Chapter 8:
Discussions and Conclusions

The ever increasing concentration of atmospheric carbon dioxide (CO_2), its strong influence on climate change and global warming and high vulnerability to human activities have recognized it as a significant man-made greenhouse gas and have raised awareness on CO_2 monitoring during the past few decades. The modern CO_2 sensors, either ground-based or air/satellite-borne, are based on spectroscopic detection of the gaseous concentration related to its characteristic molecular absorption features at specific wavelengths of the solar radiation spectra. In this connection, the hyperspectral remote sensing technique, more popularly known as 'imaging spectroscopy' has grown immense importance.

The present work has conducted investigations on the assessment of atmospheric CO_2 applying hyperspectral remote sensing techniques with the use of all the above three types of data, namely ground measured, retrieved from airborne hyperspectral images and derived from satellite-borne hyperspectral database. Analyses are made from different points of view, in particular at global level, at local level and explicitly in the Indian context. Both the atmospheric column average and the surface level CO_2 concentrations are taken into consideration. The spatial as well as the temporal variations of the column concentration are explored.

In a nutshell, this work has attempted to address all the facets of the present CO_2 scenario and its correlations with human activities. In addition to CO_2, considering the urban aerosol is a factor closely associated with man-made changes, this work has been attentive to urban aerosols also through determination of the optical depth from hyperspectral images and observation of the temporal variation along with that of CO_2. The summary of the work is given in Chapter 1 and a precise review on the related studies is given in Chapter 2. The original work is illustrated through chapters 3 to 7. As conclusive remarks, the following parts of the work are highlighted and discussed.

8.1. Spectral Calibration of CO_2 Absorption Features

Though the radiation absorption by CO_2 is a known phenomenon, the present work realized the importance of re-investigating and calibrating the same in the light of high spectral resolution for a tropical atmosphere like that of India where the large changes in temperature, pressure and atmospheric water vapour may cause some changes in the absorption features. Such work has seldom been carried out. Also, the new findings, if any, should be validated with high resolution remotely sensed data.

Keeping the above in mind, the present work has compared the CO_2 absorption profiles on the solar radiance spectra obtained from ground spectroscopy and those retrieved from the hyperspectral images of *Airborne Visible/Infrared Imaging Spectrometer Next Generation* (AVIRIS-NG) sensor and *Hyperion* space-borne sensor. The water vapour (H_2O) absorption was found to significantly affect the CO_2 absorption profile. Two different methods are suggested for the correct retrieval of the CO_2 absorption feature (Chapter 3).

One is a modification of the conventional simulation and fitting technique. The other is an absolutely new approach where the terrestrial solar radiance spectra obtained from AVIRIS-NG containing the H_2O absorption are compared with the solar radiance spectra obtained at the atmosphere of planet Mars, which is largely comprised of CO_2 at very low pressure and H_2O being negligible. Thus, using the Martian spectra as a 'natural laboratory', the present work demonstrates with MODTRAN6 atmospheric simulation code that the spectral absorption profile changes gradually from 'Earth-like' to 'Mars-like' with the change in atmospheric composition. Based on this finding, a methodology is suggested for the proper retrieval of CO_2 absorption information using the ratio of two consecutive absorption depths.

Application of similar methodology is hoped to explore more findings in planetary remote sensing and identify comparative features of terrestrial atmosphere illuminated by the same solar radiation.

8.2. New Techniques for CO_2, Aerosol and H_2O Retrievals

This work put forward a new technique (Chapter 3), named as *a*-DOAS for estimating the atmospheric column average of CO_2. This is a modified version of differential optical absorption spectroscopy based on the principle of linear summation of weighted average of the radiance values at absorbing and non-absorbing wavebands. This method has the advantage of being simple and dependent mostly on experimental parameters. It is a generalized process depending on the solar radiation absorption by a trace gas at a certain wavelength. So, it is expected that a similar algorithm may be adopted to the assessment of other greenhouse gases, such as methane. Not only that, another potential benefit of the technique may be realized in the following way.

If one thinks from the point of view of fundamental physics, the actual phenomenon of radiation absorption should take place at sub-nanometer level. If that is to be detected experimentally, the spectroscopy too should be executed with a resolution of sub-nanometer level. And that is to be achieved not in the laboratory but up above the sky. Achieving such ultra-spectral measurement from space is not impossible today. Indeed, the dedicated sensors, such as Orbiting Carbon Observatory-2 & 3 (OCO-2 & 3) manufactured exclusively for CO_2 detection actually do so but at the cost of spatial resolution. This point has been discussed further in Chapter 4. The general purpose moderate resolution imaging spectrometers, such as AVIRIS-NG and Hyperion used in the present work can trace only an average absorption profile of CO_2 or other trace gas. In contrast, these sensors have greater importance in regard to the imaging of the whole earth with much better spatial resolution. These have the potential of detecting the local natural (e.g., volcanic eruption) or man-made (e.g., nuclear power plants) changes of CO_2 and other greenhouse gas concentration. Also, the images procured by such sensors are multipurpose and of various applications. So, developing a methodology for the retrieval of CO_2 column average with reasonable accuracy using such sensors is of prime importance.

Along with CO_2 assessment, the present work has propounded two more innovations. A methodology is suggested for assessing the spatial distribution of atmospheric H_2O, an important agent of tropical atmosphere like that of India and is validated with AVIRIS-NG images (Chapter 4). Also, a new technique is developed for estimating the relative changes of aerosol optical depth from the strong absorption band of atmospheric oxygen (Chapter 5). While validating the method with hyperspectral space-borne images of Hyperion for urban areas, the depth is found to be more pronounced at places of dense population and more urban congestion. These two studies provide scopes for further extension in future.

8.3. Spatial Variation and Point Source of CO_2

The spatial distributions of the atmospheric column average of CO_2 are estimated from high spatial resolution AVIRIS-NG images (Chapter 4), applying the *a*-DOAS technique (Chapter 3), for different parts of India having different extents of natural and anthropogenic features, such as vegetation, sea and urban congestion. Wide variations of CO_2 are noted depending on the sequestering agents, such as vegetation and the neighbouring sea. However, when the same small regions are accommodated to the coarser resolution global CO_2 sensor OCO-2, the diversified conditions of natural and man-made features in each region gets mixed up with the surrounding features in connection with emission and sequestration and a resultant overall uniformity of CO_2 column average is obtained all the way. The deep sea regions surrounding India, supposed to be free from human activities are expected to yield lower values of CO_2 but that does not occur in practice.

The above results indicate both hopeful and apprehensive conclusions. An equilibrium of CO_2 emission and sequestration is revealed in Indian environment, which is cross-checked with the long term average variation of CO_2 over Indian atmosphere obtained from open data sources. Maintenance of a reasonably steady state in the atmospheric CO_2 enhancement in India is certainly a benefit and that may be ascribed to the extensive vegetated regions distributed throughout the country. In contrast, it is apprehended that the slow marine sequestration of CO_2 is not sufficient to meet the increase at global level. These findings are to be pondered over in future.

It is demonstrated (Chapter 4) that the global CO_2 sensors like OCO-2, by dint of less spatial resolution may overlook local point sources of CO_2, such as a coal field. These are not convenient to distinguish the local atmospheric changes from the general urban enhancements. This work develops a technique for detecting point sources of CO_2 from high spatial resolution, hyperspectral images of AVIRIS-NG and validates it with the spatial CO_2 distributions obtained at a coalfield area that is likely to contain larger amount of CO_2.

This opens the scope for an independent study in future. Adopting a similar methodology with hyperspectral sensors on board more adjustable platforms, such as drones can be a suitable tool for detecting the local changes of atmospheric CO_2 due to human activities. The database built up with a series of such imaging and proper networking of the database (similar to those existing with aerosols) can develop an Internet of things for smart monitoring of local CO_2 variations.

8.4. Seasonal CO_2 Change

The annual variation of atmospheric CO_2 exhibits a well-known periodic increase and decrease and a supposed-to-be accepted explanation is the seasonal variation of the growth of terrestrial vegetation that causes CO_2 uptake. Nevertheless, this topic has become a subject of renewed interest due to many interesting reports on CO_2 changes, such as semiannual fluctuation, climate variability, atmospheric turbulences and others, which are not in conformity with the concept of vegetation alone. Also, the actual trend of the periodicity is not well defined.

Considering the above findings, the present work has investigated the seasonal periodicity of CO_2 in both time and frequency domains and explored the links between CO_2 and atmospheric pressure and temperature. The problem is addressed with a combination of ground-based spectroradiometric measurements and open source satellite data of OCO-2 and NASA-Giovanni. The vegetation parameters, namely solar-induced chlorophyll fluorescence of chlorophyll and normalized difference vegetation index are also included in the analysis. A mathematical model is developed for interpreting the seasonal change in terms of vertical redistribution of CO_2 molecules under changed temperature and pressure.

It is established that the vertical rearrangement of air-mixed CO_2 molecules due to the seasonal alterations of surface temperature and atmospheric pressure can cause an apparent change in the radiation absorption path through the atmosphere resulting in a change in the spectroscopic assessment of the gas concentration. This is hoped to be a useful climate model for interpreting the CO_2 concentration at an arbitrary altitude under the changed conditions of temperature and pressure.

8.5. CO_2 in Indian and Global Contexts

As reviewed in Chapter 2 and mentioned in Chapter 4, the atmospheric CO_2 assessment in India has some special significances. It is a large and highly populated country with high fossil fuel demand responsible to the emission and diversified environments with sequestration potential. Also, the tropical atmosphere contains highly varying quantity of water vapour that can partly mask the radiation absorption feature of CO_2. In regard of these features, the spatial and temporal variations of CO_2 in India has been studied from different angles by

- conducting field work of surface level CO_2 measurement and spectroradiometric assessment of the average CO_2 throughout the atmospheric column,
- analyzing the airborne hyperspectral images and open source satellite data and
- taking into account the spectral standardization, the seasonal and spatial variations and the long term temporal changes.

The work intended to retrieve the seasonal change of CO_2 from the open source database of Orbiting Carbon Observatory-3 (OCO-3), the latest space-borne global CO_2 sensor projected by the National Aeronautics and Space Administration (NASA). It is a subsequent version of its predecessor Orbiting Carbon Observatory-2 (OCO-2) with some distinctions in the construction and novelties in the data procuring techniques. However, the sudden, unpredicted global lockdown and restricted fossil fuel burning situation arising of the COVID-19 pandemic has changed the original plan.

The global closure period that has caused remarkable reduction in the surface level CO_2 emission overlaps with a large portion of OCO-3 life span and it is totally unpredictable to assess the modification, if any, of the atmospheric column average of air-mixed CO_2 during this time. This poses a big question to the suitability of OCO-3 data for estimating the annual change of CO_2 at global level including India.

The present work has used the database of OCO-2, the predecessor, as a reference and makes a comparative analysis of CO_2 including vegetation and aerosol parameters for populated and unmanned regions of various countries across the globe including India. The similarities and the differences in the annual variation trends are analyzed and a significant reduction is found in the CO_2 column average for urban, populated areas. A wavelet transform technique is suggested for quantifying the deviation from the usual annual variation and a similar methodology is hoped to be useful for comparing with the own data of OCO-3 data procured in future normal conditions.