

Solar Radiation Assessment and Forecasting Over India in the Presence of Dust and Fog Activity

A Thesis

Submitted
by

YASHWANT KASHYAP (D12079)

For the award of the degree of

Doctor of Philosophy



**SCHOOL OF ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MANDI
Mandi-175005, Himachal Pradesh, India**

January, 2017

Dedicated to
Lord Shri Krishna

Declaration by the Research Scholar

I hereby declare that the entire work embodied in this thesis entitled “**Solar Radiation Assessment and Forecasting Over India in the Presence of Dust and Fog Activity**” is the result of investigations carried out by me in the **School of Engineering**, Indian Institute of Technology Mandi, under the supervision of **Dr Anil K Sao** and **Dr Ankit Bansal** for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work carried out by me and that it has not been submitted elsewhere for any degree or diploma. In keeping with the general practice, due acknowledgements have been made wherever the work described based on a finding of other investigators.

Yashwant Kashyap
Enrollment No.: D12079
School of Engineering
Indian Institute of Technology Mandi
Mandi (India)-175005

Place: Mandi

Date: 23 January 2017

Thesis Certificate

I hereby certify that the entire work in this thesis titled “Solar Radiation Assessment and Forecasting Over India in the Presence of Dust and Fog Activity” has been carried out by Yashwant Kashyap, under my supervision in the School of Engineering, Indian Institute of Technology Mandi for the award of the degree Doctor of Philosophy. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr Anil K Sao
Associate Professor
School of Computing and Electrical
Engineering
Indian Institute of Technology Mandi
Mandi, (India)-175005

Place: Mandi

Date: ___ January 2017

Dr Ankit Bansal
Assistant Professor
Mechanical and Industrial Engineering
Indian Institute of Technology Roorkee
Roorkee, (India)-247667

Place: Roorkee

Date: ___ January 2017

Acknowledgements

At the outset, I would like to express my gratitude to research supervisors Dr Anil K. Sao and Dr Ankit Bansal for their supervision, advice, and guidance. Thankful to them for providing computational and other facilities at IIT Mandi and IIT Roorkee. It were Dr Anil and Dr Ankit who discovered my aptitude for research early on and put in the necessary effort to groom and help to deliver the best. Everything that I am today, I owe to their meticulous support and counselling. They helped, not only with academics but also through all walks of my life. Their energetic persona, interesting discussions, and charismatic charm have always inspired me to excel. Always had their support and encouragement whenever needed. Also largely benefited from their scientific intuition, vast knowledge of the subject and wealth of experience. Forever indebted to them for everything I am today and for whatever I will achieve in my time to come. It has been a pleasure working with them.

I would like to extend my thanks to the faculty at IIT Mandi Dr Ramesh Orunganti, Dr Bharat Singh Rajpurohit, Dr Rahul Vaish, Dr Manoj Thakur, and Dr Sarita Azad for their teaching, guidance and necessary help to progress with my research.

I also wish to acknowledge the members of my doctoral committee for their critical appraise of my research and annual progress. My obligations to Dr Vishal Singh Chauhan, Dr Rajeev Kumar, Dr Sarita Azad and Dr P Anil Kishan for valuable time and consideration and impartial judgments of my research work.

I am pleased to acknowledge the support and encouragement of Dr Anette Hammer from Carl von Ossietzky University Oldenburg, Germany for her help and support in various collaborative research topics. Further, special thanks to D.D.G.M. of SAT-MET division of Indian Meteorological Department (IMD), New Delhi for their support of data.

I wish to express gratitude for the support I received from administration at IIT Mandi for making my trip to Singapore and Germany a great success. It was one of the best moments of my life, made possible thanks to their effort and help.

I would also like to thank my colleague-cum-friends for their unwavering help as and when I needed. Special goes to Dr Satyanarayan Patel, Mr Himmat Singh Kushwaha, Mr Manoj Dhiman, Mr Ankit Sharma and Mr Shesh Dhurandar.

I would like to acknowledge the help and cooperation of the School staff Miss Gunjan Kapoor, Mrs Nidhi Sehgal and Mrs Mamta in carrying out my research.

I always had a stream of constant support at my disposal, all thanks to my friends Nilesh, Vijay, Lalaram, Gopinath, Devender, Shashi Bhushan, Pawan, Punit, Anmol, Srikanth, Ajay, Naresh, and Tushar. You people were a source of constant optimism and fun.

I was extraordinarily fortunate in having Verma Sir, Saxena Sir and Subramanian Sir as my teachers. I could never have embarked and started all of this without their prior teachings and without which I would not have reached this stage.

Where would I be without my family? Words are not enough to express the gratitude that I feel towards my family. I thank you grandmother, for being proud and supportive of my choices in life. I would like to thank my parents for having always stood beside me and for their blessings. Also, thank you for not marrying me off in a hurry that would have been a serious inconvenience. I thank my Sister Mrs Bharti and brother-in-law Mr Rajiv, Uncle Mr Purushotam and Aunt Mrs Padma, and my relatives for their deep affection, constant support, and encouragement.

Finally, I would like to thank everybody who was important to the successful realisation of the thesis, as well as expressing my apology that I could not mention personally one by one.

Yashwant Kashyap

January 2017

Table of Contents

DECLARATION BY THE RESEARCH SCHOLAR	I
THESIS CERTIFICATE	II
ACKNOWLEDGEMENTS.....	III
TABLE OF CONTENTS.....	V
LIST OF FIGURES	VIII
LIST OF TABLES	X
NOMENCLATURE	XI
ABBREVIATION.....	XIV
Chapter 1: Introduction.....	1
1.1 Fundamentals of Solar Energy.....	2
1.1.1 Direct, Diffuse and Global Radiation.....	3
1.1.2 Effect of Atmosphere on GHI.....	4
1.1.3 Clearness Index.....	5
1.1.4 Solar Variability.....	6
1.2 Solar Radiation Data:.....	6
1.3 GHI Assessment Models:	8
1.4 Clear SKY Models.....	9
1.5 Forecasting Models:.....	10
1.6 Data Assimilation.....	13
1.7 Thesis Contribution.....	13
Chapter 2: Parameter Estimation for ARMA Time Series Model	16
2.1 Parameter Estimation	18
2.1.1 Recursive Least Square Method.....	18
2.1.2 Kalman Filter (KF).....	18
2.2 Evaluation criteria.....	19
2.3 Results and discussion	20
2.4 Conclusions.....	22
Chapter 3: Forecasting with Artificial Neural Networks	24
3.1 Theoretical background of ANN	25

3.2	Results and discussions.....	28
3.3	Enhanced ANN Model With Spatial GHI Data.....	32
3.4	Conclusion	34
Chapter 4:	Tracking Clouds Using Computer Vision Techniques and Data	
	assimilation	35
4.1	Data.....	36
4.2	Methodology.....	36
4.3	Results and discussions.....	40
4.4	Conclusions.....	43
Chapter 5:	GHI Estimation Model in Presence of Dust, Fog and Clouds.....	44
5.1	Data.....	44
5.1.1	<i>Satellite Data</i>	<i>44</i>
5.1.2	<i>Ground Data.....</i>	<i>45</i>
5.2	Methodology.....	46
5.2.1	<i>The HELIOSAT model</i>	<i>46</i>
5.2.2	<i>Pre-processing spectral band data from satellite.....</i>	<i>47</i>
5.2.3	<i>Image Segmentation with k-Mean Clustering.....</i>	<i>48</i>
5.2.4	<i>All-Day Index (ADI).....</i>	<i>53</i>
5.2.5	<i>Estimation of GHI.....</i>	<i>54</i>
5.2.6	<i>GHI assimilation with Kalman filter.....</i>	<i>55</i>
5.3	Result and discussion.....	56
5.4	Conclusion	60
Chapter 6:	GHI Forecasting in the Presence of Dust, Fog and Cloud	61
6.1	Methodology.....	62
6.1.1	<i>Wavelet Transform Based Image Segmentation</i>	<i>62</i>
6.1.2	<i>Tracking All-Day Index with Kalman Filter.....</i>	<i>63</i>
6.1.3	<i>Hybrid Model to Improve Forecast Accuracy</i>	<i>64</i>
6.1.4	<i>Artificial Neural Network Approach.....</i>	<i>65</i>
6.1.5	<i>Extended Kalman Filter Approach:.....</i>	<i>65</i>
6.2	Result and discussion.....	67
6.3	Conclusion	72
Chapter 7:	Conclusions and Future Work.....	73
	List of Publications Based on the Thesis	74
	References.....	75

