1.1 Prelude to the Study
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Introduction

Introductory chapter-1 is dealing with background to the study, remote sensing aspects of ocean colour, objectives of the study and organization of chapters in the thesis.

1.1 Prelude to the Study

Oceans play a vital role in various climatic processes of the Earth System. One of the key elements of the climatic processes and oceanic eco-system is surface phytoplanktons that can be detected by ocean colour remote sensing. A large number of ocean colour missions are presently collecting valuable data sets on the bio-geo-chemical parameters from space. The role of oceans in global carbon cycle is to be understood with the help of optical radiometers onboard the Earth orbiting satellites. These instruments can estimate the oceanic absorption of CO₂ by means of light-photosynthesis models. Ocean colour data has many other important applications for marine resources management in coastal and open ocean waters. Application of ocean colour data for exploration of fisheries resources have proved very cost effective and currently being used by a large number of fishermen.

Oceans occupy a vast part of the Earth's surface and economy of mankind is intimately associated with the oceans. Living resources like fisheries, non-living resources like petroleum, transport and even climate change are dependent on the ocean. The use of space-borne remote sensing for the detection of ocean colour has come to be widely accepted over the past two and a half decades. This is caused by the ever-growing need for information on oceanic bio-productivity. It also helps to observe on a synoptic scale the biological features of ocean gyre systems, oceanic fronts, meso-scale eddies and shelf-ocean boundaries. Ocean colour yields information on the constituents of seawater, such as the concentration of phytoplankton pigments, suspended sediments and yellow substance.

The methods of detecting and mapping seawater constituents from space-borne platforms have been successfully developed during the past three decades (Arvensen et al. 1973, Clarke et al. 1970). Routine monitoring of the regional and temporal variability of
ocean chlorophyll provides information on primary production and subsequent assessment of secondary production processes such as marine fisheries. Ocean colour information on a global scale is also of importance in studying the bio-geo-chemical cycles of carbon, nitrogen and sulfur. Satellites are wonderful tools for looking at very large areas of the world in a very short time as they provide synoptic coverage. The first exclusive sensor called Coastal Zone Colour Scanner (CZCS) launched in 1978 demonstrated utility of ocean colour data for various studies related to ocean biology. CZCS data have also provided information on suspended sediments, fronts, algal patchiness and ocean circulation in some areas.

The colour of ocean is not just blue. The colour of the ocean is determined by the interaction of incident light with substances or particulates present in the water. The most significant constituents are phytoplanktons, suspended sediments and inorganic particulate matter. Chlorophyll-a is a living pigment in the phytoplanktons and is having specific signatures since it absorbs in the blue and the red regions and reemits in the red region of the visible spectrum. Inorganic Particulate matter has light scattering characteristics. Substances dissolved in water mainly absorb light at shorter wavelengths.

Suspended sediments are inorganic particulate matter in seawater. Major sources of suspended sediments are from river discharge and resuspension of bottom sediments. Back scattering by suspended matter provides higher reflectance and are prominent in coastal regions. Yellow substance (Gelbstoff) are humic and fulvic acids coming from land runoff and transported to sea by rivers. A fraction of these are also generated by decomposition of marine organisms.

The scientific understanding of the biological oceanography is not only important from the angle of ocean productivity and bio-geo-chemical cycling but also due to its impact on the oceanic CO$_2$ and flux of carbon from surface to deep ocean. Phytoplanktons, which convert the inorganic compounds in the presence of nutrients, into organic compounds through photosynthesis are the main producers in the upper ocean. This is the basis of ocean food chain and understanding the ocean primary production is important for the study of carbon cycle. Data from Coastal Zone Colour Scanner (CZCS), which
operated from 1978 to 1986, have been used in numerous studies to describe patterns of chlorophyll concentration, primary production and diffuse attenuation coefficients (Austin 1981; Sathyendranath et al 1989).

The productivity due to plankton of the ocean biosphere is principally supported by the primary production of micro plants, which grow rapidly compared to terrestrial plants. Although there is no direct way to measure the plankton productivity from spaceborne data, it can be estimated from chlorophyll-a concentration using both remotely sensed data and in-situ data. In order to calculate the algal biomass in the oceanic upper layers, it is important to develop accurate algorithms to process the raw ocean colour data. A sophisticated atmospheric correction procedure, which can correct the space-borne measurements of oceanic reflectance from the effects of intervening atmosphere, is a fundamental requirement to retrieve ocean colour parameters such as chlorophyll-a, suspended sediments and diffuse attenuation coefficients (K - parameter).

The introduction of photoelectric cells for marine observations (Shelford and Gail, 1922) revolutionized optical technique. In the 1930's much pioneering work was done on the design and use of radiance and irradiance meters (Atkins and Poole, 1933, Clarke, 1933, Utterback and Boyle, 1933, Petersson and Landberg, 1934; Jerlov and Liljequest, 1938, Takenouti, 1940 and Whitney, 1941). Peterson (1934) also devised the first examples of in-situ beam transmittance and scattering meters. Kalle (1938) obtained important results on the significance of soluble yellow matter for the transmission of light and for the colour of the sea. The study of particle distribution in the deep sea by means of scattering meter is based on his original method. There is an important paper by Le Grand (1939), which presents an analysis of methods employed in underwater optics with deductions of fundamental laws. Since 1955, introduction of photomultiplier tubes and interference filters changed the situation of measurements of penetration of light in offshore waters.

The diffuse attenuation coefficient is one of the optical properties of sea, which is very important from the physical, biological and climatic points of view. In fact, ocean colour remote sensing is basically characterized by optical aspects of the ocean and the
branch is considered as optical oceanography. Underwater optics has wide applications in oceanography and related fields and attracts growing attention to the possibility of characterizing water types by means of their optical properties. Ocean optics is important for the study of ocean colour. The progress of optical oceanography has been intimately connected with the evolution of instrumental techniques for underwater optics. For the earliest measurements, only photographic methods were available. The initial study of radiant energy dates back to 1885 when Fol and Sarasin exposed photographic plates in Mediterranean off the Cote d’ Ezur (Jerlov, 1976). Knudsen (1922) used a submerged spectrograph together with a photographic recording method and successfully measured spectral radiance at different levels in the sea.

The vertical diffuse attenuation coefficient is an apparent optical property of water, which is varying from one water type to other water type. Indirectly it is a measure of penetration of light field in water. The diffuse attenuation coefficient of oceanic water is a property that is inferred from the ocean color satellite data. It has been used by Jerlov (1976) and Smith and Baker (1978b) to classify ocean waters. The diffuse attenuation coefficient is of significance to a variety of problems associated with the penetration of natural light into the ocean and is also an important variable in evaluating propagation of artificial light in seawater for various optical, communication and surveillance systems. The knowledge of the optical attenuation within upper ocean water column is also useful to understand the heating of the upper ocean, which occurs through the absorption of solar irradiance (400- 800 nm). Approximately half of the solar irradiance occurs in the visible and infrared region of electromagnetic spectrum, and most of this is absorbed and converted into heat within the first few centimeters of the upper ocean (Mobely, 1994). The SeaWiFS derived global $K(490)$ maps have been used by Rochford et al. (2001) for the calculation of solar subsurface heating for the prediction of sea surface temperature (SST) and mixed layer depth (MLD) using ocean general circulation models. More recently SeaWiFS project of NASA has been providing the diffuse attenuation coefficient at 490 nm, $K(490)$, as one of the standard ocean data products. SeaWiFS uses a revised $K(490)$ algorithm based on the work of Mueller and Trees (1996). These relationships have been shown to be robust (in Case 1 and Case 2 waters) if accurate water leaving radiances
can be derived from satellite ocean color data (McClain et al. 2000a). In primary productivity models K-parameters can be used as one of the inputs for the model.

The Indian mission for ocean colour remote sensing started from IRS-P3 satellite and is being continued by IRS-P4 satellite. IRS-P3 satellite was launched successfully by the Polar Satellite Launch Vehicle (PSLV) on March 21st, 1996 from Sriharikota, India. It carried onboard, three remote sensing payloads: Modular Opto-electronic Scanner (MOS), Wide Field Sensor (WiFS) and X-ray astronomy payload. The MOS payload comprises of MOS-A, MOS-B & MOS-C modules. The MOS-B module of the MOS payload has been designed to study ocean-atmospheric system and in particular ocean colour related properties. The module MOS-B comprises of thirteen narrow channels ranging from 400 to 1010nm and has a swath of 200km and a relatively high radiometric resolution of 16 bit with 10nm spectral band-width. The details of IRS-P3 MOS-B technical characteristics are available in Mohan et. al. (1998). MOS-A, B, C payloads, developed at DLR, Germany, were characterized by unique features such as narrow spectral bands, high radiometric resolution (16 bit quantization), and optimum wavelength selection for atmospheric and ocean colour applications.

The IRS-P4 satellite (also known as Oceansat-2), launched on May 26, 1999 by Indian Space Research Organization (ISRO), carried two oceanographic payloads i.e. Ocean Colour Monitor (OCM) and Microwave Scanning Multi-frequency Radiometer (MSMR). The first payload OCM is designed to measure ocean colour, the spectral variation of water leaving radiance that can be related to concentration of phytoplankton pigments, suspended matter and coloured dissolved organic matter in coastal and oceanic waters, and the characterization of atmospheric aerosols.

1.2 Relevance of Ocean Colour Remote Sensing

The ocean colour remote sensing from space has started since the launch of first ocean colour sensor in 1978 on board Coastal Zone Colour Scanner (CZCS). A large number of ocean colour missions are presently collecting valuable data sets providing the biogeochemical parameters from space. The relevance of ocean colour remote sensing is
very well understood. Ocean has a large climatic impact on our earth’s atmosphere. The role of ocean in global carbon cycle can be understood with the help of ocean colour sensors. One of the vital importances of ocean colour remote sensing is its usefulness in the study of primary productivity of oceans.

Primary Production (PP) from space is in the exploratory stage. Most of the current PP algorithms are based on the biomass of phytoplanktons (as estimated from satellite derived chlorophyll) and an expected physiological response of phytoplankton to light (in-situ P-I algorithms). Platt’s (1990) non-spectral photosynthesis irradiance model has been used to estimate mixed layer production in Arabian Sea during winter monsoon and NE monsoon of 1999-2000 period using IRS-P4 OCM data. Synoptic coverage offered by OCM was quite useful in studying the extent and the patchy distribution of Primary Productivity. Primary productivity models are being used in fishery forecasts. India having a long coastal line has high potential for marine fisheries development. Marine resources will increasingly need to meet food requirements. Most of the oceanographic features observed on satellite images like the areas of upwelling, eddies, fronts, meanders etc are known to be highly productive. These processes help in vertical mixing and transport of nutrients in a given region. Ocean colour discriminates even those water masses, which are non-distinguishable from surface thermal signatures, such as frontal signatures. Time series of chlorophyll images enables detection of developing or decaying stages of the frontal structures. This is important since increasing trend of chlorophyll (with other parameters likes SST, nutrients etc) is useful for fishery. Colour gradients provide column information and reveal subsurface picture of water circulation and productivity. Therefore they can be detected during summer. So use of visible and thermal infrared data offer more exhaustive information on dynamic processes of ocean relative to fish occurrence. Using chlorophyll or suspended sediment as a tracer, patterns related to eddies, upwelling, frontal dynamics, gyres etc can be delineated in the ocean. Using multi date images advective velocity can be obtained.

Ocean biology is important not only for understanding ocean primary productivity and bio-geochemical cycling but also because of its impact on oceanic CO₂ from the surface to deep-ocean. Oceans have a fundamental role in the global climate system, through oceanic
carbon cycle. Phytoplanktons transform CO\textsubscript{2} into sugars and other simple organic 
molecules and release oxygen and use nitrogen, phosphorous etc. to produce proteins. Thus 
they play key role in the global geochemical cycle of carbon critical to marine and 
terrestrial life. The estimation of primary production of ocean is a major requirement in 
understanding global biogeochemical cycle, including the exchange of critical elements 
and gases between atmosphere and ocean. Along with the altimeter data, ocean colour data 
can be used for large-scale ocean circulation patterns for understanding the coupling 
between physical and biological patterns of variability. Frequent fields of diffuse 
attenuation coefficients are likely to find their use in large-scale physical and biological 
models for calculating upper ocean heat budget (Hooker et. al. 1992).

Phytoplankton forms a base in the marine food chain and its abundance can be 
indirectly associated with aggregation of fish for assessment of fish stock. Synoptic 
estimation of chlorophyll is important to understand the variability of food resources in 
space and time. The time of beginning of phytoplankton production, peak and decline 
show great fluctuations. This is of great importance to all animals, which directly or 
indirectly rely on phytoplankton for food. Chlorophyll-\textalpha measurements are used for 
assessing the distribution of phytoplanktons. Ocean colour from space provides a measure 
of the areas of enhanced biological production that occur at the fronts, eddies, upwelling 
zones, certain topographic structures, etc. where the zooplankton and fish populations are 
known to accumulate for feeding. SST explains oceanic environment suitable for enhanced 
production. The use of both parameters would explain the oceanic environment and food 
resource availability in an ecosystem for exploring fishery resources.

Blooms of plant origin are known to occur under various conditions in the 
nearshore regions. These may take place, often with cyclical regularity in any particular 
area. Some of the planktons produce certain toxins, which have an adverse effect on the 
marine life there by causing mass mortality or migration of fish. Besides, phytoplankton 
 bloom plays an important role in fixation of nitrogen and affects marine resources. One 
such bloom due to cyanobacteria was detected, east of Australia and estimate was made for 
nitrogen fixation (Dupouy et. al. 1988). The bloom usually takes place rather suddenly and 
may spread with amazing speed. During certain periods, phytoplankton blooms of some
species occur which turn water colour green, red, yellow or pink according to the pigmentation of the organisms concerned in the coastal waters. This modifies the optical properties of water thus enabling the detection of blooms through remote sensing.

The detection, monitoring and forecasting of harmful algal blooms are also requirements of ocean colour remote sensing. Much of the flux of carbon from surface to deep sea occurs as a result of specific types of phytoplanktons. One issue concerns the optical signals contributed by Coloured Dissolved Organic Matter (CDOM) that contaminates the plankton signal observed from satellites. It is also essential to calibrate different ocean colour sensors to ensure compatibility of results.

As phytoplankton concentration in the bloom-affected area is much higher than what is normally observed even during the productive season, separate algorithms need to be developed for detection and assessment of the intensity of the blooms in these areas. It is necessary to investigate timing and duration of phytoplankton blooms and to track the movements and persistence of ocean features to understand dynamic processes.

Quantitative analysis of Sea Surface Temperatures (SST) and chlorophyll improve our understanding of the circulation and distribution of water masses. Solanki et al. (1998) used a clustering technique in which unsupervised classification was applied to these data to classify different water masses and to understand the relationship between the satellite derived SST and ocean colour. An inverse correlation between the two parameters was observed in coastal areas (Solanki et al. 1998). The relationship was not significant between these parameters in gulf and offshore waters.

The infrared sensors can detect radiation emitted from the sea surface only, hence it provide surface information on temperature distribution. The ocean colour sensor has the ability to visualise the marine structure originated from surface to one-attenuation depth. Hence the colour sensor can distinguish the water masses based on the different column production. The chlorophyll frontal position coincides with temperature boundaries. This indicates that the physical and biochemical processes are closely coupled at these locations. The co-existence of colour and temperature features with some horizontal

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displacement and with some difference in fine morphology of the features may be due to cross frontal diffusion or difference in the observation time.

The surface wind induced oceanic upwelling and chlorophyll concentrations are directly related to each other. The OCM derived chlorophyll concentrations also provide useful information on upwelling processes. Upwelling occurs in the regions of divergence in the open ocean and along the coasts where the net transport is directed offshore. Low oxygen, but nutrient rich and relatively cooler subsurface water is thus brought to the surface in these regions. Upwelling plays an important role in the replenishment of nutrients in the surface waters, which in turn helps to assess/predict the coastal fishery resources. During the southwest monsoon, upwelling of considerable magnitude has been reported in the Arabian Sea (Muraleedharan et. al., 1996). The need to understand the temporal variation and intensity of upwelling along the coast and the process that triggers the phenomenon is important.

Fronts play important role in dynamic and chemical processes in the sea as they may be associated with strong transverse gradients of salinity, temperature, velocity and density. The features detected using satellite data include wave refraction, foam or debris. It is now possible to recognize mesoscale processes using ocean colour features. The information about their location and movement is useful to understand various oceanographic phenomena.

Land ocean interaction in coastal zone require information on temporal and spatial development of plankton blooms, primary production including determination of euphotic depth, the Photosynthetic Available Radiation (PAR), transport of dissolved organic material from rivers to sea, erosion, transport and sedimentation of suspended matter. Aerosols and thin cirrus clouds including contrails are important not only because of their masking effect for water surfaces but also because of their impact on the atmospheric radiation and energy budget. Coastal areas require special attention on algorithms and in situ procedures in order to separate the contribution by the different water constituents to the water leaving radiance spectrum. Optical in situ measurements along with space-borne data are required to carry out these studies.
1.3 Objectives of the Study

In the above segment the relevance of ocean colour remote sensing has been given in detail, the present thesis emphasizes on optical aspects of ocean colour remote sensing. The scattering and absorption are inherent optical properties of seawater whereas diffuse attenuation coefficient is an apparent optical property. In the present thesis diffuse attenuation coefficient at 490 nm (K-490) has been studied in detail for North Eastern Arabian Sea (off Gujarat, Maharashtra and Goa coast) and Bay of Bengal (around Sagar Island, off Gopalpur coast, Orissa and around Visakhapatnam, extending upto Godavari river delta, off Andhra coast). As diffuse attenuation coefficient is a measure of water clarity and penetration of light field into water, it is having a large impact on primary productivity as well as on the climatic processes. The thesis is focused on the spectral diffuse attenuation coefficient at 490 nm. The main objectives of the study are:

1. To develop a model to retrieve the diffuse attenuation coefficient at 490nm
2. To validate the above model (K-490) using in-situ data.
3. Optical classification of water on the basis of K-490 parameter

Though the Indian satellite sensor IRS-P4 OCM has been used for generating K-490 maps but this technique can be used for routine generation of K-490 map from any other satellite’s optical data. The inverse of K-490 is $Z_{90}$ (i.e. first optical attenuation depth) and it is the index of water clarity. Variation of K-490 in different months can be attributed to the absorption of light in various seasons. It has been shown clearly that in bloom conditions water type of high attenuation coefficient exists in the study area. K is being used as one of the parameters for ocean general circulation models (OGCM) to calculate the subsurface heating (Rochford et al., 2001), and is also being used as one of the inputs in primary productivity.

Major applications of K-490 are in the field of

- Propagation of natural and artificial light into seawater
- Physical oceanography
- Biological oceanography and
- Climate modeling
1.4 Organization of the Thesis

The present thesis has been divided into six chapters.

Introductory chapter-1 deals with background to the study, remote sensing aspects of ocean colour with relevance to ocean colour remote sensing, objectives of the study and the organization of chapters in the thesis.

Chapter-2 deals with the review of literature throwing light on physical basis of ocean colour remote sensing, basics of remote sensing and status of ocean colour. Later in this chapter, optical aspects of ocean colour have been discussed in detail. Geometry of inherent optical properties (scattering and attenuation) has been discussed as these are fundamental optical quantities and further apparent optical properties (spectral hemispherical reflectance and spectral remote sensing reflectance) have also been discussed. Since bio-optical properties of ocean is the sum of bio-optical properties of pure seawater, phytoplanktons, suspended sediments and combined dissolved organic matter, so the optical properties i.e. scattering and absorption spectra (some sample profiles) of these constituents have been discussed in detail in the last section of this chapter.

Chapter-3 deals with the methodology of the algorithm development for the retrieval of diffuse attenuation coefficient at 490nm using in-situ data. Satlantic underwater radiometer has been used for collection of in-situ data. It measures downwelling irradiance and upwelling radiance in seven visible and near infrared regions as well as it collects other optical and ancillary parameters like temperature and chlorophyll at different depths. In-situ measurement techniques and measurement profiles have been discussed with details of Satlantic underwater radiometer. Effect of ship-shadow on the in-water radiance measurements has also been discussed.

Chapter-4 describes spectral diffuse attenuation coefficient at 490 nm (K-490). The study area has been defined in this chapter, which includes
A: North Eastern Arabian Sea;
B: Bay of Bengal,
B1: around Sagar Island, off Gopalpur coast, Orissa and
B2: around Visakhapatnam, extending up to Godavari river delta, off Andhra coast.

Then the K-490 algorithm has been developed using the data from 110 observation points within the study area. It has been validated further taking 41 stations with independent in-situ ship-borne data collected during Sagar Kanya cruise (SK-186).

Chapter-5 deals with the optical classification of seawater using K-490 parameter. At first the Ocean Colour Monitor (OCM) data acquired over alternate days is used to prepare monthly composites of K-490 parameter for the year 2000. Then the Jerlov’s method of classification is discussed in detail and the same is used to classify the open ocean water into three water types (Type-I, Type-II and Type-III). Then the results of classification of the monthly composites are grouped into four seasons:

- Winter Monsoon (December- March)
- Inter-monsoon (April- May)
- Summer Monsoon (June-September)
- Inter-monsoon (October-November)

Finally the intra seasonal variability of the K-490 parameter is discussed for the year 2000 over the study area.

Chapter-6 gives the summary of the work done and the conclusions of the study with a brief description of the future scope of research in this field. At first, the salient features of the work are discussed. The research findings suggest that the spectral diffuse attenuation coefficient at 490 nm can be routinely derived for the study area using the algorithm presented in chapter-4 and this derived parameter can be further used for water classification and for other scientific analyses such as those related to primary productivity, subsurface heating etc.