

# MONITORING OF CROP GROWTH AND SOIL MOISTURE RETRIEVAL USING MULTI-SENSOR SATELLITE DATA



Thesis submitted in partial fulfillment for the  
Award of Degree of  
**Doctor of Philosophy**

By  
*Pradeep Kumar*

DEPARTMENT OF PHYSICS  
INDIAN INSTITUTE OF TECHNOLOGY  
(BANARAS HINDU UNIVERSITY)  
VARANASI - 221005

Roll No. 12610EN001

2017



भारतीय  
प्रौद्योगिकी  
संस्थान  
काशी हिन्दू विश्वविद्यालय



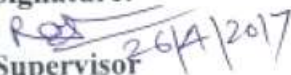
INDIAN  
INSTITUTE OF  
TECHNOLOGY  
BANARAS HINDU UNIVERSITY

## CERTIFICATE

It is certified that the work contained in the thesis titled "*MONITORING OF CROP GROWTH AND SOIL MOISTURE RETRIEVAL USING MULTI-SENSOR SATELLITE DATA*" by "*PRADEEP KUMAR*" has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

Signature:

  
Supervisor

Rajendra Prasad

(Professor)

Department of Physics

Indian Institute of Technology

(Banaras Hindu University)

Varanasi (U.P.) - 221005

Professor

Department of Physics

Indian Institute of Technology

(Banaras Hindu University)

Varanasi-221005



भारतीय  
प्रौद्योगिकी  
संस्थान

काशी हिन्दू विश्वविद्यालय



INDIAN  
INSTITUTE OF  
TECHNOLOGY  
BANARAS HINDU UNIVERSITY

---

## COPYRIGHT TRANSFER CERTIFICATE

**Title of the Thesis:** Monitoring of crop growth and soil moisture retrieval using multi-sensor satellite data

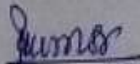
**Name of the Student:** Pradeep Kumar

### Copyright Transfer

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the "*DOCTOR OF PHILOSOPHY*".

Date: 26.04.2017

Place: IIT BHU, VARANASI

  
Signature of the Student  
(*PRADEEP KUMAR*)

**Note:** However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

## ACKNOWLEDGEMENT

I express my sincere gratitude and indebtedness to my supervisor Prof. Rajendra Prasad, Department of Physics, Indian Institute of Technology (Banaras Hindu University), Varanasi for his valuable guidance, encouragement and help throughout the tenure of research work. I am extremely grateful to him for his keen interest in the investigation and the academic help. In course of time, he motivated, inspired and extended the necessary academic help in carrying out my research work. In spite of his busy schedule, he participated in each minute details of my progress of work and shared my pleasures and anxieties as well on the research findings.

I am grateful to my RPEC members Prof. O. N. Singh, Department of Physics and Prof. P. K. S. Dikshit, Department of Civil Engineering, Indian Institute of Technology (Banaras Hindu University) for their guidance. In the entire research tenure, their valuable discussions and encouragement helped this journey to a fruitful end.

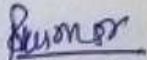
I am immensely rejoiced to owe my deep sense of gratitude to Prof. B. N. Dwivedi, Prof. D. Giri, Prof. P. Singh, Prof. S. Chatterjee, Dr. A. Mohan, Dr. P. C. Pandey, Dr. S. Upadhyay, Dr. U. N. Singh, Dr. A. K. Srivastava, Dr. S. K. Mishra, Dr. S. Mishra, Dr. S. K. Singh, Dr. S. Patil, Dr. P. Dutta, Dr. S. Tripathi, Dr. A. S. Parmar, Dr. R. Singh, Dr. A. K. Tripathi, Dr. N. Agnihotri, Department of Physics, Prof. S. B. Dwivedi, Prof. R. Kumar, Dr. A. Ohri, Department of Civil Engineering, Dr. R. S. Singh, Department of Computer Science and Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi, Dr. P. K. Srivastava, Institute of Environment and Sustainable Development (Banaras Hindu University), Varanasi, Dr. S. K. Singh, K. Banerjee Centre of Atmospheric and Ocean Studies, IIDS Nehru Science Centre, University of Allahabad, D. R. Avtar, Centre of Environmental Science, University of Allahabad for their constant encouragement during research work.

I am thankful to all non-teaching staff members of the Department of Physics for their kind cooperation and inspiration. I wish to express my deep gratitude to all those who have extended their helping hands in various ways during my tenure at Indian Institute of Technology (Banaras Hindu University), Varanasi, India. I am very thankful to my friends D. K. Gupta, V. N. Mishra, A. K. Vishwakarma, R. Bala, V. P. Yadav, Md. J. Ansaree etc. for providing company during the Ph. D. research work.

I am specially very much grateful to my parents (Shyamlal and Krishnawati) and pay endless thanks to my wife (Dr. Arti Choudhary), brothers (Shrawan Kumar, Ravi Kumar and Arbind Kumar), sisters (Suman Lata, Manju Lata and Rani Devi), sister-in-laws (Pushpa, Arti and Preeti), nephews and nieces whose love and blessings encouraged me a lot.

Date: 26.04.2017

Place: IIT (BHU), Varanasi

  
Pradeep Kumar

**DEDICATED  
TO  
MY PARENTS  
&  
WIFE**

## TABLE OF CONTENTS

CERTIFICATE	iii
DECLARATION BY THE CANDIDATE	v
COPY RIGHT TRANSFER CERTIFICATE	vii
ACKNOWLEDGEMENT	ix
TABLE OF CONTENTS	xiii
LIST OF FIGURES	xix
LIST OF TABLES	xxiii
LIST OF ABBREVIATIONS	xxv
LIST OF SYMBOLES	xxvii
PREFACE	xxix
CHAPTER 1 INTRODUCTION	1-24
1.1 REMOTE SENSING AN OVERVIEW	1
1.1.1 Passive remote sensing	2
1.1.2 Active remote sensing	3
1.2 ELECTROMAGNETIC WAVES USED IN THE REMOTE SENSING	4
1.3 SPECTRAL REFLECTANCE AND EARTH SURFACE INTERACTION	5
1. 4 RESOLUTIONS IN THE REMOTE SENSING	6
1.4.1 Spatial resolution	6
1.4.2 Spectral resolution	6
1.4.3 Radiometric resolution	7
1.4.4 Temporal resolution	7
1.5 ATMOSHPERIC EFFECT AND ITS CORRECTION	7
1.6 NEED OF CROP GROWTH MONITORING	8
1.7 CROP GROWTH MONITORING	8
1.7.1 Crop classification and mapping	8
1.7.2 Crop growth parameters estimation	9
1.8 THE ROLE OF REMOTE SENSING IN CROP GROWTH MONITORING	10
1.8.1 Role of optical remote sensing	10
1.8.2 Role of microwave remote sensing	10

1.9 NEED OF SOIL MOISTURE RETRIEVAL	11
1.10 SOIL MOISTURE RETRIEVAL	12
1.11 THE ROLE OF REMOTE SENSING IN SOIL MOISTURE RETRIEVAL	12
1.12 LITERATURE REVIEW	13
1.13 MOTIVATION	22
1.14 ORGANIZATION OF THE THESIS	23
<b>CHAPTER 2 STATISTICAL SIGNIFICANCE IN THE CROP CLASSIFICATION ACCURACY USING DIFFERENT ALGORITHMS</b>	<b>25-46</b>
2.1 INTRODUCTION	25
2.2 STUDY AREA AND MATERIALS	28
2.3 METHODOLOGY	29
2.3.1 Image pre-processing and data preparation	29
2.3.2 Spectral separability	30
2.3.3 Support vector machines based classification	31
2.3.4 Maximum likelihood based classification	33
2.3.5 Normalized difference vegetation index based classification	34
2.3.6 Classification accuracy	35
2.3.7 Statistical significance of classifiers performance	36
2.4 RESULTS AND DISCUSSION	37
2.4.1 Assessment of classification accuracies using different algorithms	37
2.4.2 Test for statistical significance in the classification accuracy	44
2.5 CONCLUSION	46
<b>CHAPTER 3 PERFORMANCE ANALYSIS OF SUPERVISED ALGORITHMS FOR THE LAND FEATURES CLASSIFICATION</b>	<b>47-72</b>
3.1 INTRODUCTION	47
3.2 DESCRIPTION OF THE STUDY AREA AND MATERIALS	50
3.3 METHODOLOGY	51
3.3.1 Image processing of satellite data	51
3.3.2 Image pre-processing	51
3.3.3 Separability analysis	52
3.3.4 Image classification	54



3.3.5 Selected measures	57
3.4 Statistical significance of classification accuracy by Z-test	58
3.5 RESULTS AND DISCUSSION	59
3.5.1 Support vector machines based summary of classification accuracy	62
3.5.2 Artificial neural network based summary of classification accuracy	65
3.5.3 Random forest based summary of classification accuracy	67
3.5.4 Post-processing summary of classification accuracy	68
3.5.5 Analyses of statistical significance in the classification accuracy between two algorithms	70
3.6 CONCLUSION	73-86
<b>CHAPTER 4 ARTIFICIAL NEURAL NETWORK WITH DIFFERENT LEARNING PARAMETERS FOR CROP CLASSIFICATION USING MULTI-SENSOR SATELLITE DATA</b>	
4.1 INTRODUCTION	73
<b>PART A</b>	<b>74-82</b>
4.2 DESCRIPTION OF THE STUDY AREA	74
4.3 MATERIALS AND METHODOLOGY	74
4.3.1 Ground reference data collection	75
4.3.2 Remotely sensed data collection	75
4.3.3 Image processing of remotely sensed data	76
4.3.4 Creation of region of interest files	76
4.3.5 Image classification	77
4.4 RESULTS AND DISCUSSION	81
4.5 CONCLUSION	<b>82-85</b>
<b>PART B</b>	
4.6 STUDY AREA AND DATA-SETS	83
4.7 METHODOLOGY	83
4.7.1 Image processing	83
4.7.2 Separability analysis	83
4.7.3 Artificial neural network based Classification	84
4.8 RESULTS AND DISCUSSION	

4.9 CONCLUSION	85
<b>CHAPTER 5 ESTIMATION OF WINTER WHEAT CROP GROWTH PARAMETERS USING SENTINEL-1A SAR DATA</b>	<b>87-108</b>
5.1 INTRODUCTION	87
5.2 WINTER WHEAT CROP GROWTH STAGES	90
5.3 MATERIALS AND METHODOLOGY	91
5.3.1 Study area	91
5.3.2 Measurements of winter wheat crop growth parameters	92
5.3.3 Satellite data collection and processing	93
5.3.4 Random forest regression algorithm	93
5.3.5 Support vector regression algorithm	94
5.3.6 Artificial neural network regression algorithm	95
5.3.7 Linear regression algorithm	95
5.3.8 Validation	96
5.4 RESULTS AND DISCUSSION	96
5.5 CONCLUSION	107
<b>CHAPTER 6 ESTIMATION OF CORN CROP GROWTH PARAMETERS BY WATER CLOUD MODEL USING SAR DATA</b>	<b>109-116</b>
6.1 INTRODUCTION	109
6.2 MATERIALS AND METHODOLOGY	110
6.2.1 Corn crop growth stages	110
6.2.2 Leaf area index measurements	111
6.2.3 Satellite data collection and processing	111
6.2.4 Water cloud model	112
6.2.5 Estimation of crop growth parameters	113
6.3 RESULTS AND DISCUSSION	114
6.4 CONCLUSION	116
<b>CHAPTER 7 COMPREHENSIVE EVALUATION OF SOIL MOISTURE RETRIEVAL MODELS UNDER DIFFERENT CROP COVER TYPES USING SENTINEL-1A DATA</b>	<b>117-136</b>
7.1 INTRODUCTION	117
7.2 MATERIALS AND METHODOLOGY	119
7.2.1 Ground soil samples collection	119

7.2.2 SAR data collection and processing	121
7.2.3 Random forest regression model	121
7.2.4 Support vector regression model	122
7.2.5 Artificial neural network regression model	123
7.2.6 Performance indicators	123
<b>7.3 RESULTS AND DISCUSSION</b>	<b>124</b>
7.3.1 Retrieval of wheat crop covered soil moisture using RFR, SVR and ANNR models	125
7.3.2 Retrieval of barley crop covered soil moisture using RFR, SVR and ANNR models	128
7.3.3 Retrieval of corn crop covered soil moisture using RFR, SVR and ANNR models	131
7.4 CONCLUSION	135
<b>CHAPTER 8 SUMMARY AND CONCLUSIONS</b>	<b>137-140</b>
8.1 SCOPE FOR FURTHER WORK	139
<b>REFERENCES</b>	<b>141</b>
<b>LIST OF PUBLICATIONS</b>	<b>161</b>

0  
0  
1  
1  
2  
3  
4  
6  
36

17

## LIST OF FIGURES

1.1	Data acquisition by the passive remote sensing process	2
1.2	Data acquisition by the active remote sensing process	3
1.3	Electromagnetic waves used in the remote sensing	4
1.4	Spectral reflectance curves for soil, vegetation and water	5
2.1	The location map of study area with false colour composite (FCC) image of LISS-IV sensor	29
2.2	(a) SVMs with linear kernel (b) SVMs with polynomial of degree 2 (c) SVMs with polynomial degree 3 (d) SVMs with polynomial degree 4 (e) SVMs with polynomial degree 5 (f) SVMs with polynomial degree 6 classification maps	39
2.3	(a) SVMs with radial basis kernel (b) SVMs with sigmoid kernel (c) ML classification (d) NDVI classification maps	40
3.1	Flow-chart of methodology	51
3.2	The structure of a three-layer ANN	55
3.3	Representation of training pixels in 2D space between bands 3 and 4	60
3.4	(a) SVMs with linear kernel (b) SVMs with polynomial of degree 2 kernel (c) SVMs with radial basis kernel (d) SVMs with sigmoid function kernel based classification	62
3.5	ANN based classification	66
3.6	RF based classification	67
4.1	(a) Study area using LISS-IV data and (b) using Landsat 8-OLI data	74
4.2	Overall classification accuracies produced for different configurations of the learning rate (first value), momentum term (second value) and RMSE (last value) using LISS-IV data	79
4.3	Overall classification accuracies produced for different configurations of the learning rate (first value), momentum term (second value) and RMSE (last value) using Landsat 8-OLI data	80
4.4	Location map of the study area using RISAT-1 data (Red-HV, Green-HH, Blue-HH)	82
5.1	Winter wheat crop growth stages: (a) tillering; (b) jointing; (c) booting; (d) heading; and (e) ripening	90
5.2	The study area using Sentinel-1A satellite image at VV polarization	91
5.3	Average square error rates against number of trees in training and testing data in the implementation of LAI estimation	98
5.4	Average square error rates against number of trees in training and testing data in the implementation of VWC estimation	98

5.5	Average square error rates against number of trees in training and testing data in the implementation of FB estimation	99
5.6	Average square error rates against number of trees in training and testing data in the implementation of DB estimation	99
5.7	Average square error rates against number of trees in training and testing data in the implementation of PH estimation	100
5.8	Scatter plots of observed and estimated LAI values for winter wheat crop by RFR, SVR, ANNR and LR algorithms	101
5.9	Scatter plots of observed and estimated VWC values for winter wheat crop by RFR, SVR, ANNR and LR algorithms	102
5.10	Scatter plots of observed and estimated FB values for winter wheat crop by RFR, SVR, ANNR and LR algorithms	103
5.11	Scatter plots of observed and estimated DB values for winter wheat crop by RFR, SVR, ANNR and LR algorithms	105
5.12	Scatter plots of observed and estimated PH values for winter wheat crop by RFR, SVR, ANNR and LR algorithms	106
6.1	Different growth stages of the corn crop	110
6.2	Comparison between observed and modelled leaf area index at VV polarization	114
6.3	Comparison between observed and modelled leaf water area index at VV polarization	115
7.1	Study area using Sentinel-1A satellite image at VH polarization	120
7.2	Average square error against number of trees in training and testing data for the soil moisture retrieval covered by wheat crop at VV polarization	125
7.3	Average square error against number of trees in training and testing data for the soil moisture retrieval covered by wheat crop at VH polarization	126
7.4	Scatter plots of observed and retrieved soil moisture covered by wheat crop using RFR, SVR and ANNR models at VV polarization	126
7.5	Scatter plots of observed and retrieved soil moisture covered by wheat crop using RFR, SVR and ANNR models at VH polarization	127
7.6	Average square error against number of trees in training and testing data for the soil moisture retrieval covered by barley crop at VV polarization	129
7.7	Average square error against number of trees in training and testing data for the soil moisture retrieval covered by barley crop at VH polarization	129
7.8	Scatter plots of observed and retrieved soil moisture covered by barley crop using RFR, SVR and ANNR models at VV polarization	130

7.9	Scatter plots of observed and retrieved soil moisture covered by barley crop using RFR, SVR and ANNR models at VH polarization	130
7.10	Average square error against number of trees in training and testing data for the soil moisture retrieval covered by corn crop at VV polarization	132
7.11	Average square error against number of trees in training and testing data for the soil moisture retrieval covered by corn crop at VH polarization	132
7.12	Scatter plots of observed and retrieved soil moisture covered by corn crop using RFR, SVR and ANNR models at VV polarization	133
7.13	Scatter plots of observed and retrieved soil moisture covered by corn crop using RFR, SVR and ANNR models at VH polarization	134

## LIST OF TABLES

2.1	Specification of LISS-IV sensor	29
2.2	Training and validation data-sets used for the classification	30
2.3	Cross tabulation of number of correctly and wrongly classified pixels for two algorithms	37
2.4	Separability analysis between different crop and non-crop classes using <i>J-M</i> distance method	38
2.5	Accuracy measures by SVMs with linear kernel and polynomial kernel of degrees 2 to 6	41
2.6	Accuracy achieved by SVMs with radial basis and sigmoid kernels, ML and NDVI classification algorithms	42
2.7	Statistical significance of differences in classification accuracy between two different algorithms	45
3.1	Training and testing pixels used in the classification	52
3.2	Number of correctly and wrongly classified pixels for the two algorithms	59
3.3	Separability analysis between diverse crop and non-crop classes using <i>TD</i> method	61
3.4	Separability analysis between diverse crop and non-crop classes using <i>J-M</i> distance method	61
3.5	Selected measures (SVMs with linear kernel)	63
3.6	Selected measures (SVMs with polynomial kernel)	63
3.7	Selected measures (SVMs with radial basis kernel)	64
3.8	Selected measures (SVMs with sigmoid kernel)	65
3.9	Selected measures (ANN based classification)	66
3.10	Selected measures (RF based classification)	68
3.11	Classification algorithms <i>OA</i> , $\kappa$ results before and after post processing steps	69
3.12	Statistical significance in the accuracy between two different algorithms by Z-test	70
4.1	Training and testing data-sets used for the classification study by different satellite imagery	76
4.2	Error matrix produced by ANN using RISAT-1 data-sets	85
5.1	Sentinel-1A SAR satellite data specification	93
5.2	Summary of the ground collected data for the winter wheat crop growth parameters	97
5.3	Summary of the results in the adj. $R^2$ and RMSE using RFR, SVR, ANNR and LR algorithms	104
6.1	Sentinel-1A satellite data features	112

7.1	Specification of Sentinel-1A SAR satellite data	121
7.2	Retrieval of soil moisture covered by wheat crop using RFR, SVR and ANNR models at VV and VH polarizations	128
7.3	Retrieval of soil moisture covered by barley crop using RFR, SVR and ANNR models at VV and VH polarizations	131
7.4	Retrieval of soil moisture covered by corn crop using RFR, SVR and ANNR models at VV and VH polarizations	135



## LIST OF ABBREVIATIONS

Syntax	Description
NIR	Near- infrared
SAR	Synthetic Aperture Radar
TIR	Thermal infrared
IR	Infrared
LiDAR	Light Detection and Ranging
SWIR	Short wave infrared
MWIR	Mid wave infrared
LWIR	Long wave infrared
FIR	Far infrared
LISS	Linear Imaging Self-Scanner
CSI	Classification Success Index
JCC	Jaccard's Coefficient of community
OLI	Operational Land Imager
RISAT-1	Radar Imaging Satellite-1
VWC	Vegetation water content
PH	Plant height
LAI	Leaf area index
SVM	Support vector machine
ANN	Artificial neural network
RF	Random forest
ML	Maximum likelihood
DT	Decision tree
TM	Thematic Mapper
MODIS	Moderate Resolution Imaging Spectroradiometer
AVHRR	Advanced Very High Resolution Radiometer
LWAI	Leaf water area index
RTM	Radiative transfer models
WCM	Water cloud model
RFR	Random forest regression