Chapter 6

Conclusion

6.1 Summary

Three main topics have been studied and discussed in this thesis: the use of the NRCS combined with PRDF measurements from dual polarized SAR stripmap data in a sea surface wind retrieval scheme, the NRCS and Doppler models based on the generalized curvature ocean surface scattering model.

Using dual polarized X-band data, we have explored the potential use of the PRDF in sea surface wind retrieval. Such a task requires two separate GMFs for the NRCS and Doppler centroid estimations, respectively. The GCM-NRCS and GCM-Dop GMFs have been selected in this study, where wind fields are inferred from a series of dual polarized X-band TerraSAR-X images obtained along the Norwegian coast. These wind field estimations are compared with in proximity *in situ* measurements for validation purposes. We find that mean estimated wind speeds from each selected TerraSAR-X scenes agree well with their respective collocated *in situ* measurements. We also note the use of the PRDF helps decrease the number of wind ambiguities down to two. Furthermore, the PRDF helps decrease geometric D_c contribution and possible instrumental Doppler errors.

The backscatter model based on the electromagnetic surface scattering model, first introduced in [Engen et al., 2006], is also revisited. A sea surface spectrum undressing procedure is now being included in the model, as well as a more realistic description of the sea surface. The latter is made possible by including asymmetrical surface waves into the model, which we refer to as a skewness related phase component. Such an approach helps improve the GCM-NRCS GMF performance compared to CMOD5.n GMF, where an up/down-wind asymmetry is now present for all tested wind and radar conditions.

This skewness related phase component is also included in the GCM-Dop, first introduced in [Pedersen et al., 2004], for winds up to 10 m/s. For winds greater than 10 m/s, a wave breaking component is included instead. The performance of this Doppler model is measured against the semi-empirical CDOP GMF for various wind and radar conditions. The model has been found to perform well compared to CDOP, by providing a more realistic Doppler centroid model. Just as with the backscatter model, the GCM-Dop now exhibits up/down-wind asymmetry when either the skewness phase related coefficient or the wave breaking component is included in the model. In certain wind and radar conditions however (e.g. between 7 and 10 m/s wind speed with incidence angle less than 32 degrees), the GCM-Dop overestimates the D_c especially in the up-wind condition. This may indicate that the current version of the skewness phase related coefficient needs further work.

6.2 Future works

While the potential use of the PRDF in SAR sea surface wind retrieval measurements is explored in this thesis, we make the claim that this metric helps reduce significantly possible surface current D_c contribution. Follow-up work could include dedicated SAR data acquisitions over coastal areas exhibiting both surface current and wind field; combined with *in situ* measurements, validation work would either confirm or deny this claim. Furthermore, the PRDF performance in SAR sea surface wind retrieval measurements could be analyzed for different radar operating frequency other than X-band.

At this point, the improved versions of the backscatter and Doppler models have only been tested against semi-empirical GMFs such as CMOD5.n and CDOP, respectively. The next step should include actual sea surface wind retrievals using these two models combined with actual NRCS and D_c measurements from a SAR instrument such as TerraSAR-X, RadarSAT-2, or Sentinel-1. These retrieved measurements could then be compared to *in situ* measurements.

Finally, both backscatter and Doppler models do not have to be tied to the electromagnetic scattering model from [Engen et al., 2006]. It would be interesting to re-derive these models using a different electromagnetic model and measure their respective performance.

Bibliography

[Ainsworth et al., 1995] T. Ainsworth, S. Chubb, R. Fusina, R. M. Goldstein, R. Jansen, J.-S. Lee and G. Valenzuela. *Insar imagery of surface currents, wave fields, and fronts. Geoscience and Remote Sensing, IEEE Transactions on*, **33**(5): 1117–1123, 1995.

[Airy, 1841] G. B. Airy. *Encyclopedia metropolitana (1817-1845)*, chapter Tides and waves, pp. 241–396. London, 1841.

[Alpers and Rufenach, 1979] W. Alpers and C. Rufenach. *The effect of orbital motions on synthetic aperture radar imagery of ocean waves. Antennas and Propagation, IEEE Transactions on*, **27**(5): 685–690, 1979.

[Beckmann and Spizzichino, 1963] P. Beckmann and A. Spizzichino. *The Scattering of Electromagnetic Waves from Rough Surfaces*, volume 4. MacMillan, 1963.

[Bentamy et al., 1999] A. Bentamy, P. Queffeulou, Y. Quilfen and K. Katsaros. *Ocean surface wind fields estimated from satellite active and passive microwave instruments. Geoscience and Remote Sensing, IEEE Transactions on*, **37**(5): 2469–2486, 1999.

[Bergeron et al., 2011] T. Bergeron, M. Bernier, K. Chokmani, A. Lessard-Fontaine, G. Lafrance and P. Beaucage. *Wind speed estimation using polarimetric RADARSAT-2 images: Finding the best polarization and polarization ratio. Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of*, **4**(4): 896 –904, December 2011.

[Chapron et al., 2005] B. Chapron, F. Collard and F. Ardhuin. *Direct measurements of ocean surface velocity from space: interpretation and validation. Journal of Geophysical Research*, **110**(C07008), 2005. Doi:10.1029/2004JC002809.

[Christopher R. Jackson, 2004a] J. R. A. Christopher R. Jackson, ed. *Synthetic Aperture Radar: Marine User's Manual*, chapter Wind Speed and Direction. U.S. Government Printing Office, 2004a.

[Christopher R. Jackson, 2004b] J. R. A. Christopher R. Jackson, ed. *Synthetic Aperture Radar: Marine User's Manual*, chapter Microwave Scattering from the Sea. U.S. Government Printing Office, 2004b.

[Collard et al., 2008] F. Collard, A. A. Mouche, B. Chapron, C. Danilo and J. Johannessen. *Routine high resolution observation of selected major surface currents from space*. In *Proceedings of SEASAR 2008, SP-656*. ESA, ESA - ESRIN, Frascati, Italy, 2008.

[Cumming and Wong, 2005] I. G. Cumming and F. H. Wong. *digital processing of SYNTHETIC APERTURE RADAR DATA*, chapter Doppler Centroid Estimation. ARTECH HOUSE, 2005.

[Elfouhaily et al., 1999] T. Elfouhaily, D. R. Thompson, D. Vandemark and B. Chapron. *A new bistatic model for electromagnetic scattering from perfectly conducting random surfaces*. *Waves in Random Media*, **9**(3): 281–294, 1999.

[Elfouhaily et al., 2001] T. Elfouhaily, D. R. Thompson, D. E. Freund, D. Vandemark and B. Chapron. *A new bistatic model for electromagnetic scattering from perfectly conducting random surfaces: numerical evaluation and comparison with spm*. *Waves in Random Media*, **11**(1): 33–43, 2001.

[Engen et al., 2000] G. Engen, P. W. Vachon, H. Johnsen and F. W. Dobson. *Retrieval of ocean wave spectra and rar mtf's from dual-polarization SAR data*. *IEEE Transactions on Geoscience and Remote Sensing*, **38**(1): 391–403, January 2000.

[Engen et al., 2006] G. Engen, I. Friestad-Pedersen, H. Johnsen and T. Elfouhaily. *Curvature effects in ocean surface scattering*. *IEEE Transactions on Antennas and Propagation*, **54**(5): 1370–1379, May 2006.

[Gohil et al., 2013] B. S. Gohil, R. Sikhakolli and R. Gangwar. *Development of geophysical model functions for oceansat-2 scatterometer*. *Geoscience and Remote Sensing Letters, IEEE*, **10**(2): 377–380, 2013.

[Hersbach, 2010] H. Hersbach. *Comparison of C-Band Scatterometer CMOD5.N Equivalent Neutral Winds with ECMWF*. *Journal of Atmospheric and Oceanic Technology*, **27**: 721–736, 2010.

[Horstmann and Koch, 2005] J. Horstmann and W. Koch. *Measurement of ocean surface winds using synthetic aperture radars*. *Oceanic Engineering, IEEE Journal of*, **30**(3): 508–515, July 2005.

[Johannessen et al., 2005] J. A. Johannessen, V. Kudryavtsev, D. Akimov, T. Eldevik, N. Winther and B. Chapron. *On radar imaging of current features: 2. mesoscale eddy and current front detection*. *Journal of Geophysical Research: Oceans*, **110**(C7): n/a–n/a, 2005.

[Johnsen et al., 2008] H. Johnsen, G. Engen and G. Guitton. *Sea-surface polarization ratio from envisat ASAR AP data*. *IEEE Transactions on Geoscience and Remote Sensing*, **46**(11): 3637–3646, November 2008.

[Jones et al., 1977] W. Jones, L. Schroeder and J. Mitchell. *Aircraft measurements of the microwave scattering signature of the ocean*. *Antennas and Propagation, IEEE Transactions on*, **25**(1): 52–61, 1977.

[Kudryavtsev et al., 2003] V. Kudryavtsev, D. Hauser, G. Caudal and B. Chapron. *A semiempirical model of the normalized radar cross-section of the sea surface*. *Journal of Geophysical Research*, **108**(C3): 8054, 2003.

[Kudryavtsev et al., 2005] V. Kudryavtsev, D. Akimov, J. Johannessen and B. Chapron. *On radar imaging of current features: 1. model and comparison with observations*. *Journal of Geophysical Research: Oceans*, **110**(C7): n/a–n/a, 2005.

[Long, 1995] A. Long. *C-band v-polarized radar sea-echo model from ers-1 haltenbanken campaign*. *Journal of Electromagnetic Waves and Applications*, **9**(3): 373–391, 1995.

[Lungu, 2006] T. Lungu. *QuikSCAT Science Data Product User's Manual: Overview and Geophysical Data Products, version 3.0*. Jet Propulsion Lab., Pasadena, Calif., June 2006.

[Mouche et al., 2005] A. Mouche, D. Hauser, J.-F. Daloze and C. Guérin. *Dual polarization measurements at C-band over the ocean: Results from airborne radar observations and comparison with ENVISAT ASAR data*. *IEEE Transactions on Geoscience and Remote Sensing*, **43**: 753–769, 2005.

[Mouche et al., 2012] A. A. Mouche, F. Collard, B. Chapron, K.-F. Dagestad, G. Guitton, J. A. Johannessen, V. Kerbaol and M. W. Hansen. *On the use of Doppler shift for sea surface wind retrieval from SAR*. *Geoscience and Remote Sensing, IEEE Transactions on*, **50**(7): 2901–2909, July 2012.

[Ocean and SAF, 2011] Ocean and S. I. SAF. *ASCAT Wind Product User Manual*. KNMI, De Bilt, the Nertherlands, August 2011.

[Pedersen et al., 2004] I. F. Pedersen, G. Engen and H. Johnsen. *Polarization dependency in sea surface Doppler frequency and its application to envisat ASAR alt-pol data*. In *Envisat and ERS Symposium*. Norut Information Technology, September 2004.

[Richards, 2005] M. A. Richards. *Fundamentals of Radar Signal Processing*. McGraw-Hill, 2005.

[Romeiser and Thompson, 2000] R. Romeiser and D. R. Thompson. *Numerical study on the along-track interferometric radar imaging mechanism of oceanic surface currents*. *IEEE Transactions on Geoscience and Remote Sensing*, **38**(1): 446–458, 2000.

[Stewart, 1985] R. H. Stewart. *Methods of Satellite Oceanography*, volume 1. 1985.

[Ulaby et al., 1981] F. T. Ulaby, R. K. Moore and A. K. Fung. *Microwave Remote Sensing: Active and Passive Volume I: Microwave Remote Sensing Fundamentals and Radiometry*. Addison-Wesley, 1981.

[Ulaby et al., 1982] F. T. Ulaby, R. K. Moore and A. K. Fung. *Microwave Remote Sensing: Active and Passive Volume II: Radar Remote Sensing and Surface Scattering and Emission Theory*. Addison-Wesley, 1982.

[Wackerman et al., 1996] C. Wackerman, C. Rufenach, R. Shuchman, J. Johannessen and K. Davidson. *Wind vector retrieval using ERS-1 synthetic aperture radar imagery*. *Geoscience and Remote Sensing, IEEE Transactions on*, **34**(6): 1343 –1352, November 1996.

[Wentz and Smith, 1999] F. J. Wentz and D. K. Smith. *A model function for the ocean-normalized radar cross section at 14 ghz derived from nscat observations*. *Journal of Geophysical Research: Oceans*, **104**(C5): 11499–11514, 1999.

[Wentz et al., 1984] F. J. Wentz, S. Peteherych and L. A. Thomas. *A model function for ocean radar cross sections at 14.6 ghz*. *Journal of Geophysical Research: Oceans*, **89**(C3): 3689–3704, 1984.

About the author — *Faozi Said* was born in France but grew up in the beautiful islands of French Polynesia. He first received both his Bachelor and Master of Science in Electrical Engineering from Brigham Young University in Provo, Utah in 2007 and 2009, respectively. He has spent a total of four years working fulltime towards the Ph.D degree, two of them spent in Tromsø, Norway, and the last two years as a guest scientist at Ifremer-Brest, France. He is now living with his family in the United States of America where he works as a support scientist for the Ocean Surface Winds Team (OSWT) of the Center for Satellite Application and Research, at the National Oceanic and Atmospheric Administration (NOAA) in College Park, Maryland.

UiT

THE ARCTIC UNIVERSITY OF NORWAY