*CHAPTER 7*

# CONCLUSIONS AND FUTURE RESEARCH

## 7.1 CONCLUSIONS

The potential of using bistatic scatterometer measurements for estimating crop growth parameters and soil moisture was investigated by the fuzzy inference system in specular direction for the angle of incidence 20° to 60° for different microwave bands and polarizations. The best system parameters for bistatic measurements (i.e., incidence angle, polarization, and frequency band) have been singled out by the correlation analysis. The dominant scattering contribution to bistatic specular scattering coefficients ($\sigma^0$) was analyzed with the crop growth stages at the various angle of incidence. The purpose of these measurements was to find out whether the bistatic radar systems can provide performance in terms of sensitivity to crop parameters and soil moisture. The remote sensing technique is basically based on the accurate interpretation of the interaction mechanism of electromagnetic waves with different features of the Earth's surface. The microwave scattering response of different crops and soil moisture depends on (i) frequency, polarization and angle of incidence of the sensors, (ii) phenological changes (leaf area index, biomass, crop height, crop water content, etc.) of the crops at various growth stages, (iv) dielectric constant and the soil surface parameters. Therefore, the computed specular scattering coefficients ($\sigma°$) at multi-frequencies for different polarizations of crops/soil field were analyzed with measured crop growth parameters and soil moisture for the angular incidence angle ranging from 20° - 60° at various growth stages of the crops and soil moisture. The most important contribution to $\sigma°$ is essentially due to the coherent specular reflection from the soil, which appears to be the dominant component in the scattering process. The scattering coefficients are the key to understand and evaluate the target properties in

microwave remote sensing. By measuring the crop canopy/soil surface scattering from multiple incidence angles, we can better understand how the crop growth parameters and its geometry like shape, size, orientation, density, and dielectric affect the canopy scattering mechanism. The goal of our present work was to study bistatic radar response at multiple measurement angles, multiple frequencies, and polarizations for the estimation of crop growth parameters and soil moisture. In this thesis, we have performed an investigation based on experimental measurements on the bistatic radar measurements for estimating crop growth parameters and soils moisture. The response of $\sigma°$ for each band and polarizations shows very distinct behaviours at different growth stages, which can be used to discriminate the early and later growth stages of the crops. The differences between the HH- and VV-polarization of $\sigma°$ from crop canopy clearly indicate that $\sigma°$ is polarization dependent. These explored investigations of the bistatic scattering characteristics for crops and soil moisture are important in providing reference for crop monitoring, environment change prediction, target detection, and future bistatic radar system design.

The results obtained for the estimation of some crop growth parameters and soil moisture from slightly rough bare soil surface using bistatic scatterometer data and FIS led to the following conclusions:

- The significant temporal and angular variations of $\sigma^0$ for the different crops were observed at different bands and polarizations.
- The contribution to $\sigma°$ is from the direct crop canopy scattering as a dominant component at the higher frequency, whereas ground scattering as a dominant scattering component at the lower frequency.
- The high frequency band found highly correlated with the crop growth parameters as compared to the lower frequency band.

- The temporal trend of $\sigma^0$ was found decreasing with crop growth stage at HH-and VV-polarization, whereas it was found increasing at cross-polarization.
- The crop growth parameters (FBm, LAI, PH, and VWC) of all the crops (rice, wheat, and ladyfinger) showed the increasing trend with the age of the crop.
- The higher sensitivity of $\sigma^0$ for the rice growth parameters was found at 40° incidence angle for HH- polarization at X-band. The estimation of LAI was found better as compared to other crop growth parameters for the optimum value of cluster radius using developed S-FIS algorithm.
- The higher sensitivity of $\sigma^0$ for the wheat crop growth parameters was found at 40° incidence angle for HH- polarization at C-bands. The estimation of FBm was found better as compared to other crop growth parameters for the optimum number of Gauss MF using developed G-FIS algorithm.
- The higher sensitivity of bistatic scattering coefficients for the ladyfinger crop growth parameters was found at 40° incidence angle for VV-polarization at X-band. The estimation of VWC of ladyfinger crop was found better as compared to other crop growth parameters for the optimum value of cluster radius using developed S-ANFIS algorithm.
- The higher sensitivity of *P (dB*) for the soil moisture from a slightly rough bare soil surface was found at 50° incidence angle. The gbell MF based G-ANFIS was found better estimator among the three MF (gbell, Gauss, tri) followed by Gauss and tri for the estimation of soil moisture from slightly rough bare soil surfaces using bistatic scatterometer data.
- The RMSE values between observed and estimated values showed that the performance of the FIS was improved by using the FIS combined with ANN.

## 7.2 FUTURE RESEARCH

The next era of microwave remote sensing will be based on bistatic or multi-dimensional sensors using air-borne and space-borne platforms. This is necessary to increase the knowledge of microwave signature. The following topics will be considered in the future to improve further the understanding of bistatic microwave signature and some advanced computational techniques for monitoring the crops and soil moisture using bistatic radar remote sensing:

- The bistatic measurement of an object is also important to make the observation in elevation and azimuthal directions.
- The measurement should be repeated several times for the same target may increase the degree of confidence for the accurate acquisition of information about the target.
- The use of various polarizations and frequencies would provide a better degree of confidence in announcing the results globally.
- The experimental outcomes should be explained by the theoretical and or empirical models. The statistical analysis to analyze the results obtained by experimental and theoretical models may be useful to evaluate the potentiality of the application of computational techniques in the field of agriculture and hydrology.
- The other fast computational algorithms should be developed for accurate discrimination of healthy and stressed crops at different growth stages and estimation of soil moisture to classify wet and dry fields for the better management of drought and flood monitoring using bistatic radar remote sensing.