commonly referred to as swath, and locate them on the ground. A reasonable approximation is to only locate the main beam footprint, therefore to find the limits along the $y$-axis

$$
\begin{align*}
y_{\text {near }} & =z \tan \left(\theta_{l}-\theta_{3 d B}\right)  \tag{2.18}\\
y_{\text {far }} & =z \tan \left(\theta_{l}+\theta_{3 d B}\right) \tag{2.19}
\end{align*}
$$

where $\theta_{3 d B}$ is the antenna beamwidth. Similarly, to find the limits along the x-axis

$$
\begin{align*}
x_{\text {near }} & =r_{\text {slant }} \tan \left(\theta_{s q}-\theta_{3 d B}\right)  \tag{2.20}\\
x_{\text {far }} & =r_{\text {slant }} \tan \left(\theta_{s q}+\theta_{3 d B}\right) \tag{2.21}
\end{align*}
$$

where $\theta_{s q}$ is the squint angle illustrated in Figure 2.1a which can be calculated as

$$
\begin{equation*}
\theta_{s q}=\arcsin \frac{x}{\sqrt{\left(x^{2}+y^{2}\right)}} \tag{2.22}
\end{equation*}
$$

The time-domain backprojection algorithm consits of accurately locating each pulse's footprint on the ground or from the inverse side, finding out which pulses illuminate a given target. Once this is known, the range from that target to each radar pulse is calculated and so is a phase correction term. A complex backscatter value (one per pulse) is interpolated from each pulse's range compressed data, according to the estimated antenna to target distance. The phase correction is applied to the interpolated value and then all the terms are coherently added. This operation focuses one pixel and if repeated over a grid of pixels will generate a focused SAR image. Note that the range is estimated from the antenna phase center to the pixel center, which may not be exactly where the target is located. In summary, the enhanced azimuth resolution is achived by adding the contributions of multiple pulses correcting the propagation phase and this is how the azimuth compression is carried out.

At this point, it is most important to characterize the signal phase as a function of time (or location), since the main goal of the backprojection algorithm is to correct for this changing variable in order to create a focused image. Recall that the received signal for an FMCW radar can be modeled by integrating over the illuminated volume which has contributions from all targets located at different spatial positions, but all at the same slant range. The time delay $t_{d}=\frac{2 r}{c}$ depends on the scatter position as, $r$ is the magnitude of $\bar{p}=[x, y, z]$, therefore

$$
\begin{equation*}
s_{c}(t)=\int_{V_{\text {illum. }}} \frac{G}{2} w(t) \sigma(\bar{p}) \cos \left(2 \pi\left(f_{0} t_{d}(\bar{p})-\frac{k_{s}}{2} t_{d}^{2}(\bar{p})+t k_{s} t_{d}(\bar{p})\right)\right) d V \tag{2.23}
\end{equation*}
$$

note that the backscatter coefficient has the incidence angle dependence built-in by the use of $\bar{p}$. Taking the Fourier Transform of (2.23) finishes the range compression operation and converts the rectangular pulse into a sinc improving the range resolution, if keeping only the positive frequency content then

$$
\begin{array}{r}
s_{c}\left(f_{b}\right)=\int_{V_{\text {illum. }}} \frac{G}{2} \sigma(\bar{p}) \exp \left(j 2 \pi\left(f_{0} t_{d}(\bar{p})-\frac{k_{s}}{2} t_{d}^{2}(\bar{p})+f_{b} k_{s} t_{d}(\bar{p})\right)\right)  \tag{2.24}\\
\tau \operatorname{sinc}\left(\tau\left(f_{b}-k_{s} t_{d}(\bar{p})\right) d V .\right.
\end{array}
$$

Finally, the phase correction term is

$$
\begin{equation*}
\phi_{\text {corr }}=-2 \pi f_{0} t_{d}+\pi k_{s}\left(t_{d}\right)^{2}=-2 \pi f_{0} \frac{2 r}{c}+\pi K \frac{(2 r)^{2}}{c^{2}} \tag{2.25}
\end{equation*}
$$

which is directly applied to $s_{c}$ by

$$
\begin{equation*}
s_{c o r r}=s_{c} e^{j \phi_{c o r r}} \tag{2.26}
\end{equation*}
$$

and ideally that would remove phase shift due to propagation and focuse the pixel. When this operation is repeated for every pulse that illuminates one target, then one pixel becomes

$$
\begin{equation*}
I=\sum_{i \in N} s_{c}^{i}\left(f_{b}(r)\right) e^{j \phi_{c o r r}^{i}(r)} \tag{2.27}
\end{equation*}
$$

where $i$ is corresponds to a radar pulse, in other words, a vector of range compressed data, and $N$ is the space of pulses that illuminate pixel $I$.

In summary, a SAR sensor is able locate a target in a 2D coordinate map defined by range and azimuth. For platforms with less attitude variations such as satellites or large airplanes flying at high altitudes, the squint angle tends to be more constant and can be more reliably estimated from the data measuring the Doppler shift between two conescutive azimuth lines. If $S_{c}[a z, r]$ is a matrix of range compressed data generated by stacking azimuth lines, then the phase shift

$$
\begin{gather*}
\varphi(r)=\sum_{a z=2}^{M} S_{c}[a z, r] S_{c}^{*}[a z-1, r]  \tag{2.28}\\
\phi_{\text {dop }}=\arctan \frac{\operatorname{Im}\{\varphi(r)\}}{\operatorname{Re}\{\varphi(r)\}} \tag{2.29}
\end{gather*}
$$

converting from radians to Hertz and normalizing by the pulse repetition time (PRT),

$$
\begin{equation*}
f_{\text {dop }}=\frac{\phi_{\text {dop }}}{2 \pi P R T} \tag{2.30}
\end{equation*}
$$

from the platform velocity $v$ the Doppler shift is

$$
\begin{equation*}
f_{d o p}=\frac{2 v}{\lambda} \sin \left(\theta_{s q}\right) \tag{2.31}
\end{equation*}
$$

and then solving for the squint angle

$$
\begin{equation*}
\theta_{s q}=\arcsin \left(\frac{\lambda f_{d o p}}{2 v}\right) \tag{2.32}
\end{equation*}
$$

where $\lambda$ is the wavelength of the radar center frequency. In many cases, when working on terrestrial remote sensing, it is of interest to estimate the target vertical component for further studies.

The next section describes the principles to estimate the scatterer height so that it can be fully mapped onto the Earth's surface.

### 2.3 Interferometry

Some SAR instruments may be composed by two receive antennas separated in the cross-track dimension, each one generating two separate SAR images. When the antennas are placed perpendicular to the direction of travel, each antenna will image the same region but seen from a slightly different range. The measured phase difference between these two antennas is due to the slightly different path lengths. This technique is called interferometry and when the phase difference is estimated from SAR images, the observing method is called Interferometric SAR (InSAR). The phase difference can be estimated from the coherence of the two images as

$$
\begin{equation*}
\gamma=\frac{s_{i} s_{j}^{*}}{\sqrt{\left|s_{i}^{2}\right|} \sqrt{\left|s_{j}^{2}\right|}} \tag{2.33}
\end{equation*}
$$



Figure 2.2: Interferometry geometry
where $\gamma$ is a complex number that can be re-written as $\gamma=|\gamma| e^{j \Delta \phi}$, where $\Delta \phi$ is the phase difference. In this case, $s_{i}$ and $s_{j}$ represent images from two separate receiving antennas. If the distance between the antennas (baseline) is known, based on simple geometry, the phase difference can be converted into a terrain height. This data collection geometry is referred to as cross-track interferometer and is the option chosen for the systems used in this thesis.

In the case that one antenna is transmiting and two are receiving simultaenously it is called bistatic mode and the interferometric phase (phase difference) is written as

$$
\begin{equation*}
\Delta \phi=\frac{2 \pi}{\lambda}((\rho+\delta \rho)-\rho)=\frac{2 \pi}{\lambda} \delta \rho . \tag{2.34}
\end{equation*}
$$

As shown in Figure 2.2a, letting $\overline{l_{1}}=\bar{T}-\overline{p_{1}}$, whose magnitude is $\rho$ and similarly, $\overline{l_{2}}=\bar{T}-\overline{p_{2}}$ with magnitude $\rho+\delta \rho=\rho_{2}$. The interferometric phase [11] in (2.34) is

$$
\begin{equation*}
\Delta \phi=\frac{2 \pi}{\lambda}\left(\left|\overline{l_{2}}\right|-\left|\overline{l_{1}}\right|\right) \tag{2.35}
\end{equation*}
$$

The baseline vector, $\bar{B}$, is written as $\bar{B}=\overline{p_{2}}-\overline{p_{1}}=\overline{l_{1}}-\overline{l_{2}}$, then

$$
\begin{equation*}
\Delta \phi=\frac{2 \pi}{\lambda}\left(\left|\left(\overline{l_{1}}-\bar{B}\right)\right|-\rho\right) \tag{2.36}
\end{equation*}
$$

$$
\begin{equation*}
\Delta \phi=\frac{2 \pi}{\lambda}\left(\left(\rho^{2}-2\left(\overline{l_{1}} \cdot \bar{B}\right)+B^{2}\right)^{0.5}-\rho\right)=\frac{2 \pi \rho}{\lambda}\left(\left(1-\frac{2\left(\hat{l_{1}} \cdot \bar{B}\right)}{\rho}+\frac{B^{2}}{\rho^{2}}\right)^{0.5}-1\right) \tag{2.37}
\end{equation*}
$$

where • is the dot product and $\hat{l}_{1}$ is the unit vector. Assuming that the baseline is much smaller than the range and taking the first term of the Taylor series of $\sqrt{(1-x)} \approx 1-\frac{x}{2},(2.37)$ becomes

$$
\begin{equation*}
\Delta \phi \approx \frac{2 \pi}{\lambda}<\hat{l}_{1}, \bar{B}> \tag{2.38}
\end{equation*}
$$

where $\left\langle\hat{l_{1}}, \bar{B}\right\rangle$ is the projection of the baseline over $\hat{l_{1}}$. Following the axis convention in Figure 2.2b, the vectors can be expressed as

$$
\begin{gather*}
\bar{B}=[B \cos \alpha, 0, B \sin \alpha]  \tag{2.39}\\
\hat{l_{1}}=[\sin (\theta), 0,-\cos (\theta)]  \tag{2.40}\\
\hat{l_{1}} \cdot \bar{B}=\sin (\theta) B \cos (\alpha)-B \sin (\alpha) \cos (\theta)=B \sin (\theta-\alpha) . \tag{2.41}
\end{gather*}
$$

where the notation $[x, y, z]$ indicates the dimensions of $x, y$ and $z$ in the along-track, cross-track, and vertical direction. Hence, the interferometric phase can be written as

$$
\begin{equation*}
\Delta \phi=\frac{2 \pi}{\lambda} B \sin (\theta-\alpha) . \tag{2.42}
\end{equation*}
$$

To reconstruct the target height, the vectors of $\overline{p_{1}}$ and $\hat{l_{1}}$ can be recombined, as in

$$
\begin{equation*}
\bar{T}=\overline{p_{1}}+\rho \cdot \hat{l_{1}} . \tag{2.43}
\end{equation*}
$$

If $\overline{p_{1}}$ is written as $\overline{p_{1}}=\left[x_{0}, 0, h\right]$, then

$$
\begin{equation*}
\bar{T}=\left[x_{0}, 0, \rho \sin \theta\right]+\rho[\sin \theta, 0,-\cos \theta]=\left[x_{0}+\rho \sin \theta, 0, h-\rho \cos \theta\right] . \tag{2.44}
\end{equation*}
$$

Here, the third coordinate is the target height, which is the desired parameter. Solving for the look angle $\theta$,

$$
\begin{equation*}
\theta=\arcsin \left(\frac{-\lambda \Delta \phi}{2 \pi B}+\alpha\right) \tag{2.45}
\end{equation*}
$$

and combining with (2.44), the target height is

$$
\begin{equation*}
h_{t}=h-\rho \cos \theta=h-\rho \cos \left(\arcsin \left(\frac{-\lambda \Delta \phi}{2 \pi B}\right)+\alpha\right) . \tag{2.46}
\end{equation*}
$$

Due to phase wrapping, every multiple of $2 \pi$ in the phase there will be uncertainty in estimating the height. This is called the height ambiguity, whose value is given by

$$
\begin{equation*}
h_{a}=\frac{-\lambda \rho \sin \theta}{B \cos (\theta-\alpha)} . \tag{2.47}
\end{equation*}
$$

This phase wrapping is visually translate into what are called 'fringes' and these will become more visible in mountaneous or irregular terrain.

### 2.3.1 Backprojection Interferometry

Having reviewed the basic principles of interferometry, the approach taken when the backprojection processing is used to generate the images is slightly different. Recall that in the process of focusing an image, the main goal was to accurately estimate the range and correct the signal phase. The accuracy of the range estimation obviously increases by using a digital elevation model (DEM) rather than assuming a flat topograhpy. In doing so, the contribution from a flat Earth and the topography is already removed, therefore the contributions to the interferometric phase will only come from deviations from the reference, in this case a DEM.


Figure 2.3: Interferometry from the backprojection perspective.

For clarity, this is illustrated in Figure 2.3, and the major assumption is that the red vectors are parallel with each other and similarly is assumed for the black ones. From Figure 2.3 the target height can be estimated as

$$
\begin{equation*}
h_{t}=\frac{\delta \rho}{\cos \theta}=\frac{\delta \rho^{\prime}}{\cos \theta^{\prime}} . \tag{2.48}
\end{equation*}
$$

The interferometric phase, in terms of the path differences is

$$
\begin{equation*}
\Delta \phi=\frac{2 \pi}{\lambda}\left(h_{t} \cos \theta-h_{t} \cos \theta^{\prime}\right) . \tag{2.49}
\end{equation*}
$$

The target height is given by

$$
\begin{equation*}
h_{t}=\frac{\Delta \phi}{\frac{2 \pi}{\lambda}\left(\cos \theta-\cos \theta^{\prime}\right)} . \tag{2.50}
\end{equation*}
$$

In summary, the interferometric phase from backprojection will provide, if processed with a DEM, target heights above or below the DEM, commonly referred to as differential heights.

## CHAPTER 3

## ATTITUDE CONTROL

The unstable motion of a small airplane flying at low altitudes can make the task of taking measurements with a radar aiming at nadir become very difficult. Having a mechanical steerable antenna is a mechanism that can provide aid in collecting measurements with such a viewing geometry while relaxing the airplane attitude constraint during a flight line. The attitude control presented in this chapter mitigates the problems found in previous flights when trying to mimick SWOT's look angle, enabling for the possibility of aiming at a fixed point or scanning a targeted region of angles. This chapter is broken down into several sections explaining first how to orient a rigid body in space, then presenting the system proposed and its operation, and finally the results obtained in test flights.

### 3.1 Aircraft Orientation

The orientation of a rigid body in space is often described in reference to a coordinate system. In general, the Earth Centered Earth Fixed (ECEF) geographic coordinate system will be used here to specify a location as well as Latitude, Longitude and Altitude (LLA) coordinates in the WGS84 ellipsoid. A convenient step in describing a body's orientation is to use an intermediate frame of reference such as East North Up (ENU). ENU is a local geographical coordinate system whose axes point towards: the North celestial pole, East is tangent to Earth's parallels and the third vector is choosen accordingly to the right-hand rule. The term local refers to the fact that ENU is a plane tangent to the Earth's surface on a given location and
this plane is used as a reference to describe the orientation of the object. Similar to ENU, another convention commonly adopted is North East Up (NED). In both cases, a geographic location and three angles to rotate a local reference frame will suffice to fully describe an orientation.

The object's coordinate system is refered to as body (airplane) frame and is defined as the $y$-axis pointing to the nose of the airplane, z -axis points out through the roof perpendicular to the floor and x -axis completes the right-handed system. The angles that define the rotation between the body and local reference frame are called Euler angles. Each angle representes the amount of rotation to apply about one axis and when concatenating them, a full rotation between frames is achieved. The convention used here is NED where the Euler angles yaw, pitch, and roll are shown in Figure 3.1b, following a typical rotation sequence of $\mathrm{z}, \mathrm{y}$ and x . The rotation for each axis is given by

$$
\begin{align*}
& R_{z}(\text { yaw })=\left[\begin{array}{ccc}
\cos \alpha & -\sin \alpha & 0 \\
\sin \alpha & \cos \alpha & 0 \\
0 & 0 & 1
\end{array}\right]  \tag{3.1}\\
& R_{y}(\text { pitch })=\left[\begin{array}{ccc}
\cos \alpha & 0 & \sin \alpha \\
0 & 1 & 0 \\
-\sin \alpha & 0 & \cos \alpha
\end{array}\right]  \tag{3.2}\\
& R_{x}(\text { roll })=\left[\begin{array}{ccc}
1 & 0 & 0 \\
0 & \cos \alpha & -\sin \alpha \\
0 & \sin \alpha & \cos \alpha
\end{array}\right] . \tag{3.3}
\end{align*}
$$

A full rotation is calculated by

$$
\begin{equation*}
R_{n e d 2 b o d y}=R_{z} R_{y} R_{x} \tag{3.4}
\end{equation*}
$$

and it is simply applied by a matrix multiplication as

$$
\begin{equation*}
V_{\text {rot }}=R V . \tag{3.5}
\end{equation*}
$$

As mentioned above, the orientation of the local level reference frame will change as a function of its location on Earth. The correct ENU coordinate system can be obtained from a known position in the WGS84 datum as

$$
R_{\text {enu2ecef }}=\left[\begin{array}{ccc}
-\sin \varphi & \cos \varphi & 0  \tag{3.6}\\
-\cos \varphi \sin \varphi & -\sin \varphi \sin \lambda & \cos \lambda \\
\cos \varphi \cos \lambda & \sin \varphi \cos \lambda & \sin \lambda
\end{array}\right]
$$

where $\varphi$ and $\lambda$ are the latitude and longitude respectively. Then, the conversion from ENU to NED is given by

$$
R_{\text {enu2ned }}=R_{n e d 2 e n u}=\left[\begin{array}{ccc}
0 & 1 & 0  \tag{3.7}\\
1 & 0 & 0 \\
0 & 0 & -1
\end{array}\right]
$$

Several different transformations are available to convert from ECEF to LLA, often this is already built-in most softwares but a good reference whose solution is stable at the poles is found in [16].


Figure 3.1: Coordinate systems for attitude representation. a) Geodetic longitude and latitude are represented by $\lambda$ and $\varphi$ respectively. b) Airplane body frame in NED convention showing the direction of positive rotation of yaw, pitch and roll.

### 3.2 Motion Compensation Overview

The system proposed is able to independently rotate the radar antennas in pitch and roll axis, with one of the main goals being to compensate for the airplane attitude and stabilizing the antenna looking down to nadir. Because yaw plays a less significant role in the incidence angle and it will mostly affect the polarization, it has not been incorporated in the motion compensation.

The system is formed by two plates that are connected to each other by two hinges. The lower plate attaches to the airplane floor while the top can move freely carrying the antennas and other equipment. The top plate has two sets of brackets, each one holding a set of two vertical plates. The radar antennas are attached to the inner of those vertical plates whereas the outters are bolted onto the brackets. This configuration allows for the desired movement in 2D.

In order to regulate the rotations, a stepper motor controls the roll and is connected through a rod to the top part of the antenna. Such a linkage results in a movement that can be modeled by the piston equations when accounting for an off-


Figure 3.2: Radar Antennas setup
sett crankshaft. Another actuator resting on the lower platform lifts the upper plate in a direction that is perpendicular to the stepper motor operation and by leaning the plate up or down is effectively changing the antenna pitch.

### 3.3 Motion Compensation Implementation

In order to move the antennas in a way that cancels the aircraft attitude the latter must be known. An Intertial Measurement Unit (IMU) is flown onboard the airplane to measure its attitude, this provides accurate measurements for yaw, pitch and roll. The unit provides two types of logs for attitude, one with gyroscopes and accelerometer raw data at 125 Hz meant to be used in the post-processing to generate high precision results and a second $\log$ with the solution computed in real time at 15 Hz. Due to the nature of attitude cancelation, which requires short lag, the raw data log cannot be used to inform the motors about the aircraft attitude and instead the lower rate measurement is used.

A Python-based software interfaces with the IMU, actuators and an absolute encoder attached to the shaft of the stepper motor. The program runs separate processes
in parallel to read the IMU and move the actuators, this architecture accomodates different update rates between pitch and roll. The process that reads data from IMU will put the measured pitch and roll into two separate queues limited to a size of 1 that are shared with the processes that move the actuators. Before the put operation of the IMU process the queues are always cleared and in order to avoid concurrence problems these are shared using Python locks. Using this methodology, the motors will always update to the latest value read from the IMU and in case that the queue is empty, it means that is still a reasonable approximation to keep using the value previously read. The processes in charge of moving actuators compute the difference between the aircraft's current value and the target, they convert the angle to steps and subtract the current position of the antenna. This calculates the amount of displacement and the sign dictates the direction of movement. In fact, the combination of all these operations implement a basic open-loop feedback system.

Having the ability to set different goals for roll and pitch opens the possibility to not only cancel the airplane attitude but also to fix the antennas to a desired viewing geometry. Furthermore, repeatedly changing the goals inflight will produce a desired scanning effect. Both possibilities are exploited here, giving the software two modes of operation: fixed or scanning mode. When the latter mode is in use, two additional processes change the target pitch and roll according to a user-specified grid. These two processes interact with each other, once the roll has finished scanning one line, informs that the pitch can be updated in order to avoid data gaps. The grid is split into several sections along the pitch direction and generates redundancy by overlapping these sections. This, intends to avoid loss of information in some pitch values that may result after a sudden change in the aircraft attitude due to winds or other external factors that may produce a rotation faster than what the system is able to keep up with.

Physical limitations due to antenna size forced the use of software limits in the dynamic range to prevent the antenna from hitting the airplane and avoid possible damage. The roll was limited to $\pm 7.5$ degrees and pitch to $0-5$ degrees. When the target position exceeds the limits, the software disengages the motor operations and mantains the previous position until a new target below the limits is read. This may cause undesired attitude variations but is unlikely to happen in the course of a flight line, instead, is very useful when turning since the software can keep running without trying to cancel such large rolls.

For geometric consistency between flights an encoder was mounted on the back of the roll motor, the combination provides a motor with absolute encoding, necessary to remove offsets when finding nadir. A calibration routine runs before the take-off that consists of finding an absolute mark in the encoder named index, then rotates the antenna in roll until it reaches 0.0 degrees, at that point the offset between nadir and index is saved and the stepper motor is reset. Once the motor is calibrated, the encoder starts recording data into a text file, this procedure decouples the position update rate from the measurement rate and provides high accuracy and frequency angular measurements.


Figure 3.3: Block-diagram of the motion compensation system operations.


Figure 3.4: Grid generated during a 2D scan, each dot represents a sample point. The sections are colorcoded to show the overlap that generates redundancy.

### 3.4 Performance results

Initially, the complete system was tested in the laboratory and after having successful results it was mounted in the airplane for engineering flights. Figure 3.5 shows the results of several different flights. In the figures, actuator refers to the angular inclination the motor enforced and when combined with airplane results in the true antenna orientation. The improvement in stabilization can be observed in Figure 3.5a if compared to the true attitude of the airplane, as expected though, more variations are experienced in pitch than roll. The results of roll scanning are shown in Figure 3.5 c where the control software linearly sweeps $\pm 5$ deg generating a triangular-like shape. Notice that this is achieved by simulteanously cancelling the airplane roll and adding the desired true roll on top of the correction. A pitch scan is shown in Figure 3.5 d , the sweeping is considerably slower since one roll scan is performed for every pitch value. The modular architecture shown in Figure 3.4 allows to have a scanning time that can fit in a flight line and then recover the full 2D map by combining several lines.

To evaluate the performance of both software and motors, the time between motor updates was measured, which is the time elapsed between two consecutive actuator movements were finished and logged. The system responsiveness is limited by the speed of the motors, the more time is spent moving the less often the position can be updated and therefore the older the sample gets.

The results for each actuator are shown in Figure 3.6, the pitch averages an update rate of 19.41 Hz due to the combination of faster speed and short travel movements. On the contrary, the roll actuator has a slower driver that in conjunction with larger angle corrections results in a lower update rate of 7.44 Hz . In an effort to reduce the latency of the system, it was investigated what portion of the time between updates is spent moving. The values in Figure 3.7 show that roughly the $90 \%$ of the time is moving while the rest is considered either waiting or IDLE.

(a) Roll in nadir-looking mode

(b) Pitch in nadir-looking mode

(c) Roll scanning mode

(d) Pitch scanning mode

Figure 3.5: Attitude compensation results in various flight lines.

(a) Pitch averaged an update rate of 19.41 (b) Roll averaged an update rate of 7.44 Hz Hz

Figure 3.6: Histograms of the time elapsed between position updates during a test flight.


Figure 3.7: Roll timing statistics.

## CHAPTER 4

## KA-BAND SCATTEROMETER

This chapter gives an overview of the Ka-band radar used in a scatterometer configuration and flown on a Cessna-206. In what follows is a description of the principle of operation, its relation to SWOT and results obtained using the motion compensation system shown in the previous chapter. Having control on the viewing geometry helps to mimick SWOT's look angle. The integration of a high performance IMU improves the estimation of the incidence angle which subsequently leads to a better backscatter coefficient characterization.

### 4.1 System description

The Ka-band transceiver is an FMCW radar at 35 GHz which consists of a dualstage up- and down-converter. It has one transmit channel and two channels for reception, and hence being capable of dual-polarization operation. At the receive channels the signals are mixed down to base band, additionaly, pulse compression is performed in hardware by directly mixing a replica of the transmitted waveform with the received echo. An Ettus Research USRP N210 software defined radio is used to sample and digitize the base band data. This same device also sends the data to a computer to record it together with other control parameters such as timestamps and radar settings.

A Tektronix AFG3252 waveform generator (AWG) provides a linear FM up-chirp going from 5 MHz to 105 MHz that feeds the transceiver. The AWG triggers the Ettus data acquisition board (DAQ) at every pulse. To mantain timing, all share a

10 MHz reference to phase-lock the oscillators. The basic radar parameters including the transmitted waveform are described in Table 4.1. For synchronization purposes the DAQ board has a GPS antenna connected that provides one pulse per second (1PPS) and GPS time.

This system, in scatterometer configuration, is mounted pointing downwards with the antennas fitted through a circular opening at the bottom of the airplane. The radar uses a standard gain horn antenna with a gain of 15 dB to transmit and a Gaussian Optics Antenna (GOA) for reception. The latter provides a very narrow beamwidth allowing the system to have a smaller footprint and therefore, to focus the beam on smaller area minimizing contributions of other scatterers. On the other hand, the wide beamwidth of the transmit antenna let the system work under the reasonable assumption that all of the targets within the receive main beam are uniformly illuminated.

The flight system, in addition to the radar, is comprised by the motion compensation system, an IMU unit including the GPS receiver and a dedicated computer that logs navigation data and runs the motion compensation software. The computer additionally records relevant actuator logs for post-processing.

| Parameter | Value |
| :---: | :---: |
| Center Frequency | 34.95 GHz |
| System Bandwidth | 100 MHz |
| Transmitted Power | 1 mW |
| Noise Figure | 9 dB |
| PRF | 999 Hz |
| Range resolution | 1.5 m |
| TX antenna beamwidth | $30^{\circ}$ |
| RX antenna beamwidth | $2.1^{\circ}$ |

Table 4.1: Basic parameters of the Ka-band system.

(a) Ka-band transceiver box.

(b) The KaScat system mounted in the airplane. The RF box is on the bottom left corner of the image and the (black) antennas are pointing down through the metalic platform.

Figure 4.1: Ka-band radar system operating as a scatterometer.

### 4.2 Scatterometry

The goal of the scatterometer is to measure the absolute power backscattered from a target and after some signal processing, to estimate the backscatter coefficient of the target. The critical issue is that the radar cross section is, among others, a function of the incidence angle. Therefore, a single observation at one incidence angle will not suffice to characterize a specific target, but instead a curve of data points for several incidence angles is necessary. Morevover, the backscatter coefficient from the same target may differ between observations as the state of the target changes. It is a proxy for the target's shape and therefore its roughness and it is broadly used to characterize material compositions or surface roughness.

There are three main surface backscattering models available in the literature, each one with different regimes of applicability. The Geometrical Optics (GO) [14] solution models the responses at nadir or for small incidence angles, the small perturbation method (SMP) [14] focuses on large incidence angles and the Integral Equation Method (IEM) [6] is a single model that includes both GO and SMP components. The effect of surface roughness is depicted in Figure 4.2. As the roughnes increases the angular spread of the scattered wave increases, and as it is spreads, more power is reflected back in the direction of incidence. If comparing Figure 4.2a with 4.2c, the first has specular reflection, returning no signal back to the radar (if off-nadir) whereas the latter due to its roughness, regardless the incidence angle, still reflects power back. For water bodies like rivers or oceans, windy conditions break the smooth surface and create waves whose height depend on the wind intensity. Thus, one could use the characterization the backscatter coefficient as a function of the incidence angle for wind speed retrieval.

Because these measurements rely on absolute power, one must consider the total size of the antenna footprint and normalize for it to have a significant result. The recevied power at the radar antenna can be written as

(a) Smooth surface

(b) Slightly rough surface

(c) Very rough surface

Figure 4.2: Power scattered back for different surface conditions

$$
\begin{equation*}
P_{r}=\frac{P_{t} \lambda^{2} G_{r} G_{t} A_{r}(\phi, \theta) A_{t}(\phi, \theta) \sigma}{(4 \pi)^{3} R^{4}} \tag{4.1}
\end{equation*}
$$

where $P_{t}$ is the transmitted power, $\lambda$ is the wavelength at the carrier frequency, $G_{t}$ and $G_{r}$ are the gains of the transmitter and receiver chain respectively, $A_{r}$ and $A_{t}$ are the antenna radiattion patterns and $R$ is the distance from the radar to the target. As shown in Table 2.1, since the transmit antenna has a much wider beamwidth the footprint area is limited by the recieve antenna. If the radar beam is narrow enough one can approximate the illuminated surface with constant backscattering coefficient and calculate the RCS for an illuminated area, $A_{i}$, as

$$
\begin{equation*}
\sigma=\iint_{A_{i}} \sigma^{0}\left(\theta_{i}\right) d S \tag{4.2}
\end{equation*}
$$

where $\theta_{i}$ is the incidence angle and $\sigma^{0}$ is the backscattering coefficient or the Normalized Radar Cross Section (NRCS). Most of the data processing of this chapter focuses on retrieving $\sigma^{0}$ to evaluate the performance of both the radar and the steerable antenna system.

### 4.3 Calibration

The process of measuring an absolute magnitude requires the need for a radar calibration. The system is calibrated on the ground using corner reflectors. The calibration principle is very simple: the corner reflector is placed at a known distance and has a known radar cross section, the received echos are recorded while measuring the transmit power. With the system parameters measured and properly characterized in a laboratory environment, using the radar equation one can estimate a calibration constant that will later be used in the data processing chain. From the measurements

$$
\begin{equation*}
K_{\text {cal }}=\frac{P_{r} R^{4}}{P_{t} \sigma_{\text {reflector }}} \tag{4.3}
\end{equation*}
$$

where $P_{r}$ is the received power as in (4.1). Combining (4.1) and (4.3), and solving for the calibration constant gives

$$
\begin{equation*}
K_{n o m}=\frac{G_{r} G_{t} A_{r}(\phi, \theta) A_{t}(\phi, \theta) \lambda^{2}}{(4 \pi)^{3}} \tag{4.4}
\end{equation*}
$$

From these two, and though deviations can occur, (4.4) is the theoretical calibration constant the radar should give from its nominal parameters. The previous constant, $K_{\text {cal }}$, is the real constant measured by the system which helps to determine how large the biases are between the theoretical values and the observations. In any case, and because the latter includes any possible gain drift, the real measurement is ultimately used to calibrate the flight data.

Every radar pulse will estimate a slightly different power, therefore a standard practice is to leave the radar on during a span time of about 10 minutes and generate histograms of the calibration constant, as shown in Figure 4.3. If during a calibration different distances are used, the final constant will be the average of the mean of every distance histogram.

The amplifier gain drifts as the temperature changes affecting the transmitted power. To reduce the variance of the radar temperature, the transceiver box was in-


Figure 4.3: Example of a calibration histogram to estimate the radar constant. Results shown here are from the co-polarized channel.
sulated and fitted with a temperature control system. Still, if not properly monitored the drift in transmitted power may result in a biased estimation of the backscattering coefficient. In order to improve the accuracy of the radar, a system temperaturepower dependance was modeled. The test employed a power detector at 35 GHz positioned immediately before the transmit antenna, a laboratory power meter and the temperature control readings. Figure 4.4 shows the experiment results and the final fit. The temperature control has 4 sensors in the transceiver box, and as shown in the figure, sensor T4 has almost a linear dependance with the power, and hence is used to generate the system model. Having such a model offers inflight redundancy and in case the power detector logging fails, it is safe to rely on the temperature to estimate the transmitted power.


Figure 4.4: KaScat power-temperature dependance model.

### 4.4 Data Processing

This section describes the KaScat processor chain, presents the results and some further data analysis done with the processing results. In general most of the data was acquired over water bodies like rivers and ocean, and the results here are classified by target and state: smooth river, rough river and ocean.

The processor is a Matlab-based program and does not require any user interaction, only an input file with basic processor settings and the path to the dataset. Due to the high RAM requirements Matlab has, the radar data cannot be processed in one block. Instead, the program reads one radar file and only stores the target estimated range and power. The first stage of the processor reads radar raw data and takes the FFT of the signal to estimate Power Spectral Density (PSD) using the Periodogram as

$$
\begin{equation*}
S_{c c}(f) \approx X_{c}(f) \cdot X_{c}(f)^{*}=\left|X_{c}(f)\right|^{2} \tag{4.5}
\end{equation*}
$$

where $X_{c}(f)=\mathcal{F} \mathcal{T}\left\{s_{c}(t)\right\}$, and recalling from (2.15) that the frequency can be mapped to radar range. In order to find the surface return, the first range bins are discared due to near field coupling between the FMCW antennas, a search operation is performed around the range equivalent to the flight altitude. Once the power peak is found, neighboring samples are integrated to estimate the power. This process takes into account the main lobe beamwidth. The target range is that of the index corresponding to the maximum power return within that window. Auxiliary data such as GPS, IMU and other sensors are read and interpolated to a common base using the radar time stamp at 999 Hz . At this stage, the RCS is estimated using the calibration constant as in (4.3) and the program proceeds to compute the SNR.

Once finished processing all of the radar files, the next stage in processing reads all of the acutators $\log$ files and, together with the IMU data, calculates the antenna true pitch and roll angles. Using the true attitude and the IMU yaw, the radar pulse is geolocated. The approach taken here is rather simple and assumes a flat Earth
model, which is acceptable due to the low flight altitude and small swath. Starting with a vector pointing down with magnitude equal to the measured range

$$
\begin{equation*}
p_{b o d y}=[0,0, r] \tag{4.6}
\end{equation*}
$$

the vector in body frame coordinates is rotated using the yaw and resultant pitch and roll as

$$
p_{\text {ned }}=\left[\begin{array}{ccc}
\cos (y) & -\sin (y) & 0  \tag{4.7}\\
\sin (y) & \cos (y) & 0 \\
0 & 0 & 1
\end{array}\right]\left[\begin{array}{ccc}
\cos (r) & 0 & \sin (r) \\
0 & 1 & 0 \\
-\sin (r) & 0 & \cos (r)
\end{array}\right]\left[\begin{array}{ccc}
1 & 0 & 0 \\
0 & \cos (p) & -\sin (p) \\
0 & \sin (p) & \cos (p)
\end{array}\right] p_{\text {body }}
$$

where $y$ is the yaw, $r$ the roll and $p$ the pitch. Having the orientation in a local coordinate system, $p_{\text {ned }}$ needs to be converted to ECEF in order to add the airplane position, as in

$$
\begin{equation*}
p_{\text {ecef }}=R_{\text {enu2ecef }} \cdot R_{\text {ned } 2 e n u} \cdot p_{\text {ned }} . \tag{4.8}
\end{equation*}
$$

Similiarly for the aircraft, GPS positions are given in coordinates of LLA which must be converted to ECEF by

$$
\begin{equation*}
a_{\text {ecef }}=R_{\text {lla2ecef }} \cdot a_{\text {lla }} \tag{4.9}
\end{equation*}
$$

where $R_{\text {lla2ecef }}$ uses the transformation in [16]. Finally, the target location in ECEF coordinates are given by

$$
\begin{equation*}
t_{\text {ecef }}=a_{\text {ecef }}+p_{\text {ecef }} \tag{4.10}
\end{equation*}
$$

and is converted back to LLA coordinates for mapping representation

$$
\begin{equation*}
t_{l l a}=R_{\text {ecef2lla }} \cdot t_{\text {ecef }} \tag{4.11}
\end{equation*}
$$

Repeating a procedure similar as the one above, and as done in [2], a nominal antenna pattern is sampled and then projected on the ground using the above rota-


Figure 4.5: For high altitudes, the radar observes Earth's curvature as shown in the image. At low altitudes, Earth can be assumed flat and then look and incidence angle become the same.
tions. The rotation distorts the pattern from a circle, if the beamwidth is the same in both directions, to an ellipse. The area of that ellipse is estimated by calculating the euclidean distance, $d$, from each sample to the center point, where the maximum is the semi-major axis and the minimum the semi-minor axis. Thus, the area is calculated by $A_{\text {ell }}=\pi \max (d) \min (d)$. After geolocating the pulse and estimating the footprint area, normalization to the RCS previously calculated by $A_{\text {ell }}$ is needed to obtain the backscatter coefficient $\sigma^{0}$. In short, the inverse of (4.2).

A critical step in the above process is to calculate the incidence angle, necessary to properly characterize the backscatter coefficient. As shown in Figure 4.5, for a flat Earth geometry both incidence and look angle become the same. Therefore, one can estimate the look angle as

$$
\begin{equation*}
\theta_{l}=\arccos \left(\frac{\left(-\bar{a}_{\text {ecef }} \cdot\left(\bar{t}_{\text {ecef }}-\bar{a}_{\text {ecef }}\right)\right)}{\left\|-\bar{a}_{\text {ecef }}\right\|\left\|\left(\bar{t}_{\text {ecef }}-\bar{a}_{\text {ecef }}\right)\right\|}\right)=\theta_{i} \tag{4.12}
\end{equation*}
$$

where • is the vector dot product and $\|\bar{a}\|$ is the vector magnitude. When all of the tasks are finished, the program used to implement the algorithm stores the workspace into a folder and creates a file with all the settings used during the processing in order
to replicate the results if needed at any given time. In general the processing outputs are concatenated by flight lines to readily analyze the data as various experiments may be ran in different lines.

### 4.5 Results

The results presented here come from a combination of several flights in which the attitude compensation system transitioned to include new features and improved to have more accuracy and repeatability. Most of the data was acquired over the Connecticut river, Figure 4.6a shows an example of a river flight line. Furthermore, with the system proven to work properly, another flight was done over the Atlantic ocean on the northern part of the US East Coast. The site was chosen to have a buoy nearby in order to have local wind speed measurements to compare with the ones inferred from the ocean surface backscatter.

### 4.5.1 Smooth river

One of the first tests to assess the operation of the airplane attitude compensation with the radar was to fly under very low wind conditions, when the river surface would offer specular reflection. Because nadir look angles will have a maximum radar return comparing the radar data against the true antenna attitude would provide evidence if the behavior was as expected and help to determine if any orientation offset was present between the radar and aircraft nadir directions. Figure 4.7 shows the backscattering response as the antennas were scanning in the roll direction while keeping pitch relatively constant. The roll zero crossings correspond to the backscattering peaks as expected since is the combination that gives an incidence angle closer to nadir. The system, at the time, was only able to correct for positive pitch values and that created a span in the pitch direction of about 2 deg. as observed in Figure 4.8. This radar cross section map allows one to see the rapid decrease of $\sigma_{0}$ as the


Figure 4.6: Example of flight lines extracted from the GPS data on the two survey sites where all the data was collected.
target is illuminated away from nadir, a response that assesses the correct operation of the radar, attitutde control and signal processing chain.

Furthermore, the incidence angle is computed using the true pitch and roll, and a heat map of $\sigma_{0}$ is plotted in Figure 4.9. The heat map indicates which regions are populated and its density over the total number of samples used. The return power peaks at $\theta_{i}=0$ and rapidly decreases between 1-2 degrees. The slight increase after the main lobe is from an antenna side-lobe with the pattern continuing to decrease past 3 degrees. As mentioned before, due to the physical limitations of the airplane,
only incidence angles up to 5 deg. were possible to control, above that the control software disengages and keeps the antenna from moving to prevent any damage.

The small jump observed corresponds to the radiation pattern of the receive antenna. The reason for that is that, even though broadside is rotated away from nadir, the antenna transmits a radiation pattern which means that at nadir there is in fact power being transmitted only that is attenuated by the pattern evaluated at the corresponding offset. Knowing that, if pitch is being corrected and the antenna is scanned in roll, one should be able to measure the radiation pattern for very smooth surface conditions. Such an experiment was conducted and the results are shown in Figure 4.10. These show that there is a very good accuracy and match for the sidelobe level and location.


Figure 4.7: Flight line results over smooth river water, scanning roll $\pm 5 \mathrm{deg}$.


Figure 4.8: Radar cross section map as a function of pitch and roll for smooth river conditions. Shows large values at the center as expected.


Figure 4.9: Backscatter coefficient $\sigma_{0}$ as a function of the incidence angle for smooth river data. Yellow regions show points that are heavily densified.


Figure 4.10: Backscatter coefficient $\sigma_{0}$ as a function of roll with pitch being compensated (close to 0 deg ) with GOA radiation pattern superposed. Shows good fit and demonstrates that smooth water surfaces measure the radiation pattern.

### 4.5.2 Rough river

The attitude control software in this flight was configurated to not only scan in roll the direction, but also in pitch. Because the upper platform that holds the antenna can only move up, this results in negative pitch. Since the incidence angle is a function of both pitch and roll and the radiation pattern is symmetric, leaving a side the direction of watter ripples effects, it does not make much of difference to be scanning on the negative or in the positive region.

The flight that collected data under rough surface conditions was bumpier than normal. This made it harder for the controller to obtain data exactly at nadir. Moreover, the week prior to this flight heavy rain was reported ${ }^{1}$ which resulted in substancial waves on the surface of the river. Additionally, during the flight time wind speeds ranging from 11 to 16 mph were reported with gusts of 23 mph . As explained earlier, the scattering of a rougher surface produces a wave reflected in several directions, which results in more power backscattered for greater incidence angles. This flatter response is shown in Figure 4.11, where the pattern of $\sigma_{0}$ decreasing still holds true but it is less pronounced for the smooth surface conditions as discussed in the previous section.

The heat map for this data set also shows less dependency on the incidence angle due to the ripples on the river surface. Under these conditions, it is noticeable that the antenna pattern is not measured as it happened with the glassy river surfaces and that $\sigma_{0}$ is monothonically decreasing since antenna sidelobes do not show up.

[^0]

Figure 4.11: Radar cross section map as a function of pitch and roll, in rough river conditions.


Figure 4.12: Normalized backscatter coefficient as a function of the incidence angle for rough river surface. Shows a decreasing trend but not as rapid as in very smooth surfaces.

### 4.5.3 Atlantic Ocean

Finally, the results of KaScat's first oceanic flight are discussed here. For this flight, the control software was set to scan $\pm 2.5 \mathrm{deg}$ in pitch, this range was achieved by combining the airplane pitch with the inclination of the platform. Because it is desired to populate the map in Figure 4.14 with fine resolution, the 2D scanning


Figure 4.13: Wind speed data during the time of data collection obtained from buoy Station IOSN3
region was divided in smaller sections to reduce the scanning time and fit it into a single flight line as depicted in Figure 3.4.

For the ocean case, as expected, the radar cross section is greater around the center of the map of pitch and roll but is not as pronounced as in the smooth river conditions. The specular reflection is not present and the diffusion of scattering makes power returns off nadir to be larger than when compared to the smooth surface case. The wind speed data reported for the time of flight is shown in Figure 4.13. Furthermore, the ocean backscattering in Figure 4.15 shows a weaker dependence on the incidence angle for wind speeds similar to the case for a rough surface river conditions. Waves on the surface of the water are more present in the open ocean than in a river that is protected by surrounding trees (the Connecticut river is approximately 300 meters wide). This is why for similar wind speed conditions, ocean surface has a flatter backscattering response as a function of the incidence angle.

Using the backscatter coefficient model in [15] for Ka band with an estimated wind speed 10 meters above the ocean surface of $6.2 \mathrm{~m} / \mathrm{s}$, the results obtained by the heat map show they fit the model very well if adjusted by 1 dB , a reasonable offset that could be due to calibration and modeling uncertanties.


Figure 4.14: Radar cross section map as a function of pitch and roll for ocean data. Note the different vertical scale to highlight larger values concentrated around the center.


Figure 4.15: Backscatter coefficient as a function of the incididence angle heat map for oceanic data with wind speed model of $6.2 \mathrm{~m} / \mathrm{s}$ superimposed.

## CHAPTER 5

## KARIN REFLECTIVITY SIMULATION

This chapter gives a brief description of NASA's SWOT mission, its geometry and instrument characteristics. Describes the process carried out to provide an estimation of KaRIN's reflectivity and some of its potential use. The main distinction of the simulator done here is that the backscattering coefficients used for the simulation are real measurements at Ka-band done with the UMass KaScat, the airborne sensor described in the previous chapter. The following sections present the results and further analysis such as interferograms from the simulated data.

### 5.1 Mission and Instruments Overview

The mission goal of SWOT is to measure the height of water bodies and ocean currents worldwide. SWOT will provide a global inventory of inland surface water for areas in excess of $100 \mathrm{~m}^{2}$ and rivers whose width exceeds 50 m . The height precision for rivers is at least 10 cm of height, whereas for small lake areas, it is 25 cm of height. For that, SWOT's payload comprises a nadir altimeter and a Ka-band crosstrack interferometer, being the first mission ever to combine classical pulse-limited and interferometric wide-swath altimetry. The nadir altimeter is dual frequency operating at C- and Ku-bands. Like classical radar altimeters, its principle of operation is based on the time delay and the waveform shape is often modeled by the Brown model [12], which is a convolution of the backscatter from flat surface, height probability density function and system point target response. The return waveform can also provide more information about the state of the target. The leading edge slope is related
to significant wave height, the peak power to the ocean wind speed, and the trailing edge of the pulse will be flatter for a rough surface. The antenna beamwidth will also shape the trailing edge by not attenuating returns at larger look angles.

The radar interferometer of SWOT will employ two antennas of $5 \times 0.25$ meters (Length x Width) separated by a 10 meter baseline. An illustration of this setup is shown in Figure 1.1 and the main system parameters are given in Table 5.1. The satellite will have an average orbit height of 890 km , and very narrow look angles ranging from 0.6 to 3.8 degrees. This narrow range is the reason that it is necessary to characterize the backscattered power over water in the near nadir region between $0-5$ degrees as done in the previous chapter. From the antenna dimensions, the 3 dB beamwidths in azimuth and elevation are estimated as

$$
\begin{align*}
& \theta_{e l}=\frac{\lambda 180}{\pi W}=1.923 \mathrm{deg}  \tag{5.1}\\
& \theta_{a z}=\frac{\lambda 180}{\pi L}=0.096 \mathrm{deg} . \tag{5.2}
\end{align*}
$$

Note that these values are approximations, as the real elevation beamwidth measured from the provided look angles is 1.605 degrees. Knowing that the antennas have a view angle $\theta_{v}=2.7$ degrees, the swath is obtained by trigonometry as

$$
\begin{equation*}
\text { Swath }=h \tan \left(\theta_{v}+\theta_{e l}\right)-h \tan \left(\theta_{v}-\theta_{e l}\right) \approx 50 k m \tag{5.3}
\end{equation*}
$$

where $h$ is the orbit height of 890 km . Due to the asymetric radiation pattern, the footprint is approximated as an ellipse where the antenna peak gain is

$$
\begin{equation*}
G_{p e a k}=\frac{16}{\sin \left(\theta_{a z}\right) \sin \left(\theta_{e l}\right)}=54.5 d B \tag{5.4}
\end{equation*}
$$

The KaRIN instrument will rely on the magnitude of the returned power to discriminate water from ground targets. Water returns will appear brighter than land,

| Parameter | Value |
| :---: | :---: |
| Center Frequency | 35.75 GHz |
| System Bandwidth | 200 MHz |
| Transmitted Power | 1500 W |
| PRF | 4420 Hz |
| Range resolution | 0.75 m |
| Pulse length | $4.5 \mu \mathrm{~s}$ |
| Baseline | 10 m |

Table 5.1: KaRIn system parameters.

(a) Swaths and nadir track of descending pass 551. Enclosed in red the chosen region of study.

(b) Zoom in

Figure 5.1: Selected area of study
but due to this narrow look angle, data artifacts such as layover will make ground targets look as bright as water, contaminating the estimation of inland water areas. Such artifacts are not expected to be neglibigle and are examinated in the upcoming sections.

### 5.2 Targets generation

The first steps taken to simulate a scene start by obtaining SWOT ephemeris data and the edges of the right and left swaths. The orbit position is approximately the center of the satellite bus and the antenna locations are needed for interferometric simulations. The antennas are generated by taking the cross product of the nadir and along track unit vectors

$$
\begin{gather*}
\hat{u}_{T}=\frac{p(x, y, z)_{t+1}-p(x, y, z)_{t}}{\left\|p(x, y, z)_{t+1}-p(x, y, z)_{t}\right\|}  \tag{5.5}\\
\hat{u}_{\text {nad }}=\frac{-p(x, y, z)_{t}}{\left\|p(x, y, z)_{t}\right\|} \tag{5.6}
\end{gather*}
$$

where $t$ and $t+1$ refer to instances of time and $(x, y, z)$ are geocentric coordinates. Following the right-hand rule, $\hat{u}_{T} \times \hat{u}_{\text {nad }}$ gives the direction to the left antenna and similarly $\hat{u}_{\text {nad }} \times \hat{u}_{T}$ the right antenna. By separating the SWOT antennas 5 meters from the spacecraft center and translating the centers to the spacecraft location the baseline is generated. The antenna positions can be written as

$$
\begin{align*}
& \bar{a}_{L}(x, y, z)_{t}=\left(\hat{u}_{T} \times \hat{u}_{n a d}\right) 5+\bar{p}(x, y, z)_{t}  \tag{5.7}\\
& \bar{a}_{R}(x, y, z)_{t}=\left(\hat{u}_{n a d} \times \hat{u}_{T}\right) 5+\bar{p}(x, y, z)_{t} . \tag{5.8}
\end{align*}
$$

Separately, perpendicular to the the swath edges, straight lines are created to obtain the second sampling direction in order to generate a target grid. The input DEM ${ }^{1}$ is interpolated to the swath grid, by default and for faster simulations a 10 m posting is used but the global accuracy will greatly depend on the DEM used. To include the effect of trees, especially along the sides of rivers, a canopy height layer ${ }^{2}$ is

[^1]added on top of the DEM. Note that the surface is not tessellated, rather, point-like targets weighted by a uniform area are used instead of facets. Although less acurate, this approach facilitates the grid arrangement compared to triangulated facets that become a non-uniform grid.

Having defined the scene topography, the look and local incidence angle seen by the antennas are calculated. The incidence angle is calculated from a flat topography which accounts only for the ellipsoid curvature. The local incidence is defined relative to the terrain surface normal vector. This step is relevant since it better approximates incident wave angle and is later used to interpolate backscattering coefficients from different models. A landcover classification map ${ }^{3}$ assigns scattering models for each target, the layer used here was modified to group similar targets into the same category, i.e. trees of different scale were grouped together.

The latest data sets collected by the Ka-band scatterometer contain mostly water returns, instead an older data set from 2014 with a large variety of targets was used to retrieve the backscattering models used in the simulator. The processing used is similar to the one explained in the previous chapter. It classifies the targets based on their landcover class, calculates a heat map and then generates a curve by selecting the most dense point per bin. A moving average is applied to smooth jumps or discontinuites and then the final model is obtained by curve fitting. An example of the procedure is shown in Figure 5.3, for comparison, the weighted mean of each bin is displayed and shows that the result using a lower grade IMU is susceptible to be biased due to the large variance of the measurements. For consistency, all of the estimated models were compared to [5] which showed good agreement and backed the assumption that the mode would be a more reliable estimator.

The observations were done in the near-nadir range and to prevent large biases in

[^2]
(a) Local incidence of left swath from left antenna on pass 551

(b) Inc. angle histogram

Figure 5.2: Example of local incidence angle map for the region of interest over Western Massachusetts. Note that in flat areas of water the local incidence coincides with the look angle.

(a) Heat map of trees backscattering measured by the KaScat. The weighted mean is more affected by the high variance of the measurements.

(b) Backscattering model for trees at Ka-band fitted from the heat map and used for the simulations.

Figure 5.3: Local incidence angle example for region of interest
the estimations the models were limited to a maximum incidence angle of 30 degrees. Figure 5.2 shows a map of local incidence angles for one of the targeted regions and as observed from the histogram, a limit of 30 degrees is a reasonable approximaiton that includes most of the targets.

### 5.3 Geometric Distortion Simulations

Radar imagery is subject to distortions due to the data collection geometry and the way a radar measures range. These common effects are layover, foreshortening and shadow, all are dependent on the viewing geometry and topography being imaged. Figure 5.4 shows a summary of the mentioned distortions.

The effects of radar shadow occur when the terrain slopes away from the radar at an angle greater than the radar look angle and the effect is the same as with sunlight. The radar beam cannot reach the region underneath and will appear as dark in the image containing no information.

When the terrain slopes towards the radar, the ground range distance will appear compressed in the slant range domain, this is called foreshortening and it is agravated in the near range of the swath. Layover occurs when targets slope towards the radar, and the top feature at a further ground range is reached before the bottom which is at a near ground range. Foreshortening and layover can usually be seen as bright bands on the face and top parts of the mountains where the signal returns get accumulated.

Most radar altimeters point directly at nadir, or near-nadir, employing very fine beamwidths because it provides a more reliable height estimation. These systems have virtually no shadow and the fine beam reduces the possibilities of layover. Conversely, for these reasons, SAR systems avoid nadir geometries and use wider beams to image a larger swath. However, SWOT is a combination of the two, a near-nadir altimeter with a fairly wide swath. Such an uncommon geometry will impose severe foreshortening and layover, the latter being the most concerning because the mixture


Figure 5.4: Radar geometric distortions
of land and water returns will make less obvious the boundary of the water body and will lead to height errors.

In order to disregard shadowed regions from scientific study, shadow masks can be generated from data ahead of time provided that orbital information and topography (DEM) are known. Similarly, layover effects can be predicted and used to help locate and mitigate potential height errors. The algorithms used for shadow and layover detection are based on those found in [7] and the processing is done in iso-azimuth lines. In a flat terrain the look angle should always increase with the cross-track distance, the back slope of a mountain can keep it constant or make it decrease and that will generate radar shadow. Since SWOT's geometry will not have much shadowing, for simplicity, only the active shadow is flagged using the operator

$$
\begin{equation*}
S=\left(h_{s}-h_{t}(c)\right)+c \frac{\partial h_{t}(c)}{\partial c} \tag{5.9}
\end{equation*}
$$

where $h_{s}$ is the satellite orbit height, $c$ is the cross-track distance from the satellite nadir track to the target and $h_{t}(c)$ is the target height. When $S<0$ that pixel is flagged as shadow creating a mask. The partial derivative necessary in (5.9) is estimated from the DEM by taking the gradient weighted by the cross-track spacing. Assuming the worst case scenario for the area of study, which is the minimum slope at the farthest range, the condition for active shadow is almost never met. This is due to the terrain slopes not being steep enough to create shadow with such an orbit height and near-nadir swath. In a similar manner, layover is split into two: active and passive. Active layover are the targets that are laying over into the target pixels, whereas passive layover is used to label those regions that are causing the layover. As before, a threshold is used

$$
\begin{equation*}
L=c-\left(h_{s}-h_{t}(c)\right) \frac{\partial h_{t}(c)}{\partial c} \tag{5.10}
\end{equation*}
$$

where active layover is flagged when $L$ is negative. Due to the importance of this effect in SWOT, though it is more complex to determine, passive layover is also flagged. The algorithm used does not directly account for the interactions between several layover regions.

Typically, active layover is not a single pixel and comes as bursts, as can be observed in Figure 5.5a. To do this we label one burst of active layover pixels as $B C$, to be the region between points $B$ and $C$. In order to find the limits of the passive region, the minimum slant range within the active region is needed, which corresponds to the last pixel $C$, marked as an asterisk in Figure 5.5a. Thus, the algorithm performs a forward search of changes in $\operatorname{sign}(L)$ to map the active regions, the last pixel is the index previous to positive change in $\operatorname{sign}(L)$. Knowing the minium slant range in the active region, $C$, the algorithm runs a backwards search to find the nearest previous cross-track distance with the same slant range, namely $A$ in Figure 5.5b. The limits of the backwards search are set by the current and previous active


Figure 5.5: Implementation detail of passive layover search algorithm. a) The sign function of $L$, where the dots mark the index of the last pixel in active layover for each region. b) The region between each pair of dots AC has layover, both passive and active.
layover regions. Finally, the passive layover is the intersection of $A C \cap B C$ while the total area in layover is $A C \cup B C$.

The results obtained via this algorithm are shown in Figure 5.6. Two regions have been selected to analyze the layover simulations, the Connecticut river and Quabbin reservoir. It is noticeable that the parts where the river flows in the along-track direction are more affected by layover due to the side-looking geometry compared to the section of river that flows in the cross-track direction. Another noticeable feature is the layover extend of the islets in the Quabbin, result of height differences between water and the islets' maximum elevation, as high as 100 meters. A water mask is applied to remove land pixels and the percentage of water in layover is determined to be $49 \%$ and $36 \%$ for the Connecticut river and Quabbin reservoir respectively.

The main concern about layover in SWOT is that other land targets with diffferent power added to the water returns will shift the electric field phasor received by the satellite, and hence bias the interferometric phase and ultimately the target height.


Figure 5.6: Layover simulations results, descending pass 551 and radar looking from left to right.

Additionally to flagging layover areas, assessing the height error due to layover provides further insigth as to how impactful this effect will be. Although there are several ways to proceed, here it has been simulated from the DEM heights without generating a full interferogram. Starting from any water target that is free of layover, the electric field can be written as

$$
\begin{equation*}
E_{i}=\sigma_{i} e^{j k h_{i}} \tag{5.11}
\end{equation*}
$$

where $\sigma_{i}$ is the NRCS of the water point $i$ and $h_{i}$ is the corresponding DEM height. Similarly, for the same target with layover

$$
\begin{equation*}
E_{l}=\sigma_{i} e^{j k h_{i}}+\sum_{n \epsilon N} \sigma_{n} e^{j k h_{n}} \tag{5.12}
\end{equation*}
$$

where $N$ are all the land targets within the same slant range. The ratio is then

$$
\begin{equation*}
E_{d}=\frac{E_{l}}{E_{i}}=1+\frac{\sum_{n \epsilon N} \sigma_{n} e^{j k h_{n}}}{\sigma_{i} e^{j k h_{i}}} \tag{5.13}
\end{equation*}
$$

where the phase shift is $\angle E_{d}=\phi_{d}$. If we assume that the target heights measured from $E_{i}$ and $E_{l}$ are $H_{i}$ and $H_{l}$ respectively, one can define the error height by taking the difference between the non-biased and the observed heights as

$$
\begin{equation*}
\Delta h=H_{l}-H_{i} \tag{5.14}
\end{equation*}
$$

then recalling the target height from the interferometric phase determined by (2.46) and replacing for $H_{l}$ and $H_{i}$ yields

$$
\begin{equation*}
\Delta h=h-\rho \cos \left(\arcsin \left(\frac{-\lambda \phi_{l}}{2 \pi B}\right)\right)-h+\rho \cos \left(\arcsin \left(\frac{-\lambda \phi_{i}}{2 \pi B}\right)\right) . \tag{5.15}
\end{equation*}
$$



Figure 5.7: Height error on water caused by layover. A water mask is applied and white areas contain land targets.

By defining $\phi_{l}=\phi_{i}+\phi_{d}$ and since only the difference is of interest, one can also assume $\phi_{i}=0$, then the height error is given by

$$
\begin{equation*}
\Delta h=\rho\left(1-\cos \left(\arcsin \left(\frac{-\lambda \phi_{d}}{2 \pi B}\right)\right)\right) . \tag{5.16}
\end{equation*}
$$

Figure 5.7 shows a map of height errors on water targets that go as high as 7 cm of bias. It is observable the similarity of the extend of the error regions with the extend of the layover. Notice the regions right at the water to land transition are less affected because the mountains and trees fall further to the left in the cross-track direction.

### 5.4 Received power estimation

The main part of the simulator is for estimating the reflectivity, which is done in a separate block from the previous processes in order to decouple the scene generation from the reflectivity estimation to provide more flexibility. Given the coordinates of the swath, antenna parameters and target classification the simulation proceeds to calculate which points on the ground are illuminated. From those, it calculates the distance and radar cross section, slices the distance into range bins and coherently adds the returns of those within the same range bin. The phase shift applied to each
target is the propagation term $\exp \left(-j k\left(R_{1 i}+R_{2 i}\right)\right)$ where $R_{1 i}$ is the distance from the transmit antenna to the target $i$, and $R_{2 i}$ is the distance from the receive antenna from to the same target. Together, these distanctes constitute the round trip distance and they are equivalent when receiving and transmitting from the same antenna. Since the radar receiver measures the elapsed time to travel and assigns ranges by halving the round trip, the same operation is applied here to calculate the range $r_{i}=\frac{R_{1 i}+R_{2 i}}{2}$ to find its closest range bin, $r_{b}$. Note that $r_{b}$ is a discrete value with increments of $\delta_{r}$. Each radar cross section is weighted by the two-way path loss, considered in free space here. Finally, making use of the radar equation the accumulated complex voltage in one pixel yields the received voltage as

$$
\begin{equation*}
V\left[r_{b}\right]=\sum_{i \in R_{n}} \frac{\lambda^{2} \sigma_{i}(\theta) e^{-j k\left(R_{1 i}+R_{2 i}\right)}}{(4 \pi)^{3}\left(R_{1 i}+R_{2 i}\right)^{2}} \tag{5.17}
\end{equation*}
$$

where $R_{n}$ is the set of targets $i$ whose range $r_{i} \epsilon\left[r_{b}-\frac{\delta_{r}}{2}, r_{b}+\frac{\delta_{r}}{2}\right)$. This process is repeated for all $r_{b}$ to generate one azimuth line. To generate an image, the antenna position and illuminated scene are updated for each azimuth line. Different final products can be simulated, like pulse-to-pulse raw data by selecting the full PRF of SWOT ( 4420 Hz ), and an along-track footprint length of about 3 km calculated from the azimuth beamwidth and a range resolution of 0.75 meters.

The simulation of raw data using this approach is very time consuming and only one example of a small region was simulated. The generation of single look complex (SLC) images at nominal azimuth resolution is the product of interest, the computation times can become very long too and as a workaround lowering the PRF helps to save some computational resources. After the image is produced, the program adds thermal noise and various system parameters such as antenna and receiver gains. Although the absolute power is not so relevant for interferometry, it could be useful for wind speed estimations, and in including the system gains it intends to provide a more realistic procedure.

Initial results using this approach are shown in Figure 5.8 in radar coordinates, azimuth distance and slant range. The lack of focusing is present and to be expected in the raw data. The SLC level data was multi-looked by a factor of four in the along-track dimension showing better azimuth resolution and some layover features on the top of the mountains. Subsequently, the processing is repeated for the other antenna giving the simulation the capability to interefetre the two images. As a result, Figure 5.9 depicts an interferogram obtained from two simulated SLC images, along with the coherence magnitude. From the image itself can be observed that water has higher coherence compared to the backsides of the mountains where noise degrades the correlation.

To summarize, a simulation tool able to generate KaRIn pulse-to-pulse data has been presented in this chapter. The modeling approach for the targets at Ka-band, in conjunction with the simulation scheme, appear to work correctly according to the simulated imagery. Lastly, the impact of tree layover on the interferometric data has been estimated from the DEM and it has been converted into error height.

The next chapter presents a dual-frequency system, comprised by an S- and Kaband inferterometers. Although the KaRIn and dual-frequency system have different observing geometries, the concepts discussed in this chapter are relevant and applicable to the next one.

(a) Raw data simulated at full PRF limiting illumination to 3 dB beamwidth. The image is range compressed and the range is normalized to the first range bin.

(b) SLC level data simulated at lower PRF with smaller aperture. Notice the aspect ratio is changed to emulate a ground projected image.

Figure 5.8: Left swath reflectivity images simulated for pass 551 in the Western Massachusetts area. The bright areas on the right half of the image correspond to the Quabbin reservoir.


Figure 5.9: Interferogram and coherence magnitude from simulated data after adding noise to fill gaps on the sides of the image.

## CHAPTER 6

## DUAL-FREQUENCY INTERFEROMETER

A final step, after having simulated interferometry and measured backscattering, is to actually perform InSAR measurements. This chapter gives a brief overview of a dual-frequency airborne interferometer operating at Ka- and S-bands, first assembled in [2]. The main advantage of having such as system is that it provides two different, yet comparable, datasets since the data is collected simultaneously and that eliminates any temporal decorrelation. The following sections present the results using an upgraded navigation system and describe some hardware modifications and subsequent processor updates. Finally, this chapter shows the interferograms used to calculate differential heights. Given the difference in wavelenght between these two frquency bands, these differential heights, can be used to infer tree height.

### 6.1 System overview

The dual-frequency system is comprised by two radars operating at 3.2 GHz and 35 GHz respectively, each one having a transmit antenna and a set of two receive antennas. The systems have dual-polarization capability, though they are not fully polarized, the polarizations can be changed manually. In this configuration, the antennas are attached to the airplane side cargo door forming a cross-track interferometer as shown in Figure 6.1. The Ka-band antenna has a significant smaller azimuth beamwidth compared to the S-band system, giving a small synthetic aperture that can provide decent images when processing only real apeture data. To obtain data sets readily comparable both radars use similar waveform characteristics


Figure 6.1: Dual-frequency system mounted on airplane cargo door. Slotted waveguide antennas correspond to the Ka-band radar whereas patch arrays are the S-band antennas.
and employ 100 MHz of bandwidth, more system parameters are shown in Table 6.1. Both transceivers have dual-stage up- and down-conversions to provide more robust rejection of frequency images and to perform the FMCW mixing operation in hardware.

The flight system involves a new IMU and GPS unit, the same used in the KaScat, a dedicated software defined radio board (Ettus N210) for sampling and digitization and a laptop for each radar. The two radars share a common waveform generator with separate channels that sends the chirp to the transceivers and triggers the digitizers for every pulse. In order to mantain timing a precise 10 MHz clock reference is distributed to radars and Ettus boards, this will phase-lock the FPGA clocks and radars local oscillators. This is an improvement over previous configurations that used one GPS per laptop and where the digitizers had different base times, such

| Parameter | Ka-band | S-band |
| :---: | :---: | :---: |
| Center Frequency | 34.95 GHz | 3.2 GHz |
| System Bandwidth | 100 MHz | 100 MHz |
| Transmitted Power | 1 mW | 40 mW |
| PRF | 999 Hz | 999 Hz |
| Pulse length | 1 ms | 1 ms |
| Az. beamwidth | $1^{\circ}$ | $12^{\circ}$ |
| Baseline | 0.1 m | 0.7 m |

Table 6.1: Main parameters of the dual-frequency interferometer.
configuration resulted in significant timing errors between navigation and radar data or radars themselves. The software defined radio was modified to synchronize its time using an external GPS-18X when the serial data and one pulse per second signal are present. The Ettus synchronizes its time parsing the NMEA message from the GPS serial port, which has a UTC timestamp, and relies on the 10 MHz reference to lock onto and avoid drifts. Notice that only on power up the Ettus time reference is updated, not while in operation via the 1 PPS. The serial data from the GPS-18X and 1PPS cables are split to feed both Ettus boards providing a common time reference between radars and solving the timing offsets relative to the navigation datasets. Additionally, the navigation data logging is done in a separate computer similar to Figure 3.3. For more clarity, a diagram depicting all instrument connections is shown in Figure 6.2. Finally, the received signal is downconverted to base-band and is sent to the Ettus board which is in turn recorded by the laptops via ethernet connection.


Figure 6.2: Dual-frequency system block diagram.

### 6.2 Processor description

As mentioned before the SAR processor uses time-domain backprojection to handle the non-linear flight path as well as the continous changing attitude of the airplane. The Python-based software, extensively described in [9], is accelerated through the use of GPUs and its architecture is divided into preprocessing and azimuth compression modules. The first step is to process GPS and IMU data, and store it into two separate files that contain: unix time stamp, yaw, pitch and roll; with the other file holding unix time stamp, latitude, longitude and altitude.

These two files are fed to the preprocessor that also reads the raw radar data selected by the user. The navigation data is clipped to include only the relevant points from the radar data files and a reference track at altitude $h_{t r}$ is generated from the GPS points in SCH coordinates (S- Along-track, C- Cross-track, H- Height) [13] using a best fit. In short, SCH is a coordinate system aligned with the platform motion used in SAR processing that accounts for the Earth's curvature while keeping the simplicity of spherical coordinates. The system is fully described by defining a
peg point and sphere radius $r_{a}$. Furthermore, the preprocessor performs the necessary frame rotations and lever arm translations to locate the antennas in a right sidelooking geometry while keeping the proper baseline. Finally, the antenna coordinates and overall rotations are stored into radar state files.

The next step is the azimuth compression. The user can adjust basic parameters like aperture length, spacing or which region to process and set a DEM for processing. The module generates a target grid in $S$ and slant range (SR) coordinates with the required spacing and then proceeds to find the limits of each pulse as a function of the grid indexes. After each pixel is assigned a set of pulses, the processor splits the total grid into patches that are separately processed on GPU cores. The operations done on GPU cores are basic and consist of the phase correction, coherent accumulation as well as the calculation of the look vector and gain. The azimuth module offers as output products the SLC file, look angle, gain and target heights used during the focusing. This procedure is then repeated for another recevier channel in order to generate the two SLC images that will produce an interferogram.

Further steps are taken to generate a multi-looked image with square pixels and the coherence (magnitude and phase) between the SLC's. From the look angle, the incidence angle is calculated via the normal vector referenced to the peg point and is used to calculate the differential heights, as in (2.50).

From this point on, all products can be geolocated for further studies. Since the processor output grid is in radar coordinates SR , a few steps are required to map those into a geographic coordinate system (LLA). Firstly, the output grid is converted from SR to SCH , where H are the heights used for processing and C is given by

$$
\begin{equation*}
C=-r_{a} \arccos \left(\frac{r^{2}-\left(r_{a}+h_{t r}\right)^{2}-\left(r_{a}+h\right)^{2}}{-2\left(r_{a}+h_{t r}\right)\left(r_{a}+h\right)}\right) \tag{6.1}
\end{equation*}
$$

where $h$ is the target height and $r$ the radar range. Notice that here the DEM heights are specified as height above the ellipsoid (not orthometric heights) to mantain the
consistency with the GPS definition of altitude as well as the coordinate system conversions among ECEF, LLA and SCH. The DEM's used throughout this work are from the Shuttle Radar Topography Mission (SRTM) that provide orthometric heights but a conversion back to ellipsoid heights can be done by subtracting the geoid height. These orthometric heights are what is needed before they could be used in the processing. Once the output grid is in SCH coordinates, it is converted to ECEF and ultimately to LLA and mapped on to Google Earth.

### 6.3 InSAR Results

In this section the data collected for both radars are presented, Figures 6.3a and 6.4a show the reflectivity images obtained through SAR processing. The time-domain algorithm is very sensitive to position or attitude errors which combined with a short wavelength makes the need for precision to be very high. As a result, the Ka-band image has some lateral dark bands, a sign of poor focusing due to rapid motion changed compared to the S-band where these bands are almost non existent. Misalignments between the antenna frame and IMU frame will also lead to defocusing, since this is difficult to measure accurately and the system is very sensitive to small attitude offsets. Instead, an iterative search over angles is used to determine offsets in antenna positions, with the best results chosen by visual inspection. The main noticeable difference in reflectivity between the systems is the higher contrast between different fields of the S-band image where the Ka-band shows a more uniform return.

Furthermore, the coherence and interferometric phase are estimated for the two channels, an overlay image of magnitude and phase is shown in Figures 6.3b and 6.4b. A darker color tone means lower correlation between channels whereas brigther white areas are highly correlated. The differential phase changes follow the ground features throughout the image which is an indication of good operation as it is sensitive to ground variations. In addition, sometimes an overall pattern of phase increasing with
cross-track distance can be found in interferograms, often due to antenna multipath, which needs to be corrected by means of phase screening before proceeding to scatterer height estimation.

There are several ways to remove a phase screen from the interferogram, such as calculating the coherence-weighted mean along azimuth lines and subtracting that phase from the interferogram or performing fit operations. Here, the latter option is chosen and the phase screen is estimated in a two-step process using a 2 D polynomial fit. The first step has a low order polynomial in azimuth and higher in range to estimate the range-dependent phase slope. On that first iteration data points below a predefined coherence threshold are excluded to remove noisy regions or water. Subsequently, a second fit operation is performed on the screened phase with higher order polynomial on both directions. This second step is meant to flatten the more subtle areas that were masked by larger variations on the inital fit, specially in the near range. On the last step, the points are limited by the standard deviation in order to include the topography variations. An example of this process is shown in Figure 6.5 where the initial, phase screen and final interferogram are shown. Having removed the phase biases, they are now ready to estimate the differential heights.


Figure 6.3: S-band SAR images.


Figure 6.4: Ka-band SAR images.


Figure 6.5: Phase screen removal process for S-band interferogram: a) S-band inteferogram with range dependent phase ramp, b) Phase screen obtained via polynomial fits, c) Interferogram with phase screen removed. Notice that the random phase of water returns over the right part of the image is not taken into consideration on the screen phase and that the screened interferogram mantains the topographic variations.

### 6.3.1 Forest height estimation

One of the main advantages of using a dual-frequency system is different pentration depth. The short wavelength of the Ka-band radar will not penetrate volume scatterers such as trees, therefore it is assumed it will only measure up to the top part of the canopy. Conversely, the S-band with longer wavelength, though it may not reach the ground, will penetrate some depth through tree top branches. Recalling that the differential height from backprojection interferometry provides a target height relative to the DEM, it can be assumed the Ka-band targets in forested areas will measure a positive height corresponding the top part of the vegetation and the S-band mid or lower regions, whose height difference will be used as a proxy to estimate forest heights, even if it is necessary to correct by multiplying the net result by some factor.

Focusing this study on vegetated areas, Figure 6.6 depicts the differencial height difference between Ka- and S-band radars. The histogram show an average of 2.83 meters difference which can be assumed as the mean tree height of the zone. Despite the horizontal bands, the forested areas surrounding fields tend to haver a more yellow-orange color showing a positive height difference as expected.

To finalize, the differential heights are added to the processing DEM and the image is geolocated on Google Earth for visualization purposes, Figure 6.7 shows the an example of a final product for the S-band interferometer.


Figure 6.6: Results of height difference between frequencies for processed image. Histograms are calculated from the highlighted area.


Figure 6.7: Example of geolocated product, S-band final DEM, displayed on Google Earth.

## CHAPTER 7

## CONCLUSIONS

The majority of this thesis has involved the measurements of river and ocean backscattering and data simulations at Ka-band for SWOT, as well as flight deployments. For the last part, it has included refining the dual-frequency interferometer and InSAR processing to ultimately estimate differential heights with the main goal of measuring forest heights.

This work has shown the process of implementing a motion control system for a radar antenna both physically and at a software level. The data processor has been re-written from scratch to adopt the new radar data format, different IMU convention and attitude calculations from actuator logs. The Ka-band scatterometer has proven to benefit from such a system providing very accurate data sets which produced backscattering heatmaps with lower standard deviation in the near-nadir range. The first oceanic flight of KaScat has been carried out and it has provided high fidelity results that accurately match backscattering models adjusted for wind speed found in the literature. Additionally, further data processing done at the Jet Propulsion Laboratory (JPL) has demonstrated the oceanic data fits backscatter spectrum models obtained from the Global Precipitation Measurement (GPM) mission. Such results validate the correct operation of the KaScat and enable its use for further research.

Another major part of this thesis has been the simulation of an observing model for SWOT based primarily on public resources such as orbit data, land cover classification, DEM's and instrument parameters. The pulse-by-pulse simulator in conjunction
with backscattering models determined from KaScat could potentially be used to test on-board algorithms and evaluate river stage.

The dual-frequency system has been updated to have improved timing consistency between IMU, GPS and radar data. The new IMU has been installed to the flight system and done its first flights. The existing time-domain SAR processor has been revisited in this work and minor modifications to accomodate the new IMU data and frame have been made. Additionally, geolocation of the processor products has been added as well as a height correction for the processing DEM's to convert orthometric heights into heights above the WGS84 ellipsoid. Lastly, a best-fit routine to remove phase ramps off the interferograms has been added, generating differential heights less biased in the near range.

### 7.1 Future work

While the motion compensation software has proved to be robust and reliable throughout several deployments, the accuracy relies on the correct modeling of the linkage system. Mounting another IMU on top of the GOA antenna would have a twofold impact: it would provide a direct attitude measurement of the antenna and an extra data set to compare with the data obtained through the linkage. That in turn, could help to identify offset errors and if present, modifiy the linkage accordingly. A useful feature to make the sysem more user-friendly would be to implement a real-time display of the antennas attitude, that would help to quickly verify the correct range of operation in-flight. Modifications to fit the actual system through the airplane hole forced the use of a different transmit antenna which resulted in a degraded cross-pol isolation. Upgrading the antenna with a better polarization isolation would enable measurements of surface decorrelation, currently needed at JPL to design models for SWOT and develop processing algorithms. The next step would be to repeatedly
collect data several times during the day to study what differences can be found, and at a larger scale, the effects of seasonality.

Regarding the dual-frequency interferometer, a critical point has been the precise knowledge of the angular offsets between the IMU and antenna frames. Efforts to precisely characterize and make them repeatable will facilitate the data processing and improve their results. The next natural step is to corregister the images, that would allow for multi-pass measurements enabling Differential Interferometric SAR (DInSAR) techniques that could be used towards the measurement of terrain deformation or snow depth.

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[^0]:    ${ }^{1}$ Rain data archive accessible at www.ncdc.noaa.gov/ for 24-29 October 2017

[^1]:    ${ }^{1}$ USGS NED https://nationalmap.gov/elevation.html
    ${ }^{2}$ NBCD 2000 BAW height, https://daac.ornl.gov

[^2]:    ${ }^{3}$ NLCD 2011 from https://coast.noaa.gov/dataviewer/

