RapidScat Backscatter Measurements Calibration

Ruaa Alsabah

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RapidScat Backscatter Measurements Calibration

by

Ruaa Alsabah

A dissertation submitted to the College of Engineering and Science at Florida Institute of Technology in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Electrical Engineering

Melbourne, Florida
May, 2019
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Abstract

Title: RapidScat Backscatter Measurements Calibration

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Scatterometers are microwave radars deployed to estimate global wind speeds and directions over sea surface by measuring Normalized Radar Cross Section ($\sigma^0$) of the sea. Measured is determined by the sea surface roughness that is modulated mostly by wind, thus establishing a relationship between wind conditions. Wind vectors are retrieved by inverting an empirical Geophysical Model Function that relates measured to a wind vector (speed and direction) and radar measurement configuration (polarization, incidence, and azimuth angle). Careful scatterometer calibration is required for accurate wind retrieval. RapidScat is a National Aeronautics and Space Administration (NASA) Ku-Band scatterometer that was operated onboard the International Space Station (ISS) between September 2014 and August 2016 when the mission effectively ended after an irrecoverable instrument failure. A unique non-Sun-synchronous orbit facilitated global contiguous geographical sampling between the ±56° latitude. For the first time, such an orbit
enabled an overlap with other scatterometers flying in Sun-synchronous orbits. To assure measurement accuracy, careful scatterometer calibration and validation is required. Cross-calibration among overlapping instruments is a common calibration method. This Dissertation explores the implementation of a cross calibration method between the RapidScat and QuikScat scatterometers taking advantage of their overlapping orbits. QuikScat is RapidScat’s parent instrument whose spare parts were used to build the RapidScat. The biases of the two instruments have been calculated from observations collected during a 20-month period between Jan. 2015 and August 2016. Deviations from the common reference model are computed for both datasets, as a function of wind speed, relative wind direction, and incidence angles averaged for both polarizations over 1000 pairs of collocated QuikScat/RapidScat revolutions. For more accurate alternative to the classic single difference approach, the double-difference technique was deployed to compare measurements from these two scatterometers. This Dissertation presents the first extension of the double difference methodology to scatterometry. The methodology has been adopted for the cross-instrument calibration between RapidScat and QuikScat scatterometers simultaneously orbiting the Earth on-board two independent satellite platforms. The initial results of the statistical analysis and biases between the two scatterometers are presented. Calculated biases may be used for measurement correction and reprocessing.
# Table of Contents

Abstract .......................................................................................................................... iii

Table of Contents .......................................................................................................... v

List of Figures ................................................................................................................ vii

List of Tables .................................................................................................................. xii

Acknowledgement ......................................................................................................... xiii

Dedication ...................................................................................................................... xiv

List of Acronyms/ Abbreviations .................................................................................. xv

Chapter 1 Introduction .................................................................................................. 1
  1.1 Principles of Remote Sensing ............................................................................... 1
  1.2 Approach .............................................................................................................. 3
  1.3 Dissertation Objective and Overview ................................................................. 7

Chapter 2 Fundamental Concepts of Scatterometers ................................................. 9
  2.1 Introduction .......................................................................................................... 9
  2.2 Radar Cross Section .......................................................................................... 13
  2.3 QuikScat ............................................................................................................ 16
  2.4 RapidScat ........................................................................................................... 20
  2.3 Current and Planned Missions ............................................................................ 27

Chapter 3 Calibration of RapidScat Scatterometer .................................................. 29
  3.1 Introduction ........................................................................................................ 29
  3.2 Calibration Methodology .................................................................................. 30
  3.3 Data Sets and Match-ups .................................................................................. 32
    3.3.1 RapidScat Data Set ..................................................................................... 33
    3.3.2 QuikScat Data Set ..................................................................................... 39
    3.3.3 GDAS data .................................................................................................. 41
  3.4 GMF .................................................................................................................... 43
  3.5 Collocation Algorithm ....................................................................................... 50
  3.6 Double Differences ............................................................................................ 53

Chapter 4 Backscatter Measurement Validation ...................................................... 57
  4.1 Introduction ........................................................................................................ 57
  4.2 Evaluation versus wind speed ........................................................................... 58
  4.3 Evaluation versus Relative Wind Direction ....................................................... 68
  4.4 Evaluation versus Incidence Angle .................................................................. 73
  4.5 Evaluation versus latitude ................................................................................ 77
List of Figures

Figure 1.1: The major classes of microwave remote sensing. .................................3
Figure 2.1: Block diagram of a spaceborne radar system. ..................................10
Figure 2.2: The transmitted EM pulse and the return echo. ...............................10
Figure 2.3: Examples of surface scattering patterns. ............................................12
Figure 2.4: QuikScat Satellite. ...........................................................................16
Figure 2.5: The orbital planes as a sun-synchronous orbit. .................................18
Figure 2.6: The SeaWinds measurement geometry. ...........................................19
Figure 2.7: RapidScat’s location on ISS and its components. .............................21
Figure 2.8: A block diagram of the ISS RapidScat showing newly designed and legacy subsystems. .................................................................23
Figure 2.9: RapidScat pencil beam geometry. .......................................................24
Figure 2.10: Satellite scatterometers past and future missions. ............................28
Figure 3.1: Flow diagram of RapidScat calibration. ............................................32
Figure 3.2: SNR states of RapidScat. ..................................................................34
Figure 3.3: RapidScat’s Sigma-0 resolution elements (eggs and slices). ..............35
Figure 3.4: Wind speed distribution map. .........................................................42
Figure 3.5: The relative wind direction. .............................................................46
Figure 3.6: Corresponding readings to NSCAT-2014 GMF. ...............................47
Figure 3.7: Example of the $\sigma^0$ modeling (VV-HH) polarization via Geophysical Model Function (GMF). .................................................................49
Figure 3.8: An example of $\sigma^0$ GMF modelling of the relative wind direction at horizontal polarization, wind speed of 16 m/s and 20 m/s.

Figure 3.9: Global and focused view of the RapidScat/QuikScat collocations.

Figure 3.10: Collocation sample of Footprints between RapidScat and QuikScat.

Figure 3.11: Block diagram of RapidScat/QuikScat double-difference calibration.

Figure 4.1a: $\sigma_0$ bias as a function of wind speed, January 2016.

Figure 4.1b: $\sigma^0$ mean/std for RS as a function of wind speed, January 2016.

Figure 4.1c: $\sigma^0$ mean/std for QS as a function of wind speed, January 2016.

Figure 4.2a: $\sigma_0$ bias as a function of wind speed, May 2016.

Figure 4.2b: $\sigma^0$ mean/std for RS as a function of wind speed, May 2016.

Figure 4.2c: $\sigma^0$ mean/std for QS as a function of wind speed, May 2016.

Figure 4.3a $\sigma_0$ bias as a function of wind speed, January 2015.

Figure 4.3b $\sigma_0$ bias as a function of wind speed, January 2016.

Figure 4.4a RapidScat Single Difference as a function of wind speed outer (VV) and inner beam (HH), April 2015.

Figure 4.4b RapidScat Single Difference as a function of wind speed outer (VV) and inner beam (HH), November 2015.

Figure 4.4c: RapidScat Single Difference as a function of wind speed outer (VV) and inner beam (HH), February 2016.

Figure 4.5a RapidScat Single Difference distributions as a function of wind speed outer (VV), April 2015.

Figure 4.5b RapidScat Single Difference distributions as a function of wind speed inner beam (HH), April 2015.
Figure 4.6a RapidScat Single Difference distributions as a function of wind speed outer (VV), November 2015.................................................................66

Figure 4.6b RapidScat Single Difference distributions as a function of wind speed inner beam (HH), November 2015.................................................................66

Figure 4.7a RapidScat Single Difference distributions as a function of wind speed outer (VV), February 2016. .................................................................67

Figure 4.7b RapidScat Single Difference distributions as a function of wind speed inner beam (HH), February 2016.................................................................67

Figure 4.8a: σ₀ bias as a function of wind direction outer beam (VV), July 2015.........................................................................................................................69

Figure 4.8b: σ₀ bias as a function of wind direction outer beam (VV), March 2016.........................................................................................................................69

Figure 4.9a: σ₀ bias as a function of wind direction, July 2015........................70

Figure 4.9b: σ₀ bias as a function of wind direction, March 2016. ..........70

Figure 4.10a RapidScat σ₀ bias as a function of wind direction outer (VV) and inner beam (HH), April, 2015.................................................................71

Figure 4.10b: RapidScat σ₀ bias as a function of wind direction outer (VV) and inner beam (HH), April, 2015.................................................................71

Figure 4.10c: RapidScat σ₀ bias as a function of wind direction outer (VV) and inner beam (HH), January, 2016.................................................................72

Figure 4.11a: σ₀ bias as a function of incidence angle Inner-HH, April 2015..74

Figure 4.11b: σ₀ bias as a function of incidence angle Outer-VV, April 2015. 74

Figure 4.12a: σ₀ bias as a function of incidence angle Inner-HH, February 2016.........................................................................................................................75

Figure 4.12b: σ₀ bias as a function of incidence angle Outer-VV February 2016.........................................................................................................................75

Figure 4.13a: σ₀ bias as a function of incidence angle, April 2015..........76
Figure 4.13b: $\sigma^0$ bias as a function of incidence angle, February 2016. ..........76

Figure 4.14: $\sigma^0$ bias as a function of latitude inner (HH) and outer (VV), July 2016.........................................................................................................................77

Figure 5.1: Comparison of global monthly average RapidScat measurements and model $\sigma^0$ ..................................................................................................................80

Figure 5.2: Monthly average RapidScat/QuikScat single-difference and double-difference.................................................................................................................................82

Figure 5.3a: Selected monthly double differences (DD) distributions, March-2015.................................................................................................................................84

Figure 5.3b: Selected monthly double differences (DD) distributions, April-2015.84

Figure 5.3c: Selected monthly double differences (DD) distributions, October -2015.................................................................................................................................85

Figure 5.3d Selected monthly double differences (DD) distributions, February-2016.................................................................................................................................91

Figure 5.4a: Comparison of the double and single $\sigma^0$ differences as a function of incidence angle, March 2015.........................................................................................89

Figure 5.4b: Comparison of the double and single $\sigma^0$ differences as a function of incidence angle, July 2015.................................................................................................89

Figure 5.5a: Comparison of the double and single $\sigma^0$ differences as a function of relative wind direction Outer- VV, March 2015.........................................................90

Figure 5.5b: Comparison of the double and single $\sigma^0$ differences as a function of relative wind direction Inner-HH, March 2015..................................................................90

Figure 5.6a: Comparison of the double and single $\sigma^0$ differences as a function of latitude Outer- VV, June 2015...............................................................................................91

Figure 5.6b: Comparison of the double and single $\sigma^0$ differences as a function of latitude Inner-HH, June 2015...............................................................................................91
Figure 5.7a: Comparison of the double and single $\sigma^0$ differences as a function of wind speed Outer- VV, June 2015.................................................................92

Figure 5.7b: Comparison of the double and single $\sigma^0$ differences as a function of wind speed Inner-HH, June 2015.................................................................92

Figure (5.8) Comparison of double and single $\sigma^0$ differences per some geographical bin.................................................................94

Figure 5.9: Average $\sigma^0$ bias at different resolutions.................................................96

Figure 5.10: Standard deviation of $\sigma^0$ bias at different resolutions.................96

Figure 5.11: Double difference at multiple grid resolutions. .....................97

Figure 5.12a: Impact of grid resolution on $\sigma^0$ bias as a function of relative wind direction, 1°x1° ........................................................................................................99

Figure 5.12b: Impact of grid resolution on $\sigma^0$ bias as a function of relative wind direction 0.125° x 0.125° ..............................................................99

Figure 5.13a: Impact of grid resolution on $\sigma^0$ bias as a function of wind speed 1°x1°........................................................................................................100

Figure 5.13b: Impact of grid resolution on $\sigma^0$ bias as a function of wind speed 0.125° x 0.125° ..................................................................................100
List of Tables

Table 1.1 RapidScat and QuikScat system comparison       Error! Bookmark not defined.

Table 2.1: Characteristics of space-borne wind scatterometers. .......................26

Table 3.1: Descriptions of Selected Parameters of L2A Data.  .........................37

Table 3.2: Descriptions of Selected Parameters of L1C Data.  .........................41

Table 4.1: Single Difference monthly history for 2015.  ................................78

Table 5.1: RapidScat single difference and double difference monthly history for horizontal (HH-pol) and vertical (VV-pol) for 2015.  .........................86

Table 5.2: Monthly standard deviations of double difference (dB). ...................86
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Dedication

To my father: I wish you were alive to see this moment, but I’m sure you felt the happiness in my heart when I achieved what you wished for me when you were alive.

To my mother: You are a spot of light in the darkness, and your prayers and your faith in me made my dreams come true.

To my husband: Being here make the PhD Journey more joyful, five years of adventure Stops here, I’m looking forward for Another Journey with you.

To my lovely Kids: You participated in my PhD degree from the first moment you were created in my womb, your laughter gave me the power to overcome the difficulties I had during my studies.

To my brothers and sisters and their families: You support, and encouragement make me always felt close and never allowed me to feel distant, even when I’ve been thousands of miles away.
## List of Acronyms/Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADEOS</td>
<td>Japanese Advanced Earth Observing Satellite</td>
</tr>
<tr>
<td>CDS</td>
<td>Command and Data Subsystem</td>
</tr>
<tr>
<td>CFRSL</td>
<td>Central Florida Remote Sensing Laboratory</td>
</tr>
<tr>
<td>CMA</td>
<td>China Meteorological Administration</td>
</tr>
<tr>
<td>DD</td>
<td>Double-Difference</td>
</tr>
<tr>
<td>DIB</td>
<td>Digital Interface Bridge</td>
</tr>
<tr>
<td>ECMWF</td>
<td>Medium-Range Weather Forecasts</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>GDAS</td>
<td>Global Data Assimilation System</td>
</tr>
<tr>
<td>GFS</td>
<td>Global Forecast System</td>
</tr>
<tr>
<td>GMF</td>
<td>Geophysical Model Function</td>
</tr>
<tr>
<td>HDF4</td>
<td>Hierarchical Data Format 4</td>
</tr>
<tr>
<td>HY-2B</td>
<td>Hai Yang 2B</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>KNMI</td>
<td>Dutch Koninklijk Nederlands Meteorologisch Institutuut</td>
</tr>
<tr>
<td>L1C</td>
<td>QuikScat Level 1C</td>
</tr>
<tr>
<td>L2A</td>
<td>RapidScat Level 2A</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
</tr>
<tr>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>NCEP</td>
<td>National Center for Environmental Prediction</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NRCS</td>
<td>Normalized Radar Cross Section</td>
</tr>
<tr>
<td>NWP</td>
<td>Numerical Weather Prediction</td>
</tr>
<tr>
<td>OVW</td>
<td>Ocean Vector Winds</td>
</tr>
<tr>
<td>PCU</td>
<td>Power Control Unit</td>
</tr>
<tr>
<td>QRad</td>
<td>QuikScat Radiometer</td>
</tr>
<tr>
<td>QS</td>
<td>QuikScat</td>
</tr>
<tr>
<td>QuikScat</td>
<td>Quick Scatterometer</td>
</tr>
<tr>
<td>RapidScat</td>
<td>Rapid Scatterometer</td>
</tr>
<tr>
<td>RS</td>
<td>RapidScat</td>
</tr>
<tr>
<td>RSS</td>
<td>Remote Sensing Systems</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
</tr>
<tr>
<td>SAS</td>
<td>Scatterometer Antenna Subsystem</td>
</tr>
<tr>
<td>SASS</td>
<td>SeaSat-A Scatterometer System</td>
</tr>
<tr>
<td>SD</td>
<td>Single Differences</td>
</tr>
<tr>
<td>SD_QS</td>
<td>Single Difference of QuikScat</td>
</tr>
<tr>
<td>SD_RS</td>
<td>Single difference of RapidScat</td>
</tr>
<tr>
<td>SES</td>
<td>Scatterometer Electronics Subsystem</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SSM/I</td>
<td>Special Sensor Microwave/Imager</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>SSMIS</td>
<td>Special Sensor Microwave Imager/Sounder</td>
</tr>
<tr>
<td>SSO</td>
<td>Sun-Synchronous Orbit</td>
</tr>
<tr>
<td>SST</td>
<td>Sea Surface Temperature</td>
</tr>
<tr>
<td>STD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>UTC</td>
<td>Universal Time Coordinated</td>
</tr>
<tr>
<td>WD</td>
<td>Wind Direction</td>
</tr>
<tr>
<td>WS</td>
<td>Wind Speed</td>
</tr>
<tr>
<td>WV</td>
<td>Wind Vector</td>
</tr>
<tr>
<td>WVC</td>
<td>Wind Vector Cell</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Principles of Remote Sensing

Earth remote sensing is broadly defined as the science of acquiring detecting geophysical information about the Earth's atmosphere and surface from objects and medium without being in physical contact with it. The main employment of the remote sensing is for observing the environmental parameters at great distance such as satellites, spacecraft or aircraft. For this reason, remote sensing usually makes use of electromagnetic (EM) radiation [1]. The electromagnetic radiation is reflected or emitted from the objects with a wide range of wavelengths such as radio frequencies or beyond visible light. The geophysical information of atmosphere, land, ice and ocean comes from these EM waves. By translating these signals, the science of remote sensing can involve many applications. The main types of the remote sensing are passive known as radiometers, and active known as radars or scatterometers [2].
The passive remote sensing deal with the thermal emission which is produced by the microwave signals comes from objects. On the other hand, the first of the active (radar) is divided into two general types: the first one is the real aperture which is divided into; scatterometers, altimeters, and weather radars.

The second synthetic aperture radar (SAR) systems, are radars designed to make high resolution radar images. They operate by transmitting modulated pulses and using Doppler/range processing to construct backscatter images. Typically, they are not as well calibrated as scatterometers. Scatterometers are designed to measure radar backscatter very precisely, but typically have lower resolution than SARs. They tend to be less complicated than SARs [3]. Altimeters are radars designed to measure the height or distance, though other information. Weather radars are specially designed scatterometers which have ranged capability [4, 5]. Both classes of sensors have been used in aircraft and spacecraft to study the Earth and the other planets. Figure 1.1 shows the major classes of microwave remote sensing [6, 7].

This dissertation deals with remote sensing from satellites using active microwave techniques. Calibration of a scatterometric instrument is important to detect the errors in the measured radar cross section; for this reason, it is necessary to inter-calibrate the scatterometric radar cross section to detect the instrumental biases. In order to assist in this process, the Geophysical Model Function GMF must be used to drive the modeled radar cross section of the scatterometers with different characteristics.
1.2 Approach

For several decades now, satellite observations have been a key part of global weather and climate research, including the monitoring of damaging and life-threatening storms. Considerable effort has been dedicated to ensuring the availability and reliability of satellite measurements from both active (scatterometer) and passive (radiometer) instruments. Demand for improved calibration accuracy has been steadily increasing. A common approach has been to combine data from multiple instruments [8, 9]. A typical scenario involves comparing measurements from a pair of instruments already individually calibrated before cross-calibration.
Wind scatterometers are radars designed to measure the normalized radar cross-section ($\sigma^0$) of the Earth’s surface. The primary applications for the $\sigma^0$ measurements are wind vector retrievals over the ocean, land usage, and ice monitoring. The wind vector retrieval process is based on the modulation of the sea surface roughness, quantified with $\sigma^0$, by the wind speed and direction. Dependence between the $\sigma^0$, wind speed, and wind direction relative to the scatterometer look-angle, frequency, and polarization has been defined in an empirically derived geophysical model function. To meet the strict requirements of the wind vector retrieval, scatterometers must provide accurate and stable $\sigma^0$ measurements over time [10].

National Aeronautics and Space Administration (NASA)’s RapidScat is a speedy recovery instrument for the QuikScat scatterometer that was built to monitor ocean winds as essential input into weather predictions including hurricane monitoring.

RapidScat has been flying onboard the International Space Station (ISS) in a non-Sun-synchronous orbit, leading to different local overpass times each day. Unlike previous scatterometers in Sun-synchronous orbits, this orbit gives RapidScat the unique capability to monitor diurnal and seasonal $\sigma^0$ signatures of global land and oceans. This provides an opportunity to directly cross-calibrate RapidScat and other overlapping instruments.
RapidScat operates in the Ku-band at a 13.4 GHz carrier frequency and was built from the spare hardware from the SeaWinds -on-QuikScat scatterometer. Aside from the orbit, these two twin scatterometers differ in the antenna platform, which was redesigned to be slightly narrower for use on the ISS. The nature of the ISS as a platform presents new challenges for accurate $\sigma^0$ measurements. Main challenges include altitude and attitude, with higher variability than previous platforms hosting wind scatterometers. Additionally, ISS hosts variety of instruments, unlike previous dedicated platforms that hosted scatterometers exclusively or paired with small number of co-hosted instruments with mostly stable altitude/attitude. Therefore, it is imperative to ensure accurate measurements via a variety of calibration and validation algorithms [11, 12]. Table 1.1 compares the basic RapidScat and QuikScat configurations.

Table 1.1 RapidScat and QuikScat system comparison.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Seawinds (QS)</th>
<th>RapidScat (RS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Ku-band)</td>
<td>13.6 GHz</td>
<td>13.6 GHz</td>
</tr>
<tr>
<td>Polarizations</td>
<td>VV-outer HH-inner</td>
<td>VV-outer HH-inner</td>
</tr>
<tr>
<td>Daily coverage</td>
<td>92%</td>
<td>65% between 58°N and 58°S</td>
</tr>
<tr>
<td>Orbit type</td>
<td>Sun-synchronous</td>
<td>Non sun-synchronous</td>
</tr>
<tr>
<td>Resolution ($\sigma^0$)</td>
<td>Egg: 25x36 km Slice: 6x25 km</td>
<td>Egg: 26x37 km Slice: 8x26 km</td>
</tr>
<tr>
<td>Swath (km)</td>
<td>1400, 1800</td>
<td>900, 1100</td>
</tr>
<tr>
<td>Incidence angles</td>
<td>46° &amp; 54.4°</td>
<td>49° &amp; 56°</td>
</tr>
<tr>
<td>Ascending equatorial crossing local time</td>
<td>6:00 AM</td>
<td>Various</td>
</tr>
<tr>
<td>Altitude (nominal)</td>
<td>800 km</td>
<td>375 – 435 km</td>
</tr>
<tr>
<td>Period</td>
<td>101 min</td>
<td>92.69 min</td>
</tr>
</tbody>
</table>
The main contribution of this research is to ensure the self-consistency and the reliability of the instrument by inter-calibrating the instrument using the deviation from a common reference model which is calculated for both instruments as a function of wind speed, wind direction, latitude and incidence angle. Better understanding of these parameters gives insight about the correlation between these parameters and allows new consideration to precisely assess tradeoffs between the instrument’s measurements and specific parameters. This knowledge will give a better feedback about the instrument measurements which can then be improved and corrected for the future design and modeling of new instruments.

Another contribution of this dissertation is to present the first attempt in scatterometer measurement validation using the double difference technique. This calibration technique was developed at the University of Central Florida Remote Sensing Laboratory (CFRSL) and has been successfully applied to several microwave radiometers in the past [13]. The cross-calibration double difference algorithm was adjusted to meet the requirements of the scatterometer cross-calibration.

The focus was on quantifying the biases between the RapidScat and QuikScat instruments, as these biases can be used to correct $\sigma^0$ measurements and generate a reprocessed set of wind vectors. Reprocessed wind vectors may lead to a closer agreement with surface truth winds. Such studies are beyond the scope of this
introductory work, which aims to present the methodology and preliminary results, and will be addressed in future work.

Furthermore, the all previous researches have been implemented only on one resolution; this dissertation present additional resolutions: \((0.125° \times 0.125°, 0.25° \times 0.25°, \text{and } 0.5° \times 0.5°)\) to evaluate the impact of different resolutions. So, the double difference and the dependency of instrument’s measurements on other parameters have been recalculated for these three resolutions.

## 1.3 Dissertation Objective and Overview

This dissertation is organized into 6 chapters. Follow the introduction, the thesis proceeds as:

- **Chapter 2**: This chapter introduces a background about the Space borne as Scatterometry, Characteristics of satellite scatterometers, and explanation of Radar equation (radar cross section). In addition, it explains the goal of radar calibration. The past and future scatterometers motions, Scatterometer wind retrieval process is explained. RapidScat and QuikScat are described in more details and the future missions are also listed.

- **Chapter 3**: This chapter represents the core chapter of the dissertations. General Scatterometer calibration is explained with detailed description
about the mathematical method. Calibration of RapidScat against QuikScat. Data set selection that have been used of both instruments is explained. The procedure of the calibration algorithm has been discussed in detail. Description about the Geophysical Model Function GMF that have been used to calculate the modeled radar cross section for both instruments. The Global Data Assimilation System (GDAS) is presented, which is used to provide a common baseline for the cross-calibration, and the surface truth wind data.

- Chapter 4: This chapter presents the result of cross – calibration between the RapidScat and QuikScat. The investigation of bias stability is presented as a function of different parameters such as the bias as a function of wind speed, direction, latitude, and incidence angle. All the examinations have been done for individual polarization and combined polarization.

- Chapter 5: This chapter discusses the results of the Double Difference cross calibration between the RapidScat and QuikScat. The result of double difference presented as a monthly average and as a function of other parameters. Moreover, the results of the multi resolution are illustrated.

- Chapter 6: This chapter presents the dissertation concludes with a brief conclusion and suggested future work
Chapter 2

Fundamental Concepts of Scatterometers

2.1 Introduction

Satellite scatterometers are radar remote sensors that is used to collect information about geophysical properties that might be used for various studies that benefit society. They are designed to retrieve the near-surface vector wind over the ocean. Unlike radiometers which are receive-only devices, radar systems include a transmitter which transmits an EM pulse of microwave energy towards the Earth’s surface and measures the reflected energy, radar backscatter. The backscatter is used to calculate the reflection coefficient, called the normalized radar cross-section ($\sigma^0$) of the ocean surface area illuminated by the sensor antenna. Figure 2.1 presents the block diagram of the space-borne radar system [5, 14]. Radar is focuses on in the absolute power in the return echo of the reflected energy from the transmitted signal which had been scattered by the wind-roughened ocean surface and experienced two-
way propagation effects within the intervening atmosphere, as illustrated in Figure (2.2) [15, 16].

**Figure 2.1:** Block diagram of a space-borne radar system [5].

**Figure 2.2:** The transmitted EM pulse and the return echo [14].
The friction between the ocean surface and the steady wind results in waves to form. These waves will cause a surface roughness which is strongly dependent on the interaction of the wind and seawater. The surface is roughened by the generation of centimeter-scale capillary waves that are the major contributor to the ocean surface backscatter reflectivity through the Bragg scattering mechanism.

The resulting roughness is observed by the microwave radar named by backscatter that is related to the wind direction and wind speed. The relationship between backscatter and surface roughness wind speed is proportional, because whenever the wind speed increases, the surface roughness will increase which causes an increase in the backscatter. The wind direction and the wind speed can be estimated when the backscatter is measured at various look directions [17].

Three scattering patterns can be identified according to the surface roughness, as shown in Figure 2.3. The first scattering pattern is the Smooth Surface reflection which, as described by Fresnel laws is primarily specular reflection. The second scattering pattern is the medium rough surface, which reflects two components coherent in specular direction, and non-coherent (diffuse), which radiates power in all directions. The third scattering pattern is the Rough surface, in which the coherent component becomes negligible which causes primarily non-coherent scatter [18, 19].
Some scatterometers have two parallel receiver channels: the narrow band (250 KHz), is called the echo channel, and the wideband (1MHz), is called the noise channel. The ocean backscatter echo for the scatterometer $\sigma^0$ measurement and the blackbody noise are received from the target ocean surface, and it is captured in the echo channel. In addition, both blackbody noise and echo are also measured by the overlapping noise channel. As a scatterometer signal processing, these two channels that captured the power are used to solve for the echo power and remove the noise power. The signal-to-noise ratios (SNR’s) are different because both channels capture noise and signal. For a time period ($\tau$), the channel power is integrated, then by subtracting the output of the two channels, the echo is removed, and resulting in only noise energy.
Then, from the differential noise channel the noise energy is derived and then subtracted from (signal + noise) energy of the echo channel; this will gain only the echo signal that is used to estimate the ocean $\sigma^0$ [20].

2.2 Radar Cross Section

The wind vector retrieval from a radar scatterometer is reached by the famous relationship between normalized radar cross-section (NRSC) or sigma-0 ($\sigma^0$) and the wind vectors [16]. Using the received power at the receiver, and the radar equation $\sigma^0$ is measured. The received (backscattered) power can be obtained from applying the Friss transmission formula, to a monostatic radar which yields

$$P_r = \frac{P_t G_t \sigma}{4\pi R^2} \frac{A_{eff}}{4\pi R^2}$$

(2.1)

Where:

$P_t$ = transmitted power (W)

$G_t$ = antenna gain

$R$ = distance from antenna to the ocean surface (m)

$A_{eff}$ = effective aperture of the receiving antenna [m2]

$\sigma$ = the radar cross-section [m2].
\frac{1}{4\pi R^2} = \text{Free space spreading loss}

P_r = \text{received power (W)}

The propagation circle is illustrated in Equation (2.1) from transmitting power Pt, which is directionally attenuated due to the free-space loss \( \frac{1}{4\pi R^2} \), and is modulated by the antenna pattern gain, \( G_t \). While propagating back to radar, the reflected power is attenuated by additional free space loss. Moreover, the effective aperture \( A_{eff} \) parameter will calculate part of the received power of the antenna. By using the relation between the receiving antenna gain \( G_r \) and effective antenna aperture \( A_{eff} \):

\[ A_{eff} = \frac{\lambda^2}{4\pi} G_r \]  \hspace{1cm} (2.2)

Where

\( \lambda \) = operating wavelength (m)

From Equation (2.1) and (2.2) the receiver power can be expressed as:

\[ P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^3 R^4 \sigma} \]  \hspace{1cm} (2.3)

For point targets, Equation (2.3) can be considered as is the fundamental radar equation.
The ocean $\sigma^0$ is affected by a broad range of geophysical parameters which are generally unknown; remote sensing of these parameters is possible by calculating $\sigma$ from measured $P_r$, inverting (2.3) [14, 19]:

$$\sigma = \frac{(4\pi)^3 R^4 P_r}{P_t G_t G_r \lambda^2}$$

(2.4)

Due to the existence of a relationship between the wind roughened ocean surface and $\sigma^0$ measurements, the primary application of the scatterometer $\sigma^0$ measurements are to infer near-surface winds, by retrieving the wind vector (speed and direction). In addition to the wind vector (speed and direction) dependence, the ocean $\sigma^0$ also depends on many radar observation parameters, such as incidence angle, azimuth angle, frequency, and polarization, and it can be affected by several geophysical parameters, such as foam coverage and the sea surface temperature (SST) [18].

The backscatter from the sea surface is modulated with respect to azimuth angle, and cardinal directions can be referred to as upwind, crosswind or downwind. Since the $\sigma^0$ obtained at different wind-relative azimuth angles and by using the relation between ocean $\sigma^0$, wind vector and “look” geometry (azimuth and incidence angles), the near-ocean surface wind vector can be inferred. This relation is known as the geophysical model function (GMF). The GMF is the empirical relationship that relates radar backscatter to the radar measurement geometry and the ocean surface wind vector [21]. More details about (GMF) will discussed in Chapter 3.
2.3 QuikScat

The most recent NASA scatterometer instrument is the SeaWinds, which was developed at the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL). It is a Ku band with 13.4 GHz frequency microwave remote sensor that has operated on QuikScat satellite in a sun-synchronous polar orbit. The QuikScat satellite, which was launched in July 1999, was a quick recovery mission to stop the gap created by the loss of data from the (NSCAT) in 1997. Another SeaWinds instrument also flew onboard the Japanese Advanced Earth Observing Satellite II (ADEOS-II) from December 2002 until October 2003 when an irrecoverable solar panel failure caused a premature end to the ADEOS-II satellite. Figure 2.4 shows the QuikScat spacecraft in Earth orbit [18, 22].

Figure 2.4: QuikScat Satellite.
QuikScat launches into a sun-synchronous orbit at a mean altitude of approximately 802.4 km and has an orbit inclination of 98.616°. The local equator crossing time is 6 hours +/- 30 minutes at the ascending node and around 18:00 local time for descending satellite passes. In addition, it has a repeat period of approximately 4 days/57 orbits. The sun-synchronous orbit (SSO) is a geocentric orbit which combines inclination and altitude in a specific way so that the satellite crosses the same point on the earth’s surface at the same local solar time [23].

The orientation to Earth and the Sun of the sun-synchronous orbit is illustrated in Figure 2.5 corresponding to the constant sun. The figure shows how the orbit looks at different times of year. It can be noticed from the figure that the position of orbit is relative to the sun and varies across each orbit of the earth, but the way that the orbit appears from the point of view of the Sun is the same no matter where the Earth is in its yearly orbit.

The advantage of the satellite in such an orbit is that it can be placed in constant sunlight and for many applications such as weather satellites. In other words, the sun is at approximately the same position at any given point in the satellite’s orbit relative to the earth and the satellite. Since the QuikScat is a sun-synchronous orbit, every revolution at the ascending orbit portion passes through the equator of the earth at 6 a.m. local time. Similarly, the revolution at the descending portion of orbit crosses the equator at 6 p.m. local time [15].
Figure 2.5: The orbital planes as a sun-synchronous orbit.

Measuring the global ocean wind vector; the wind speed, and wind direction is the major mission objective of the SeaWinds, and this can be achieved by measuring the wind dependent normalized radar cross section $\sigma^0$ of the ocean’s surface. Moreover, since the SeaWinds instrument has two receiver channels which enable the instrument to receive backscatter signal (echo) and the black-body microwave emission (noise), this gives the SeaWinds the ability to observe the linearly polarized passive radiometric emission from the Earth’s surface and intervening atmosphere, in addition to measuring the backscatter. This passive radiometric measuring capability is known as QuikScat Radiometer (QRad) [24, 25].
SeaWinds is a pencil beam, conically scanning-antenna with two beams at two different earth incidence angles of $46^\circ$ for inner H-polarization, and $54.1^\circ$ for outer V-polarization. It is optimized to measure winds with a coverage of nearly 90% of the earth daily, due to its wide swath. The inner beam H-polarization has a narrower swath width (1400 km) due to its lower incidence angle, while since the outer beam V-polarization has the higher incidence angle, it provides measurements with a wider swath (1800 km). As the spacecraft moves in orbit and to collect the measurements, SeaWinds utilizes a 1-meter diameter parabolic dish antenna, which is mechanically at 18 rpm counter-clockwise. The SeaWinds measurement geometry is illustrated in Figure 2.6 [26].

![Figure 2.6: The SeaWinds measurement geometry [24].](image-url)
Unfortunately, QuikScat rotating antenna motors failed in November 2009. Despite the failure of QuikScat’s rotating antenna motors, the instrument was still able to collect data over a narrow swath and provide valuable $\sigma^0$ measurements. Operating over a narrower swath after the motor failure, extended QuikScat’s data record well over a decade, and allowed overlap with follow-up RapidScat mission [27].

### 2.4 RapidScat

RapidScat is a NASA’s Ku-Band pencil beam scatterometer that was installed on the International Space Station (ISS). The instrument launched in September 2014 to August 2016, when the mission effectively ended after an irrecoverable instrument failure. Unlike previous scatterometer missions, the ISS flies in a non-sun-synchronous orbit, visiting locations on Earth at different local times, and it has facilitated global contiguous geographical samplings between $\pm 51.6^\circ$ latitude [27].

This novel RapidScat orbit characteristic enabled the first measurements of diurnal wind changes over oceans. Moreover, since it is the first scatterometer not on a sun-synchronous platform, such orbit enables, for the first time, overlap with other scatterometers flying in sun-synchronous orbits, in addition to filling the QuikScat data gap, it enables new approaches in the determination of global patterns of measurement biases between satellite instruments [28, 29]. Figure 2.7 shows the RapidScat location on the Columbus module of ISS and its components.
The specific objective of the RapidScat scatterometer has been to provide wind data to forecasters and researchers over a two-year period to mitigate the reduction of QuikScat data volume, due to a narrowed swath. Following the malfunction of antenna rotating motors on the QuikScat scatterometer [8], NASA’s Jet Propulsion Laboratory reused the QuikScat’s spare engineering units to build the follow-up RapidScat instrument. The RapidScat sensor is nearly identical to QuikScat, except that adjustments have been made so that it can operate on the ISS [17].
Due to the difference of the ISS in the control and telemetry interfaces from the QuikScat and ADEOS busses, a new digital interface bridge (DIB) had been developed to the ISS by the RapidScat team. The SeaWinds primary subsystems are scatterometer antenna subsystem (SAS), scatterometer electronics subsystem (SES), and the command and data subsystem (CDS). The DIB implements ISS interfaces as well as a serial link for communication with the legacy CDS. To convert the 120-V ISS bus to the 48 V, a new power control unit (PCU) have been added to the DIB to meet the required lower-regulated voltages by the DIB and the legacy SeaWinds hardware. In addition, a new antenna reflector had been added to the (SAS) because of the unavailability of suitable spare [31]. Figure 2.8 is a block diagram of the ISS RapidScat showing newly designed and legacy subsystems.

RapidScat’s antenna is a 0.75-m-diameter rotating dish with vertically (VV) and horizontally (HH) polarized beams directed at the Earth’s surface at incidence angles of approximately 56° and 49°, respectively. With 51.6° ISS inclination due to the wide swath, the instrument retrieves wind up to a ±56° latitude with uniform diurnal sampling, in contrast previous Sun-synchronous scatterometer orbits with fixed diurnal overflights. The ground swath of the VV (outer) beam is approximately 1100 km wide, while the ground swath of the HH (inner) beam is approximately 900 km wide. [12, 28]. The resulting pulse resolutions are 25 km × 35 km cells that are further range-processed into 25 km × 7 km cells.
Figure 2.8: A block diagram of the ISS RapidScat showing newly designed and legacy subsystems [30].
This will show that RapidScat is fairly similar to QuikScat, especially with calibration facilitates, but there are some distinct differences, such as RapidScat has increased look angle of its beams and smaller antenna size. The altitude of RapidScat is lower than QuikScat, which results in a larger ground swath of RapidScat and larger measurement area than if the QuikScat instrument were at RapidScat’s [15]. Moreover, previous scatterometers’ orbits are polar orbits, and they covered almost the whole earth and observed the Polar Regions several times a day. This gave an opportunity to various cryosphere studies, which is possible with RapidScat. [12]. In addition, the other difference between other scatterometers and the ISS RapidScat platforms is the orbit inclination angle. Figure 2.9 illustrates the geometry of RapidScat’s pencil beams sweeping the Earth’s surface in a circular footprint.

![Figure 2.9: RapidScat pencil beam geometry.](image)
The RapidScat started a strange behavior in August 2015 in its measurements, due to a change in receiver gain. This caused a different state of signal-to-noise ratio (SNR) that have been recorded for its measurements. The nominal state is called High SNR, while the new state is called a “Low SNR” state. Three additional low SNR states were observed by March 2016. The measurements of the new states required different adjustments in gain to be similar to the measurements from the High SNR state.

The power distribution unit of the ISS Columbus module had failed by August 2016, which caused a power loss to ISS-RapidScat. Several attempts to restore ISS-RapidScat to the normal operations failed, until the last attempt on October 2016. By November 2016, the Jet Propulsion Laboratory announced the RapidScat mission had ended.

A comparison between the RapidScat and other instruments is shown in Table 2.1, including their azimuthal configurations, polarization, beam resolution, resolution ($\sigma^0$), daily coverage, mission and dates, orbit type, orbit inclination, ascending equatorial crossing local time, altitude, period, frequencies, range of incidence angles, and swath patterns, where the swath patterns represent the shape and total areas that they illuminate as they orbit the Earth. It can be seen from the table that the scatterometers that have the widest swath compared to other instruments are only the instruments that operate with a pencil-beam approach.
<table>
<thead>
<tr>
<th>Frequency (Ku-band)</th>
<th>SASS</th>
<th>NSCAT</th>
<th>SeaWinds</th>
<th>SeaWinds</th>
<th>OSCAT</th>
<th>HY-2A</th>
<th>RapidScat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14.6 GHz</td>
<td>13.995 GHz</td>
<td>13.6 GHz</td>
<td>13.6 GHz</td>
<td>13.6 GHz</td>
<td>13.256 GHz</td>
<td>13.6 GHz</td>
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<tr>
<td>Antenna azimuths</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
<tr>
<td>Polarizations</td>
<td>VV and HH</td>
<td>VV and HH</td>
<td>VV-outer HI-inner</td>
<td>VV-outer HI-inner</td>
<td>VV-outer HI-inner</td>
<td>VV-outer HI-inner</td>
<td>VV-outer HI-inner</td>
</tr>
<tr>
<td>Beam resolution</td>
<td>Fixed Doppler</td>
<td>Variable Doppler</td>
<td>Pencil-beam</td>
<td>Pencil-beam</td>
<td>Pencil-beam</td>
<td>Pencil-beam</td>
<td>Pencil-beam</td>
</tr>
<tr>
<td>Resolution (\circ)</td>
<td>Normally 50 km</td>
<td>25 km</td>
<td>Egg: 25x36 km Slice: 6x25 km</td>
<td>Egg: 25x36 km Slice: 6x25 km</td>
<td>Egg: 30x68 km Slice: 5x30 km</td>
<td>Outer beam 37 x 26 km Inner beam 33 x 23 km</td>
<td>Egg: 26x37 km Slice: 8x26 km</td>
</tr>
<tr>
<td>swath (km)</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
<tr>
<td>Incidence angles</td>
<td>0° - 70°</td>
<td>12° - 60°</td>
<td>46° &amp; 54.4°</td>
<td>46° &amp; 54.4°</td>
<td>49° &amp; 57°</td>
<td>41.36° &amp; 48.44°</td>
<td>49° &amp; 56°</td>
</tr>
<tr>
<td>Daily coverage</td>
<td>Variable</td>
<td>78%</td>
<td>92%</td>
<td>92%</td>
<td>&gt;90%</td>
<td>90%</td>
<td>65% between 58° N and 58° S</td>
</tr>
<tr>
<td>Orbit type</td>
<td>Sun-synchronous</td>
<td>Sun-synchronous</td>
<td>Sun-synchronous</td>
<td>Sun-synchronous</td>
<td>Sun-synchronous</td>
<td>Sun-synchronous</td>
<td>Non-synchronous</td>
</tr>
<tr>
<td>Ascending equatorial crossing local time</td>
<td>6:00 AM &amp; 12:00 PM</td>
<td>6:30 AM</td>
<td>6:00 AM</td>
<td>10:30 PM</td>
<td>12:00 AM</td>
<td>6:00 PM</td>
<td>Various</td>
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<td>Orbit inclination</td>
<td>108°</td>
<td>98.616°</td>
<td>98.6°</td>
<td>98.62°</td>
<td>98.28°</td>
<td>99.3°</td>
<td>51.65°</td>
</tr>
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<td>Altitude (nominal)</td>
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<td>803 km</td>
<td>800 km</td>
<td>802.9 km</td>
<td>720 km</td>
<td>970 km</td>
<td>375 – 435 km</td>
</tr>
<tr>
<td>Period</td>
<td>100.7 min</td>
<td>101 min</td>
<td>101 min</td>
<td>101 min</td>
<td>99.31 min</td>
<td>104.45 min</td>
<td>92.69 min</td>
</tr>
</tbody>
</table>
2.3 Current and Planned Missions

Many satellite microwave scatterometers have been developed to provide measurements of ocean winds since 1978, such as SeaSat-A Scatterometer System SASS (1978) [32], NSCAT (1996-1997), SeaWinds (1999-2009 and 2002), OSCAT (2009-2014) and RapidScat (2014-2016). Since 1996, RapidScat is the fourth Ku-band wind scatterometer launched by NASA. It was preceded by NSCAT in 1996 and SeaWinds in 1999 and 2002. Another Ku-band scatterometer, OSCAT was launched by India in 2009 [15].

A history of satellite wind measurements and the proposed future missions is illustrated in Figure 2.10. The figure shows four different categories of satellite missions. The blue lines represent the sensors that provide only wind speed, such as Special Sensor Microwave/Imager and Special Sensor Microwave Imager/Sounder (SSM/I and SSMIS) which are flying on series of platforms from F8 to F20. On the other hand, the pink lines indicate the microwave radiometers, which have lower frequencies that measure the wind speed, rain rates, clouds, water vapor, and sea surface temperatures. Moreover, the low frequency channels also have the ability to improve the accuracy of wind speed. The only microwave that provides wind direction is the instrument that has polarimetric channels, such as WindSat [33].
The green lines illustrate the instruments which are sensitive to the rain and provide accurate measurements of high wind speed in storms. These instruments are denoted by the L-band radiometers, such as Aquarius, SMAP, and SMOS. The last lines are the black ones, and these lines show the number of microwaves scatterometers which provide ocean vector winds (OVW). The QuikScat dotted line present the non-spinning phase of operation. The RapidScat was proposed to calibrate OSCAT-2, but it suffered a power loss in August 2016. Moreover, there are several new scatterometer missions planned for the future, such as OSCAT-2 on ScatSat (2016), CNSA HSCAT-B on Hai Yang 2B (HY-2B) (2017), OSCAT-3 on OceanSat-3 (2018), China Meteorological Administration (CMA) WindRAD (2018), Russian SCAT on Meteor-M N3 (2020), EUMETSAT SCA on MetOp-SG-B (2022) [33].

Figure 2.10: Satellite scatterometers past and future missions.
Chapter 3

Calibration of RapidScat Scatterometer

3.1 Introduction

Two types of microwave sensors, active radar scatterometers and passive radiometers, have been used to retrieve ocean surface wind speeds. Active instruments and polarimetric radiometers, such as WindSat, are also capable of retrieving the wind direction. Scatterometers are active instruments that deliver pulses of energy in the microwave range directed at the surface of the ocean at a desired incidence angle. Backscattered energy quantified by the measured radar cross section $\sigma^0$ is determined by the wind-induced sea-surface roughness, thus establishing a mechanism for wind vector retrieval. To enable accurate wind vector retrieval, scatterometers must be well calibrated. Scatterometer cross-calibration requires two sensors with collocated and co-temporal measurements [34, 35].

The unique nature of the RapidScat’s non-sun-synchronous orbit enables a new approach in the determination of global patterns of measurement biases between
satellite instruments. The main goal of the research is to analyze backscatter signal biases over the sea surface and to establish a procedure to perform cross-calibration between the RapidScat and the QuikScat (SeaWinds) scatterometers. The choice of QuikScat as the calibration reference was motivated by the instrument equivalence. RapidScat is the QuikScat’s twin instrument thus minimizing the hardware impact on the measurement difference. That enables better RapidScat validation by reducing the number of potential bias sources. The same data format additionally justifies the choice of cross-validation platforms. Thus, despite QuikScat’s operation in the fixed-angle scan mode reducing the range of conditions, it still allows sufficient overlap for statistically valid validation campaigns.

3.2 Calibration Methodology

Several methods have been previously applied to calibrate passive and active spaceborne remote sensors [8, 13 and, 35]. The variable nature of the biases in response to the spacecraft and instrument operating conditions complicates characterizing the instruments separately and in absolute terms, which is the main motivation for using relative biases. Moreover, on-orbit scatterometer calibration and validation are essential to ensure accurate and stable $\sigma^0$ measurements which leading to accurate wind vector retrievals. Both individual instrument calibration and multi-instrument cross-calibrations are necessary.
The double-difference technique has been successfully used for cross-calibrating microwave radiometers [36, 37]. The purpose of the double difference technique is to find a linear calibration transfer function between two instruments, or alternatively, to find the inter-sensor biases independent of instrument and measurement artifacts [38, 39, and 40]. When extended to scatterometry, this technique improves the direct comparison by including $\sigma^0$ models to replace the brightness temperature (TB) models in the radiometer case. Modeled $\sigma^0$ is the reference for inter-calibration between two instruments. To calculate the double difference, the observed single differences for both sensors are first evaluated as differences between the observed $\sigma^0$ values and the corresponding modeled values obtained from the GMF. The double difference is then calculated by subtracting the single difference values for each instrument [8, 9, and 13].

The process is summarized in Figure 3.1 through a flow diagram depicting measured $\sigma^0$ pairs on the left and modeled $\sigma^0$s on the right. Comparing measured and modeled $\sigma^0$ s from two instruments constitutes the essence of the Double-Difference (DD) cross-calibration method designed originally for radiometer calibration and applied in this study for the first time on scatterometers [13, 41].
Figure 3.1: Flow diagram of RapidScat calibration.

3.3 Data Sets and Match-ups

To achieve desired wind retrieval accuracy levels, $\sigma^0$ calibration accuracy has become increasingly demanding, including both individual instrument calibration and comparisons among different instruments [9]. In this work, a QuikScat instrument was chosen to cross-calibrate the RapidScat target sensor using the double-difference technique. The algorithm used the underlying Global Data Assimilation System (GDAS) wind vector fields to provide wind conditions at the times and locations of satellite overlap. The calibration also relied on a Geophysical Model Function (GMF) to model $\sigma^0$ at GDAS wind conditions at the RapidScat and QuikScat incidence and azimuth angles. A pair of sensor datasets (RapidScat and QuikScat) and a pair of modeling datasets (GMF and GDAS) are described next.
3.3.1 RapidScat Data Set

The ISS RapidScat mission produced data products for both near real-time monitoring and long-term climate data studies. Among the data products, level 2A (L2A) contains surface-flagged $\sigma^0$ in 25 km wind vector cells. The L2A data product has three versions, 1.1, 1.2, and 1.3. Version 1.2 replaced Version 1.1 data forward from orbital revolution number 5127 after August 15, 2015, when low signal-to-noise ratio (SNR) was initially recorded, prompting $\sigma^0$ re-calibration by a NASA group, during the low SNR states 3 and 4 by using re-pointed QuikScat data. Version 1.3 replaced Versions 1.1 and 1.2 when the RapidScat entered its 3rd low SNR from orbital revolution number 7873, corresponding to February 11, 2016. The essential difference between these versions is that the L1B sigma-0 has been re-calibrated during low SNR states.

The state of signal - to - noise ratio is illustrated in Figure 3.2, showing the approximate state of each month; in 2015, the SNR was in the high state until August when the RapidScat recorded the first low SNR. Although the figure shows that the RapidScat remained in the low SNR state after August, there is a short period when it returned to the high state and then changed to a new low SNR. The other reason for the multiple SNR states is that in some periods the RapidScat had no date or the processor failed when the RapidScat experienced a sudden loss of power.
Data are also provided in two resolutions, 25 km full pulse ("egg") resolution and 12.5 km range-gated ("slice") resolution. This study experimented with both resolutions and adopted the lower 25 km resolution to better match the relatively low resolution (1° × 1°) Numerical Weather Prediction (NWP) baseline. If applicable, each 25 km cell was flagged for land or ice, and attenuation correction was provided for each $\sigma^0$ measurement. Figure 3.3 shows the "slice", and the "egg" where each egg has 12 slices.
To minimize the L2A data volume, the data are stored as lists for each Wind Vector Cell (WVC) row, and each list is indexed by a cell-index to indicate the cross-track cell membership. Also, each 12.5km cell is flagged for land or ice, and attenuation correction is provided for each measurement. L2A contains 3560 rows and 2000 columns and each cell is referred to by row and column indices.

To avoid unexpected truncation of data, 156 additional WVC rows from the previous and later revolutions are added at the beginning and the end of each revolution. Data
were provided in single-orbit files in Hierarchical Data Format 4 (HDF-4). HDF4 is an efficient physical file data format used for science data storage. The L2A dataset was calibrated and formatted for consistency with the QuikScat Version 2 L2A data and leveraged much of the same processing configurations and specifications. [8, 42, 43]. As described in [44], RapidScat L2A file names are conformed in the following format:

RS_S2Annnnn.yyydddhhmm[. CPxx].

Where the (nnnnn) represents the RapidScat satellite orbital rev number. (yyyy, ddd, hh and mm) is the calendar year, day of the year, hour in twenty-four hour time, and the minute, respectively, when the data product were generated not the exact time of the orbit. The additional file extension [. CPxx] indicate when slice-composite sigma0 are used and the “xx” is to indicate the WVC grid resolution used which could be {25, 20 or12}. Some of the data elements are provided in L2A are selected in this work, such as the latitude, longitude, azimuth angle, incidence angle, sigma0, attenuation and, some flags. Table 3.1 represents list of L2A parameters of interest in this dissertation [44].
Table 3.1: Descriptions of Selected Parameters of L2A Data.

<table>
<thead>
<tr>
<th>Parameters Name</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>cell_lat</td>
<td>The latitude of the center of a sigma0 cell.</td>
</tr>
<tr>
<td>cell_lon</td>
<td>The longitude of the center of a sigma0 cell.</td>
</tr>
<tr>
<td>cell_azimuth</td>
<td>The azimuth angle of the antenna boresight at the center of a sigma0 cell.</td>
</tr>
<tr>
<td>cell_incidence</td>
<td>The angle the antenna boresight direction vector normal vector to the earth’s surface and at the center of a sigma0 cell.</td>
</tr>
<tr>
<td>sigma0</td>
<td>The normalized radar cross section calculated from the radar equation.</td>
</tr>
<tr>
<td>sigma0_attn_amsr</td>
<td>A calculated nadir attenuation of (sigma0) measurement.</td>
</tr>
<tr>
<td>sigma0_qual_flag</td>
<td>Bit flags of the quality of the sigma0 measurement.</td>
</tr>
<tr>
<td>sigma0_mode_flag</td>
<td>Bit flags which indicate the RapidScat instrument status and mode at the time the sigma0 measurement was obtained.</td>
</tr>
<tr>
<td>Surface_flag</td>
<td>Bit flags of the effect of surface conditions on the sigma0 measurements.</td>
</tr>
</tbody>
</table>
All the selected parameters are scaled by a factor of 100, except the flags scaled factor is 1. The unit of the latitude, longitude, azimuth, and incidence angle is in degrees, while the unit of sigma0 and attenuation is in [dB].

The flags are a bit field where each bit is represented by either 0 or 1. If an anomalous condition is detected for a specific sigma0, the suitable bit flag which specifies the error condition remains set to 1. For the sigma0_mode_flag, the third bit has been used which perform the Antenna Beam Flag, where (0) is Inner antenna beam and (1) is Outer antenna beam.

Also, for surface_flag, the first and the second bit has been used to filter the surface conditions such as land and ice. The first bit indicates Surface land flag where (0) means no land is present, while (1) means land is present. The second bit is Surface ice flag determined by a map where (0) mean map indicates no ice is present and (1) means ice is present.

Moreover, for sigma0_qual_flag, the first bit indicates Sigma0 Measurement Usable Flag, where (0) means the measurement is usable, while (1) means the measurement is not usable. This flag also contains some important bits that are related to the quality of sigma such as the second bit which indicates Low SNR Flag and the third bit which indicates Negative Sigma0 Flag [44].
3.3.2 QuikScat Data Set

QuikScat is a Ku-band SeaWinds scatterometer, and it provided ocean vector wind (OVW) measurements over a wide swath from 1999 until November 2009 when the antenna spin mechanism failed. Despite the failure preventing antenna spin, NASA’s SeaWinds scatterometer flying onboard the QuikScat satellite was able to operate, collecting data at a 13.4 GHz frequency across a narrowed swath of only 25 km. SeaWinds continued to provide valuable $\sigma^0$ measurements in the form of a special level 1C (L1C) data product. This data product contained geo-located and averaged $\sigma^0$ measurements and wind retrievals during the non-spinning mode. During this mode, QuikScat was maneuvered and incidence angles were varied to cross-calibrate the Oceansat-2 and RapidScat scatterometers and extend the Ku-band empirical geophysical model function domain. The $\sigma^0$ values from the non-rotating beam were averaged over approximately 50 samples. The vertically polarized (outer) or the horizontally polarized (inner) beam is set or fixed by beam processing to be relative to the corresponding beam. Due to the lack of antenna spin, a large number of independent overlapping measurements were obtained for each point on the ground. This extreme averaging led to the most precise $\sigma^0$ measurements and corresponding wind speeds that have ever been available to a global extent, converging to wind speed errors of only 0.1 m·s$^{-1}$. Level 1C (L1C) have been constructed from original QuikScat non-spinning L1B_AVE files data product. The main parameters that have
been used from the (L1C) file are longitude, latitude, sigma 0, attenuation, incidence, and azimuth angle.

QuikScat L1C file names are conformed in the following format:

QS_L1C_RRRRR_V1.dat

Where:

QS = QuikScat Project

L1C = Science Level 1C Processing

RRRRR = 5-digit satellite orbital revolution (rev) Number

V1 = Identifies the processing version of this dataset (V1 = Version 1).

dat = The file extension indicating that this is a flat binary data file.

The data files provided are uncompressed binary format. ASCII text files which have been provided are used to determine the cross-referencing of orbital revolution numbers and calendar dates and UTC time of day. This file is available in [45], while the data can be downloaded from [46]. All the provided L1C parameters are unscaled, one dimension matrix [1x10593] of double precision real values. Table 3.2 represent list the L1C parameters of interest in this dissertation.
Table 3.2: Descriptions of Selected Parameters of L1C Data.

<table>
<thead>
<tr>
<th>Parameters Name</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>clat_QS</td>
<td>The latitude of the center of a sigma 0 cell.</td>
</tr>
<tr>
<td>clon_QS</td>
<td>The longitude of the center of a sigma 0 cell.</td>
</tr>
<tr>
<td>azi</td>
<td>The azimuth angle at the center of a sigma 0 cell.</td>
</tr>
<tr>
<td>inc</td>
<td>The incidence angle at the center of a sigma 0 cell.</td>
</tr>
<tr>
<td>sig_QS</td>
<td>The normalized radar cross section calculated from the radar equation.</td>
</tr>
<tr>
<td>atten</td>
<td>A calculated nadir attenuation of sigma 0 measurement.</td>
</tr>
<tr>
<td>beam</td>
<td>Antenna Beam index, 1 for vertical a 0 for horizontal</td>
</tr>
</tbody>
</table>

3.3.3 GDAS data

To provide a baseline reference for $\sigma^0$ modeling, surface truth wind vectors were extracted from the Global Data Assimilation System (GDAS). Since 2012, GDAS has been used by the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) to initialize weather forecasts with the observed data organized in a gridded space [47].
NCEP gridded fields integrated data are collected from a variety of platforms, such as surface observations, balloon data, wind profiler data, aircraft reports, buoys, radar, and satellite observations [48]. The GDAS data are updated every six hours at 0:00, 6:00, 12:00, and 18:00 Universal Time Coordinated (UTC) and stored in a 1° × 1° latitude/longitude grid, resulting in four daily 181 × 360 matrices. Parameters listed in an NCEP file include temperature, surface pressure, humidity, cloud liquid water, sea surface temperature, and wind vectors. Wind speeds and directions from the appropriate NCEP grids corresponding to co-located RapidScat/QuikScat observations were taken as inputs for σ⁰ modeling [8, 49, and 41]. An example of the NCEP/GDAS global wind speed magnitudes is shown in Figure 3.4.

![NCEP global wind field (m·s⁻¹) on 5/22/2015 at 12:00 UTC](image)

**Figure 3.4:** Wind speed distribution map.
Sea-surface $\sigma^0$ is modeled using semi-empirical geophysical model functions (GMFs), due to the large number of factors and geophysical variables that affect the $\sigma^0$. Since the early 1960s, many research studies have been conducted on GMFs for satellite microwave scatterometers, which have been developed at institutions such as the Jet Propulsion Laboratory (JPL), the Remote Sensing Systems (RSS), Dutch Koninklijk Nederlands Meteorologisch Instituut (KNMI), and the European Centre for Medium-Range Weather Forecasts (ECMWF). These research studies define accurately the GMF relationship correlating the scatterometer $\sigma^0$ measurements to the near surface wind vector (speed and direction) over the ocean.

The GMF is a transfer function, providing the relationship between the radar observable $\sigma^0$ and the surface wind vector (speed and direction). It is dependent on measurement geometry (incidence angle and antenna beam viewing direction relative to upwind) and radar parameters (polarization and wavelength) [50, 51, and 52]. These empirical GMFs are stored in multidimensional look up tables based upon the averaged $\sigma^0$ over wind vector bins.

For more precise explanation about GMF, the following equation presenting the relationship between $\sigma^0$ and wind vector is modeled using a simple analytical
expression based upon empirical observations. Equation (3.1) represent the three-term Fourier cosine series of $WS$ and $\chi$ for $\sigma^0$ in dB

$$\sigma^0 = C_0 (WS) + C_1 (WS) \cos(\chi) + C_2 (WS) \cos(2\chi) \quad (3.1)$$

The coefficients $C_0$, $C_1$ and $C_2$ are determined empirically by correlating observed $\sigma^0$ with known surface wind vector conditions, usually from numerical weather models. And $\chi$ is the relative direction defined as:

$$\chi = \alpha - \phi \quad (3.2)$$

Where $\alpha$ is the azimuth angle, and $\phi$ is wind direction.

These results of the relationship between $\sigma^0$ and wind vector, known as the Geophysical Model Function (GMF), is illustrated by:

$$\sigma^0_{\text{GMF}} = \text{GMF}(\theta, WS, \chi, P) \quad (3.3)$$

Where $\theta$ indicates the incidence angle, and $P$ is the radar wave polarization (horizontal or vertical).
Wind vector determining two dimensions of a GMF can be expressed in two alternative ways: as a wind speed and direction or as a pair of orthogonal velocity components. In the first alternative, the wind direction is expressed following two conflicting conventions: the meteorological and oceanographic.

The oceanographic convention references the angle between the north and the direction towards which the wind is blowing, and the meteorological convention references the angle between the north and the direction from which the wind is blowing.

The meteorological convention is commonly followed in scatterometry where the relative wind direction ($\chi$) is defined as the difference between the radar azimuth look angle and the surface wind direction [2]. The wind speed and wind direction can be expressed in the following equations as defined in.

\[
WS = \sqrt{u^2 + v^2}
\]  

(3.4)

While the WD can be expressed as

\[
WD = 180/\pi \times \tan^{-1}2(-u,-v)
\]

(3.5)

Where $u$ is the component of the horizontal wind towards the East, and $v$ is the component of the horizontal wind towards the North. The concept of the relative wind direction is illustrated in Figure 3.5 [49].
To achieve the required GMF accuracy, a large amount of calibration data is required. A variety of scatterometer frequencies (L, C, Ku, etc.) and different geometries require a common calibration methodology to develop a valid GMF. RSS’s NSCAT-2014 GMF was used in this research to calculate $\sigma^0$ for horizontal and vertical polarizations covering a full range of relative wind directions (0–180°), wind speeds (0–70 m·s$^{-1}$) in steps of 0.2 m·s$^{-1}$, and incidence angles between 16° and 66° with a 0.5° resolution [8, 53, 54]. Figure 3.6 shows the range and steps for relative wind directions, wind speed, and incidence angles for GMF [57].
Wind speed

<table>
<thead>
<tr>
<th></th>
<th>......</th>
<th>34</th>
<th>......</th>
<th>52</th>
<th>......</th>
<th>70</th>
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</table>

Corresponding NSCAT-2014 GMF

<table>
<thead>
<tr>
<th></th>
<th>......</th>
<th>171</th>
<th>......</th>
<th>261</th>
<th>......</th>
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</table>

Relative Wind direction

<table>
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<tr>
<th></th>
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<th>88</th>
<th>......</th>
<th>148</th>
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<th>180</th>
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Corresponding NSCAT-2014 GMF

<table>
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<th></th>
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<th>45</th>
<th>......</th>
<th>75</th>
<th>......</th>
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Incidence angle

<table>
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<th>RapidScat</th>
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<tbody>
<tr>
<td>16</td>
</tr>
<tr>
<td>......</td>
</tr>
<tr>
<td>45.5</td>
</tr>
<tr>
<td>......</td>
</tr>
<tr>
<td>58</td>
</tr>
<tr>
<td>......</td>
</tr>
<tr>
<td>66</td>
</tr>
</tbody>
</table>

Corresponding NSCAT-2014 GMF

<table>
<thead>
<tr>
<th></th>
<th>......</th>
<th>60</th>
<th>......</th>
<th>85</th>
<th>......</th>
<th>101</th>
</tr>
</thead>
</table>

Figure 3.6: Corresponding readings to NSCAT-2014 GMF.
An example of $\sigma^0$ calculated by the NSCAT-2014 GMF (VV-pol red and HH-pol blue) as a function of wind direction at a 20 m·s$^{-1}$ and 25° incidence is shown in Figure 3.7. The NSCAT-2014 GMF was selected because it was adopted for RapidScat processing by the International Ocean Vector Wind Science Team at the meeting in Brest, France in 2014 [28], [50], and [58].

With the wind direction defined per the meteorological convention, an example of $\sigma^0$ (in logarithmic decibel units) calculated by the NSCAT-2014 GMF as a function of the relative wind direction at horizontal polarization, wind speed of 16 m/s (red) and 20m/s (blue) at 25° incidence is shown in Figure 3.8. It shows increased $\sigma^0$ at higher wind speed and slight offset between upwind and downwind ($\chi=180^\circ$). Minimum $\sigma^0$ is also offset from the $\chi=90^\circ$ cross-wind [28].

Furthermore, for future work a new QuikScat GMF named QSNS2016a, has been developed by JPL from non-spinning QuikScat data. There are two primary ways which are considered to be the main difference between NSCAT2014 and the new GMF. The QSNS2016a produces a lower Normalized Radar Cross Section (NRCS) because a new calibration adjustment has been applied to QuikScat NRCS. The other difference is the decrease of azimuthal modulation depending on the wind speed [55].

Retrieving the wind vector from a fixed beam is unique, and the NRCS is expected to give true speed and wind direction.
Figure 3.7: Example of the $\sigma^0$ modeling (VV-HH) polarization via Geophysical Model Function (GMF).

Figure 3.8: An example of $\sigma^0$ GMF modelling of the relative wind direction at horizontal polarization, wind speed of 16 m/s and 20 m/s.
3.5 Collocation Algorithm

Before engaging in any cross-calibration effort, instruments are calibrated individually to ensure $\sigma^0$ consistency. Consistent $\sigma^0$ measurements from RapidScat and QuikScat become inputs for the cross-calibration stage. Cross-calibration uses pairs of RapidScat and QuikScat revolutions collocated in time. Co-temporal data (within one-hour separation in time) from both sensors are gridded into $1^\circ \times 1^\circ$ latitude/longitude boxes over the globe.

Two grids are overlaid, assuring comparable environmental conditions within the temporal collocation window in overlapping non-empty grid points. Underlying wind vectors are extracted in each grid point from the closest (in time) GDAS file. GDAS files contain global wind vector fields at 10 m reference heights in a $1^\circ \times 1^\circ$ grid. Thus, GDAS grids provide common baseline wind conditions for $\sigma^0$ modeling and a comparison with measurements from two scatterometers. Multiple views with different azimuth angles and polarizations are present within a box. Each view produces modeled $\sigma^0$ using the GMF and an underlying GDAS wind vector. For both instruments, estimated $\sigma^0$s are compared with the measurements and the single difference calculated for each view at various azimuths and polarizations within a box [28], [58].
An example of a few RapidScat and QuikScat orbits mapped over the globe are illustrated in Figure 3.9. The figure shows RapidScat (in blue) and QuikScat following a non-spinning antenna motor (in red). The wide RapidScat swath in the non-Sun-synchronous orbit allowed collocation with QuikScat at various local overpass times over the entire swath range of latitudes ±56°. It is easy to determine the collocations between non-sun-synchronous low inclination orbit, such as RapidScat, and a sun-synchronous satellite, such as QuikScat.

An example of footprint collocation between RapidScat and QuikScat is shown in Figure 3.10. The figure presents footprints of RapidScat in red ovals and footprints of QuikScat in blue ovals. The collocated pair is found when the footprints of RapidScat and QuikScat overlap each other at the same collocation time.

In addition, after the collocation is completed, the collocated measurements are filtered by removing the unwanted measurements, such as measurements over the land or ice and by using Surface land flag and Surface ice flag. Moreover, the quality flag that indicate the quality of the data, to filter the usable $\sigma^0$. These flags were discussed in detail in the previous section.
Figure 3.9: Global and focused view of the RapidScat/QuikScat collocations.

Figure 3.10: Collocation sample of Footprints between RapidScat and QuikScat.
3.6 Double Differences

The NSCAT-2014 GMF was deployed to calculate the modeled $\sigma^0$ values at the given sensor parameters (incidence angle and polarization). The single sensor difference between the $\sigma^0$ models and measurements was then subtracted to converge with the double-difference used to cross-calibrate RapidScat and the QuikScat [28]. The double difference calculation process started by loading the measurements and the corresponding instrument configuration within a spatial resolution bin and within the chosen time-difference tolerance. The primary spatial resolution used in this study was a $1^\circ \times 1^\circ$ latitude/longitude grid, with a one-hour maximum interval between overflights, although higher resolutions were investigated with minor effect on calculated cross-biases. To avoid changes in underlying wind conditions, time intervals exceeding one hour were not considered, and we also excluded measurements taken more than one hour from the closest GDAS file. Gridded overlapping sensor $\sigma^0$ measurements and corresponding configurations (polarization, azimuth, and incidence angle) were passed to the module that uses the GMF to calculate model $\sigma^0_{\text{GMF}}$ values. Values of the $\sigma^0_{\text{GMF}}$ were calculated from the corresponding GDAS wind fields in those geographical bins containing both RapidScat (subscript RS) and QuikScat (subscript QS) observations, excluding measurements with land or ice flags:
\[
\sigma_{\text{GMF,RS}}^0 = \text{GMF}(\theta_{\text{RS}}, W, x, p_{\text{RS}}) \\
\sigma_{\text{GMF,QS}}^0 = \text{GMF}(\theta_{\text{QS}}, W, x, p_{\text{QS}})
\]  

(3.6)

In Equation (3.6), \(\theta\) indicates the incidence angle; \(W\) denotes the GDAS wind speed; \(x\) is the GDAS wind direction relative to the radar azimuth; and \(P\) is the radar wave polarization (horizontal or vertical). In the second step, the modeled \(\sigma_{\text{GMF}}^0\) was compared to the measured \(\sigma_{\text{RS}}^0/\sigma_{\text{QS}}^0\) to build the bias set where the number of delta points falling into the bin is dependent on the chosen grid resolution:

\[
\text{SD}_{\text{RS}} = \sigma_{\text{RS}}^0 - \sigma_{\text{GMF,RS}}^0(\theta, W, x, p) \\
\text{SD}_{\text{QS}} = \sigma_{\text{QS}}^0 - \sigma_{\text{GMF,QS}}^0(\theta, W, x, p)
\]  

(3.7)

Equation (3.7) defines the single difference between the actual sensor measurement and the expected measurement modeled from the GDAS weather data at the given sensor configuration. This difference is calculated for each instrument view taken at different azimuths and polarizations. Values of measured \(\sigma^0\) are not averaged within a box. Instead, for each individual measurement, a corresponding modeled \(\sigma^0\) is calculated. The 1° grid box is the reference for the underlying GDAS wind vector, so that each modeled \(\sigma^0\) in the box uses the same wind vector to calculate the model counterpart to the measured \(\sigma^0\) value and enable difference calculation. Once individual differences are calculated, they can be averaged on any desired level:
From Equations (3.6) and (3.7), the double difference (DD) is the difference between the RapidScat and QuikScat single differences (SD):

$$\text{DD} (W, x, p) = \text{SD}_{RS} (W, x, p) - \text{SD}_{QS} (W, x, p) \quad (3.8)$$

Equation (3.8) completes the double-difference cross-calibration calculation. Each DD $(W, x, p)$ point represents an individual measured/modeled $\sigma^0$ pair. It was deployed on RapidScat/QuikScat data between January 2015 and March 2016 to compile bias statistics aggregated per time and per sensor variables, as presented in the following section. The entire algorithm is summarized in a block diagram in Figure 3.11, where WS and WD are the wind speed and wind direction in a $1^\circ \times 1^\circ$ GDAS box, respectively. The collocated data within a box included multiple measurements from both QuikScat and RapidScat taken within a one-hour time interval and within one hour from the GDAS report. It also included the corresponding measurement configurations (azimuth, polarization, and incidence) and a single GDAS wind vector. The single and double difference biases calculated in Equations (3.6) – (3.8) may be used to correct $\sigma^0$ measurements and improve the wind retrieval accuracy [28].
Figure 3.11: Block diagram of RapidScat/QuikScat double-difference calibration.
Chapter 4

Backscatter Measurement Validation

4.1 Introduction

Results of the RapidScat normalized radar cross section validation are presented in this chapter. The analysis has been done based on more than 1000 RapidScat, QuikScat, and GDAS triplet files collected between January 2015 and August 2016, and falling within the ±1-hour time interval. To perform the analysis, the comparison data set was separated into vertical (VV) and (HH). Biases defined in equation (3.7) are calculated as a function of two environmental conditions, namely; wind speed, wind direction, and incidence angle as a geometry. The results are presented in a series of graphs in the following sections. From these graphs, conclusions on RapidScat accuracy, stability, and cross-calibration between RapidScat and QuikScat can be drawn. Most of this work had been already published in [8], [58].
4.2 Evaluation versus wind speed

The average single difference $\sigma^0$ biases are shown in figure 4.1 and 4.2. Figure 4.1a $\sigma^0$ bias, $\sigma^0$ mean/std for RS 4.1b, and for QS (4.1c) as a function of wind speed averaged over all directions and same for figure 4.2. The figures are generated per month to investigate bias stability over the entire period. Results for January and May 2016 are shown as an example. Since QuikScat was kept at one polarization during certain periods, only the outer beam VV-Pol is present. Significant biases are calculated for both instruments at lowest wind speeds, indicating likely GMF inaccuracies in that range and higher impact of noise. At low wind speeds, radar backscatter signal is low and sensitive to errors due to noise resulting in high bias exceeding 10dB at the lowest wind speeds. Beyond 6m/s wind speed, rms biases are close to 0.5dB. RapidScat and QuikScat show remarkable agreement, especially in early stages of RapidScat operation. The average bias in Jan. 2016 captured is the highest in the entire examined period, particularly below 5m/s, with more than 5dB at lowest wind speeds. Increased bias at lowest wind speed is expected because $\sigma^0$ is proportional to the wind speed. At lowest wind speeds, radar echo signal is weak, and noise significantly corrupts $\sigma^0$ readings. Additionally, since January 2016, SNR has additionally decreased occasionally due to increases in receiver noise temperature. The higher RapidScat bias coincides with observed occurrences of low SNR periods and potential insufficient compensation in the reprocessed V1.2 L2A
These periods of reduced SNR, together with mentioned variations in platform attitude, cause increased standard deviation at all wind speeds compared to the QuikScat, which has another benefit of deeper averaging because of non-rotating antennas. Furthermore, the unseparated polarization for the average single difference \( \sigma^0 \) biases between RapidScat and QuikScat for two months, January 2015 and January 2016 are shown as examples in figure 4.3a and 4.3b.

**Figure 4.1a:** \( \sigma^0 \) bias as a function of wind speed, January 2016.

**Figure 4.1b:** \( \sigma^0 \) mean/std for RS as a function of wind speed, January 2016.
Figure 4.1c: $\sigma^0$ mean/std for QS as a function of wind speed, January 2016.

Figure 4.2a: $\sigma_0$ bias as a function of wind speed, May 2016.
Figure 4.2b: $\sigma^o$ mean/std for RS as a function of wind speed, May 2016.

Figure 4.2c: $\sigma^o$ mean/std for QS as a function of wind speed, May 2016.
Figure 4.3a $\sigma_0$ bias as a function of wind speed, January 2015.

Figure 4.3b $\sigma_0$ bias as a function of wind speed, January 2016.
In addition, the dependence of single difference RapidScat $\sigma^0$ bias on the wind speed as an individual polarization is investigated and summarized more accurately in Figure 4.4a, 4.4b and 4.4c April 2015, November 2015 and February 2016. The figure shows $\sigma^0$ bias as a function of wind speed and indicates a good agreement between bias from both polarization above approximately 6 m/s and beyond. Below 6m/s biases diverge by approximately 2dB suggesting potential need for correction in this range. Moreover, for the same three months figures 4.5, 4.6 and 4.7 where (a) panel for each figure presents distributions of RapidScat $\sigma^0$ biases at horizontal and (b) panel for each figure presents vertical polarization. Histograms show distributions with relatively narrow spread around 0dB average $\sigma^0$ bias. Both polarizations exhibit similar distributions with vertical polarization being slightly wider than horizontal.

![Figure 4.4a RapidScat Single Difference as a function of wind speed outer (VV) and inner beam (HH), April 2015.](image)
Figure 4.4b RapidScat Single Difference as a function of wind speed outer (VV) and inner beam (HH), November 2015.

Figure 4.4c: RapidScat Single Difference as a function of wind speed outer (VV) and inner beam (HH), February 2016.
Figure 4.5a RapidScat Single Difference distributions as a function of wind speed outer (VV), April 2015.

Figure 4.5b RapidScat Single Difference distributions as a function of wind speed inner beam (HH), April 2015.
Figure 4.6a RapidScat Single Difference distributions as a function of wind speed outer (VV), November 2015.

Figure 4.6b RapidScat Single Difference distributions as a function of wind speed inner beam (HH), November 2015.
Figure 4.7a RapidScat Single Difference distributions as a function of wind speed outer (VV), February 2016.

Figure 4.7b RapidScat Single Difference distributions as a function of wind speed inner beam (HH), February 2016.
4.3 Evaluation versus Relative Wind Direction

The average $\sigma^0$ biases as a function of the relative wind direction for the outer beam VV-Pol are presented in figures 4.8a July 2015 and 4.8b March 2016, which is calculated via equation (3.7) and averaged over all wind speeds. Relative wind direction $\chi$ is defined as the difference between wind direction and antenna azimuth angle. RapidScat’s curve is much smoother, while QuikScat’s wind direction signal contains significantly higher spectral components and is much more noise-like. This shape may be attributed to lack of QuikScat antenna rotation contributing to increased wind direction sensitivity and bias deviations. However, these high spectral components seem to be Gaussian in amplitude and are therefore low-pass filtered and not observed in average wind speed bias, as seen in Figure 4.1. Particularly high bias is calculated for the QuikScat close to the cross-wind. In terms of stability over time, March 2016 shows the largest magnitude range in $\sigma^0$ biases as a function of wind direction. This low pass filtering is in effect accomplished in RapidScat via antenna rotation missing in QuikScat.

As stated previously as separated polarization only the outer beam VV-Pol is present, since QuikScat was kept at one polarization during certain periods. In addition, the average $\sigma^0$ biases as a function of the relative wind direction combined polarization is presented in figure 4.9a July 2015 and 4.9b March 2016. The figure shows the same
example for both months to show the difference in RapidScat since the QuikScat kept in same polarization.

Figure 4.8a: $\sigma_0$ bias as a function of wind direction outer beam (VV), July 2015.

Figure 4.8b: $\sigma_0$ bias as a function of wind direction outer beam (VV), March 2016.
Figure 4.9a: $\sigma_0$ bias as a function of wind direction, July 2015.

Figure 4.9b: $\sigma_0$ bias as a function of wind direction, March 2016.
For more precise analysis, RapidScat single difference dependence on relative wind direction as an individual polarization is investigated. Figure (4.10a, 4.10b and, 4.10c) represent an example of April 2015, July 2015 and, January 2016, respectively.

The red and the blue line represent biases at vertical and horizontal polarization, respectively. Biases at both polarizations follow the same pattern. Absolute value of the bias peaks around 90° relative wind direction (cross-wind) and appears as a noisy harmonic function of the relative wind direction.

![Figure 4.10a RapidScat σ0 bias as a function of wind direction outer (VV) and inner beam (HH), April 2015.](image)

Figure 4.10a RapidScat $\sigma_0$ bias as a function of wind direction outer (VV) and inner beam (HH), April 2015.
Figure 4.10b: RapidScat $\sigma_0$ bias as a function of wind direction outer (VV) and inner beam (HH), July 2015.

Figure 4.10c: RapidScat $\sigma_0$ bias as a function of wind direction outer (VV) and inner beam (HH), January 2016.
4.4 Evaluation versus Incidence Angle

In addition to the wind speed and direction, incidence angle is the third GMF dimension. It is defined as the angle between the normal to the earth’s surface and the antenna beam boresight direction vector [56]. Typical incidence angles in satellite scatterometers have been in the 40°-60° range. The stability of σ⁰ biases, as a function of the incidence angle, has been investigated to detect potential bias dependence on the incidence angle, with QuikScat incidence angle varying after rotating antenna failure to accommodate other scatterometers and enable better cross-calibration and extend the Ku-band empirical geophysical model function domain. Note that incidence angle has been varied by repositioning the fixed beams. Lack of antenna rotation is not related to the incidence angle. Results of the bias dependence on the incidence angle for both beams (HH and VV Pol) are shown in Figure 4.11a and 4.11b for April 2015 and Figure 4.12a and 4.12b for February 2016. The figures show average σ⁰ biases, stages of the observed period. RapidScat incidence angle bias signal is plotted in blue, and QuikScat in red spots. Discrete changes in QuikScat incidence angles are apparent in graphs. The absolute RapidScat bias increases at lower incidence angles and changes sign from negative to positive bias as incidence angle increases across the RapidScat angle range. The QuikScat incidence angle appears random with a discrete narrow range of incidence angles not suitable for a comprehensive analysis.
Figure 4.11a: $\sigma^0$ bias as a function of incidence angle Inner-HH, April 2015.

Figure 4.11b: $\sigma^0$ bias as a function of incidence angle Outer-VV, April 2015.
Figure 4.12a: \( \sigma^0 \) bias as a function of incidence angle Inner-HH, February 2016.

Figure 4.12b: \( \sigma^0 \) bias as a function of incidence angle Outer-VV February 2016.
As a non-individual polarization additional results are illustrated in Figure 4.13a and 4.13b early (April 2015) and late (Feb. 2016). It can be notice from figure 4.12a that the RapidScat has the same behavior as an individual polarization as in figure 4.11 and 4.12. In addition, it can be notice from the figures above that QuikScat incident angle range is much narrower than RapidScat. In common QuikScat/RapidScat ranges, the VV bias is lower than the HH. In both cases, the difference between RapidScat and QuikScat varies from 0.2-2.5dB.

Figure 4.13a: $\sigma^o$ bias as a function of incidence angle, April 2015.

Figure 4.13b: $\sigma^o$ bias as a function of incidence angle, February 2016.
4.5 Evaluation versus latitude

In addition to the incidence angle, wind speed, wind direction, stability of the $\sigma^0$ biases, as a function of latitude, was evaluated to detect potential bias dependency on the latitude as shown in figure 4.14. The figure presents an example of July 2016, the horizontal axis represents the latitude over the oceans from $55^\circ$ latitude-south to $55^\circ$ north, and the vertical axis presents the averaged biases of both beams, outer (upper panel) and inner (lower panel).

Figure 4.14: $\sigma^0$ bias a function of latitude inner (HH) and outer (VV), July 2016.
The average $\sigma^0$ obtained for both instruments shows a good agreement for both polarizations, with the orbital pattern consistent for different months.

Finally, the average monthly single-difference biases for RapidScat and QuikScat are summarized in Table 4.1 as a separated polarization. In general, biases are higher for vertically-polarized measurements for both instruments. The “Non” label that appears in some rows occurred when the QuikScat was kept at one polarization during that month.

**Table 4.1: Single Difference monthly history for 2015.**

<table>
<thead>
<tr>
<th>Polarization</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>MONTH</td>
<td>RS</td>
<td>QS</td>
</tr>
<tr>
<td>Jan-15</td>
<td>0.18</td>
<td>NON</td>
</tr>
<tr>
<td>Feb-15</td>
<td>0.55</td>
<td>NON</td>
</tr>
<tr>
<td>Mar-15</td>
<td>0.6</td>
<td>0.15</td>
</tr>
<tr>
<td>Apr-15</td>
<td>0.12</td>
<td>-0.08</td>
</tr>
<tr>
<td>May-15</td>
<td>0.26</td>
<td>0.67</td>
</tr>
<tr>
<td>Jun-15</td>
<td>0.7</td>
<td>0.82</td>
</tr>
<tr>
<td>Jul-15</td>
<td>0.63</td>
<td>0.29</td>
</tr>
<tr>
<td>Aug-15</td>
<td>0.26</td>
<td>0.17</td>
</tr>
<tr>
<td>Sep-15</td>
<td>-0.34</td>
<td>-0.16</td>
</tr>
<tr>
<td>Oct-15</td>
<td>-0.15</td>
<td>0.04</td>
</tr>
<tr>
<td>Nov-15</td>
<td>-0.53</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Chapter 5

Calibration Results

5.1 Introduction

This chapter presents the results obtained after deploying the double difference cross-calibration method (described in chapter), which considered to be the first attempt scatterometer measurement validation using this calibration method. The double difference has been applied to the same number of triplet files (RapidScat, QuikScat, and GDAS). The cross-calibration double difference algorithm has been adjusted to meet the requirements of scatterometer cross-calibration. The focus is on quantifying biases between RapidScat and QuikScat instruments.

In addition, all reported results were calculated at a 1° × 1° latitude/longitude grid resolution. To evaluate the impact of different geographical grid resolutions, a study was extended to three different resolutions: (0.125° × 0.125°, 0.25° × 0.25°, and 0.5° × 0.5°). This work had been already published in [8], [28] and [57].
In order to perform the double difference method single difference first must be calculated for each instrument by using GMF to find the modeled $\sigma^0$. Figure 5.1 shows the global monthly $\sigma^0$ averages measured by RapidScat and modeled by NSCAT-2014 GMF. Except for the 2016 data, most of the measured data in 2015 showed good overall average $\sigma^0$ agreement, within a range of ±0.5 dB from the model. In 2016, the observed $\sigma^0$ increased faster than the model, resulting in up to a 2 dB single difference bias.

![Figure 5.1: Comparison of global monthly average RapidScat measurements and model $\sigma^0$.](image)
5.2 Results of Double Difference

Single differences calculated using Equation (3.7) and double difference for both RapidScat and QuikScat are presented in Figure 5.2. For most of the processed dataset, overall agreement between the measurements and model $\sigma^0$ was similar for both sensors. Single differences were mostly within 0.5 dB, both absolutely and relative to each other. However, an increase in $\sigma^0$ measured by RapidScat in 2016 was obvious and grew to around a 2 dB bias in January and February. This bias increase coincided with detected periods of lower SNR that were attributed to the receiver gain fluctuations. A correction was applied in the published data products to compensate for the SNR reduction, but the increased bias between the RapidScat and the QuikScat indicated possible insufficient compensation.

Figure 5.2 also shows the monthly average variations of double differences within 0.5 dB at the beginning of the comparison period, until diverging from August 2015 and approaching the maximum double difference bias of 2 dB in January 2016. The largest discrepancy between the double and RapidScat single difference was recorded in November 2015 at approximately 1.5 dB. Both differences showed a similar trend in the last compared month in March 2016.
Figure 5.2: Monthly average RapidScat/QuikScat single-difference and double-difference.
Double difference distributions for four selected months are included in Figure 5.3a, 5.3b, 5.3c, and 5.3d. Histograms show distributions with a relatively narrow spread around the 0dB double difference mean until widening in February 2016. Distributions resemble Gaussian probability densities with excess peaks.

Moreover, to show the performance of RapidScat for the HH-polarized and VV-polarized measurement separately, it was noticeable that the single difference of RapidScat (SD_RS) biases were higher for vertically-polarized measurements. Monthly averaged (single and double) difference biases are summarized in Table 5.1. The “Non” label that appears in the double difference rows occurred when the QuikScat was kept at one polarization during that month.

The summarizing spread of double difference distributions, and standard deviations of double differences per month are tabulated in Table 5.2. Variations ranged mostly between 2.0–3.5 dB, until increasing to 5.5 dB in March 2016. Trends visible in Figures above and Tables point to a systematic positive bias in RS $\sigma^0$ measurements at the end of the investigation period at the beginning of 2016.
Figure 5.3a: Selected monthly double differences (DD) distributions, March-2015.

Figure 5.3b: Selected monthly double differences (DD) distributions, April-2015.
Figure 5.3c: Selected monthly double differences (DD) distributions, October -2015.

Figure 5.3d Selected monthly double differences (DD) distributions, February-2016.
### Table 5.1: RapidScat single difference and double difference monthly history for horizontal (HH-pol) and vertical (VV-pol) for 2015.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HH-POL</td>
<td>SD -0.18</td>
<td>-0.55</td>
<td>-0.6</td>
<td>-0.12</td>
<td>-0.26</td>
<td>-0.7</td>
<td>-0.63</td>
<td>-0.26</td>
<td>0.34</td>
<td>0.15</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>DD Non</td>
<td>Non</td>
<td>-0.45</td>
<td>-0.2</td>
<td>0.41</td>
<td>0.12</td>
<td>-0.34</td>
<td>-0.09</td>
<td>0.18</td>
<td>0.19</td>
<td>0.86</td>
</tr>
<tr>
<td>VV-POL</td>
<td>SD -0.7</td>
<td>-0.75</td>
<td>-0.79</td>
<td>-0.26</td>
<td>-0.36</td>
<td>-0.77</td>
<td>-0.83</td>
<td>-0.51</td>
<td>0.06</td>
<td>-0.36</td>
<td>-0.21</td>
</tr>
<tr>
<td></td>
<td>DD 0.02</td>
<td>0.06</td>
<td>Non</td>
<td>0.48</td>
<td>-0.11</td>
<td>-0.01</td>
<td>0.11</td>
<td>-0.23</td>
<td>1.11</td>
<td>0.4</td>
<td>Non</td>
</tr>
</tbody>
</table>

### Table 5.2: Monthly standard deviations of double difference (dB).

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0645</td>
<td>2.4209</td>
<td>2.097</td>
<td>3.5033</td>
<td>2.28</td>
<td>2.2547</td>
<td>2.1804</td>
</tr>
<tr>
<td>2.5195</td>
<td>3.677</td>
<td>2.7371</td>
<td>2.0645</td>
<td>3.3369</td>
<td>3.101</td>
<td>5.15</td>
</tr>
<tr>
<td>April 2016</td>
<td>May 2016</td>
<td>June 2016</td>
<td>July 2016</td>
<td>August 2015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.45</td>
<td>4.37</td>
<td>4.69</td>
<td>5.52</td>
<td>3.73</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The monthly bias variations as a comparison of the double and single $\sigma^0$ differences as a function of incidence angle, relative wind direction, latitude, and wind speed are present in the following figures. These cases were selected to show the fluctuations of RapidScat single differences and the double difference. Biases were generally centered around 0 dB mean $\sigma^0$ differences.

Figure 5.4a and 5.4b shows the ability of $\sigma^0$ biases to detect potential bias dependence on the incidence angle for combine beams, inner (45°–52°) and outer (52°–58°). Moreover Figure (5.5a and 5.5d) presents the average $\sigma^0$ biases as a function of the relative wind direction for separated beams, outer and inner. Relative wind direction was defined as the difference between wind direction and antenna azimuth angle. Biases at both polarizations followed the same pattern. The fluctuation in both beams was about ±2 dB.

In addition to the incidence angle and wind direction, stability of the $\sigma^0$ biases, as a function of latitude, was investigated to detect potential bias dependency on the latitude as shown in figure 5.6a and 5.6b. The horizontal axis represents the latitude over the oceans from 55° latitude-south to 55° north, and the vertical axis presents the averaged biases of both beams, outer figure 5.6a and inner figure 5.6b.

The average $\sigma^0$ obtained as the single difference (blue line) was higher than the double difference (red line), with the orbital pattern consistent for different months.
Finally, Figure 5.7a and 5.7b shows the dependence of the $\sigma^o$ bias on the wind speed. Significant biases were calculated for both beams, outer figure 5.7a and inner figure 5.7b. The single difference and the double difference showed remarkable agreement beyond 5 m·s$^{-1}$ wind speed, with biases within 0.5 dB. The instruments at the lowest wind speeds, indicating likely GMF inaccuracies in that range, were below 5 m·s$^{-1}$, with more than 5 dB.

Figure 5.8 summarizes monthly bias variations. For each month, a random selection of bins was chosen to show fluctuations of RapidScat and QuikScat single differences and the double difference per geographical bin. Biases are generally centered around 0dB mean $\sigma^o$ difference but exhibit large outliers in sporadic individual bins.

As indicated in Table 5.1, these graphs show visually a trend of increasing variance in 2016. Comparing the double difference (blue line) with single differences (red and green lines) illustrate effectiveness of the double difference technique to smooth single differences
Figure 5.4a: Comparison of the double and single $\sigma^0$ differences as a function of incidence angle, March 2015.

Figure 5.4b: Comparison of the double and single $\sigma^0$ differences as a function of incidence angle, July 2015.
Figure 5.5a: Comparison of the double and single $\sigma^0$ differences as a function of relative wind direction Outer- VV, March 2015.

Figure 5.5b: Comparison of the double and single $\sigma^0$ differences as a function of relative wind direction Inner-HH, March 2015.
Figure 5.6a: Comparison of the double and single $\sigma^0$ differences as a function of latitude

Outer- VV, June 2015.

Figure 5.6b: Comparison of the double and single $\sigma^0$ differences as a function of latitude Inner-HH, June 2015.
Figure 5.7a: Comparison of the double and single $\sigma^0$ differences as a function of wind speed Outer- VV, June 2015.

Figure 5.7b: Comparison of the double and single $\sigma^0$ differences as a function of wind speed Inner-HH, June 2015.
Figure (5.8) Comparison of double and single $\sigma^o$ differences per some geographical bin.
5.3 Multiple Grid Resolutions

While investigating $\sigma_0$ biases, different gridding resolutions, besides $1^\circ \times 1^\circ$ baseline, were attempted. Reducing resolution to $0.5^\circ$, $0.25^\circ$ and $0.125^\circ$ square pixels, imposes tradeoff between increased accuracy of measured $\sigma_0$ and reduced amount of points for cross-calibration averaging. For these resolutions, GDAS data interpolation is required. Enhanced resolution increases approximately 2.5 times when resolution is increased to $0.125^\circ \times 0.125^\circ$. Figures 5.9 and 5.10 summarize the effect of multiple resolutions on the average $\sigma_0$ bias and standard deviation. The calculations show that the QuikScat bias is higher than the RapidScat by approximately $0.4\text{dB}$ independent of resolution, but overall effect of varying resolution is minimal. Thus, originally chosen $1^\circ \times 1^\circ$ resolution is suitable for the RapidScat/QuikScat cross calibration.

The impact of the geographical grid resolution on monthly average biases was investigated in Figure (5.11). Furthermore, the grid resolution sensitivity may be explained by the tradeoff between the compensating effects of tighter overlap, as well as the lower measurement count per bin. While tight overlap reduced the $\sigma_0$ spread, a lower number of points reduced averaging, resulting in a negligible impact of grid resolution on the final result. Therefore, the computationally fastest coarse resolution of $1^\circ \times 1^\circ$ was adopted to report the double difference statistics.
Figure 5.9: Average $\sigma_0$ bias at different resolutions.

Figure 5.10: Standard deviation of $\sigma_0$ bias at different resolutions.
Figure 5.11: Double difference at multiple grid resolutions.
Finally, in addition to investigating RapidScat bias as a function of individual GMF dimensions (winds speed, relative wind direction, and incidence angle), Figure 5.12a and 5.12b shows the impact of grid resolution on the average σ0 bias as a function of relative wind direction for the inner beam (HH-Pol). For example, biases calculated in July 2015 are compared at nominal 1° x 1° and enhanced 0.125 x 0.125° resolutions. The top panel shows that the fluctuation of biases as a function of relative wind direction in both QuikScat and RapidScat increased after refining the resolution to 0.125° x 0.125°.

Increased contribution of higher spectral components is expected when reducing grid resolution with less averaging. QuikScat experiences much stronger fluctuation increase, due possibly to its limited narrow geometry affecting wind direction diversity. Moreover figure 5.13a and 5.13b represent an example of July 2015 where figure 5.13a is the (1° x 1°) and figure 5.13b is the (0.125° x 0.125°) for the inner beam. The figure shows the impact of grid resolution on the average σ0 bias as a function of wind speed. It can be noticed from the figure the negligible effect of resolution on the bias dependence on wind speed. Even a slight reduction in the magnitude of biases is observed, caused by reduced grid pixel size and smaller standard deviation in a pixel.
Figure 5.12a: Impact of grid resolution on $\sigma^0$ bias as a function of relative wind direction, $1^\circ \times 1^\circ$.

Figure 5.12b: Impact of grid resolution on $\sigma^0$ bias as a function of relative wind direction $0.125^\circ \times 0.125^\circ$. 
Figure 5.13a: Impact of grid resolution on $\sigma^0$ bias as a function of wind speed $1^\circ \times 1^\circ$.

Figure 5.13b: Impact of grid resolution on $\sigma^0$ bias as a function of wind speed $0.125^\circ \times 0.125^\circ$. 
Chapter 6

Conclusions and Future Works

6.1 Conclusions

The intent of this thesis was to demonstrate RapidScat capabilities to serve as a cross-calibration reference for other members of the international scatterometer constellation. Besides fulfilling the primary role to mitigate QuikScat data volume loss after failure of its rotating antenna motors, RapidScat’s partial 2 years data set (2015 and 2016) was used to cross-calibrate two instruments. Precise individual and inter-calibration have been proven by investigating normalized radar cross-section biases relative to a common baseline model.

Biases have been calculated for both RapidScat and QuikScat as a function of (incidence angle, wind speed, and relative wind direction) at both polarizations. Results obtained over two years of observations indicate that most of the measured data in 2015 show overall average $\sigma^0$ agreement. With occasional occurrence of low SNR periods in the RapidScat data, biases increased in 2016 indicating potential insufficient compensation in L2A V1.2 and V1.3 data product.
Furthermore, the double difference technique is applied for the first time for calibrating two satellite scatterometers from NASA: RapidScat and QuikScat. The double-difference methodology, originally derived for radiometers and adjusted for use in scatterometry, is presented. Single and double differences are analyzed through monthly averages, as a coarse but an immediate way to evaluate the long-term consistency of two instruments. Results obtained over 2 years observation period indicate consistency between two instruments in the first year, until the increased $\sigma^0$ divergence coinciding with detection of low SNR periods in Rapidscat data. Such biases can be used to correct $\sigma^0$ measurements and compare retrievals with and without bias relative to the common reference wind field.

In addition to investigating RapidScat bias as a function of individual GMF dimensions (winds speed, relative wind direction, and incidence angle), the impact of the geographical grid resolution on biases was investigated. The comparison of multiple resolutions has shown negligible impact on $\sigma^0$ bias as a function of wind speed and higher impact on bias as a function of relative wind direction. Therefore, the computationally fastest coarse resolution of $1^\circ \times 1^\circ$ was adopted to report the double difference statistics.

Overall, it can be concluded that RapidScat data, especially in the first year of operation, can be readily used for wind retrieval and other science data processing.
Some bias variation has been detected in the range below 6m/s wind speed. Main conclusion may be that the RapidScat satisfies the accuracy requirements by mostly converging to the successful QuikScat predecessor.

6.2 Future Works

- Further planned analyses of the RapidScat data will aim to separate biases as functions of additional variables, such as diurnal position, azimuth, etc.

- The valuable RapidScat measurement set may help estimate the relative validity and stability of other scatterometers that flew simultaneously with sun-synchronous orbits.

- The SNR states of RapidScat can be calibrated separately using the method outlined in this thesis and comparing the result. In addition to the separation of the Ascending and Descending portion of orbits.

- RapidScat land calibration for different targets with different behavior can be evaluated by implementing the method that has been discussed in this dissertation.
• The double difference technique used in this dissertation can be extended to validate and calibrate the normalized radar cross section of other scatterometers.

• Another environmental parameter source could be used instead of the GDAS such as ERA-Interim, which is a global atmospheric reanalysis produced by the European Center for Medium-Range Weather Forecast (ECMWF). Since the GDAS and ERA-Interim datasets are generated using different input datasets and independent models, so their results will be different.

• Estimate the relationship between surface normalized radar cross section and RapidScat Tb bias over the land by performing a cross-correlation analysis.
References


