Neural Network Applications to Solve Forward and Inverse Problems in Atmospheric and Oceanic Satellite Remote Sensing

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List of Acronyms

BT – Brightness Temperature  
DAS – Data Assimilation System  
FM – Forward Model  
MLP – Multi-Layer Perceptron  
NWP – Numerical Weather Prediction  
PB – Physically Based  
RMSE – Root Mean Square Error  
RS – Remote Sensing  
SSM/I – Special Sensor Microwave Imager  
SST – Sea Surface Temperature  
TF – Transfer Function

9.1 Introduction

Here we discuss two very important practical applications of the neural network (NN) technique: solution of forward and inverse problems in atmospheric and oceanic satellite remote sensing (RS). A particular example of this type of NN applications – solving the SAR wind speed retrieval problem – is also presented in Chapter 10 by G. Yung. These applications and those that we discuss in Chapter 11, from the mathematical point of view, belong to the broad class of applications called approximation of mappings. A particular type of the NN, a Multi-Layer Perceptron (MLP) NN (Rumelhart et al. 1986) is usually employed to approximate mappings. We will start by introducing a remote sensing, mapping, and NN background.

9.1.1 Remote Sensing Background

Estimating high quality geophysical parameters (information about the physical, chemical, and biological properties of the oceans, atmosphere, and land surface) from remote measurements (satellite, aircraft, etc.) is a very important problem in fields such as meteorology, oceanography, climatology and environmental modeling and prediction. Direct measurements of many parameters of interest, like vegetation moisture, phytoplankton concentrations in the ocean, and aerosol concentrations in the atmosphere are, in general, not available for the entire globe at the required spatial and temporal resolution. Even when in situ measurements are available, they are usually sparse (especially over the oceans) and located mainly at ground level or at the ocean surface. Often such measurements can be estimated indirectly from the influence of these geophysical parameters on the electromagnetic radiation measured by a remote sensor. Remote measurements allow us to obtain spatially dense measurements all over the globe at and above the level of the ground and ocean surface.

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Satellite RS data are used in a wide variety of applications and by a wide variety of users. Satellite sensors generate measurements like radiances, backscatter coefficients, brightness temperatures, etc. The applications usually utilize geophysical parameters such as pressure, temperature, wind speed and direction, water vapor concentration, etc. derived from satellite data. Satellite forward models, which simulate satellite measurements from given geophysical parameters, and retrieval algorithms, which transform satellite measurements into geophysical parameters, play the role of mediators between satellite sensors and applications. There exists an entire spectrum of different approaches in extracting geophysical information from the satellite measurements. At one end of this spectrum ‘satellite only’ approaches are located; we will call them standard or traditional retrievals. They use measurements performed by one particular sensor only, sometimes from different channels (frequencies, polarizations, etc.) of the same sensor to estimate geophysical parameters. Variational retrieval techniques or direct assimilation techniques are located at the other end of the spectrum. They use an entire data assimilation system (DAS), including a numerical weather prediction (NWP) model and analysis (Prigent et al. 1997), which in turn includes all kind of meteorological measurements (buoys, radiosondes, ships, aircrafts, etc.) as well as data from numerous satellite sensors. Data assimilation is a method in which observations of the current (and possibly, past) state of a system (atmosphere and/or ocean) are combined with the results from a numerical model to produce an analysis, which is considered as ‘the best’ estimate of the current state of the system. The analysis can be used for many purposes including initialization of the next step of the numerical model integration. Many approaches have been developed which belong to the intermediate part of this spectrum. These approaches use measurements from several satellite sensors, combine satellite measurements with other kinds of measurements, and/or use background fields or profiles from NWP models for regularization of the inverse problem (retrievals) or for ambiguity removal, i.e., these approaches use some type of data fusion to regularize (see Sections 9.1.2 and 9.4 below) the solution of the inverse problem.

It is noteworthy that over the last few years, direct assimilation of some geophysical parameters into modern DASs has been successfully developed and implemented. It improved the quality of assimilated products and numerical forecasts that use some of these products as initial conditions. Direct assimilation replaces or eliminates the need for using retrievals of these geophysical parameters in DASs. However, there are still many other geophysical parameters (e.g., precipitations, atmospheric ice) that have not yet been included, or it is not clear from both theoretical and/or practical considerations how they could be included into DASs through direct assimilation. There are also other users of the retrieved geophysical parameters. Therefore, there is still an urgent need to use the standard retrievals for these geophysical parameters and to develop the corresponding retrieval algorithms to which the NN technique could be efficiently applied. Direct assimilation is discussed below at the end of this subsection in the description of variational retrieval techniques.

The remote measurements themselves are usually very accurate. The quality of geophysical parameters derived from these measurements varies significantly depending on the strength and uniqueness of the signal from the geophysical parameter and the mathematical methods applied to extract the parameter, i.e., to solve RS forward and/or inverse problems (see Section 9.2). The NN technique is a useful mathematical tool for solving the forward and inverse problems in RS accurately. The number of NN RS applications has been increasing steadily over the last decade.

A broad class of NN applications has been developed for solving the forward and inverse problems in RS in order to infer geophysical parameters from satellite data, i.e., to produce so-called satellite retrievals. A brief review of RS NN applications was presented by Atkinson and Tatnall (1997). Examples of such applications follow. The NN technique was applied for the inversion of a multiple scattering model to estimate snow parameters from passive microwave measurements (Tsang et al. 1992). Smith (1993) used NNs for the inversion of a simple two-stream radiative transfer model to derive the leaf area index from Moderate Resolution Imaging Spectrometer data. In other studies, NNs were applied to simulate scatterometer measurements and to retrieve wind speed and direction from these measurements (Thiria et al. 1993; Cornford et al. 2001); to develop an inversion algorithm for radar scattering from vegetation canopies (Pierce et al. 1994); to estimate atmospheric humidity profiles (Cabrera-Mercader and Staelin 1995), atmospheric