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MEASUREMENT OF TOTAL ELECTRON COUNT OF THE IONOSPHERE AND THE SOCIAL GOAL OF PRATHAM, INDIAN INSTITUTE OF TECHNOLOGY BOMBAY'S FIRST STUDENT SATELLITE

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ABSTRACT

Students from the Indian Institute of Technology Bombay (IITB) are currently in the process of building a fully functional microsatellite named 'Pratham', which is slated for launch by Indian Space Research Organization (ISRO) in the fourth quarter of 2010. The satellite being built is a 260 mm cube and weighs nearly 10kg. This landmark project has completed the phases of Requirements Capture, Conceptual Design, and Preliminary Design and is currently in the Detailed Design Phase. Detailed documentation and thorough reviews were conducted by ISRO scientists and IITB faculty before the conclusion of each of the above Design phases.

The goal of the satellite project is to educate students in the field of Satellite and Space Technology in the process of building a satellite for measuring the Total Electron Count (TEC) of the Ionosphere. This paper will discuss the technique being used by Pratham for measurement of TEC with 99.9% accuracy using the principle of Faraday rotation. This method has helped in reducing the cost of the ground station as well as the onboard complexity. The satellite will enable the generation of TEC maps of India and France with the help of ground stations set up at eleven Indian universities and the Institut de Physique du Globe de Paris (IPGP), France. A novel technique for ionospheric tomography using the generated TEC data has also been discussed in this paper. The algorithm reconstructs the distribution of electron density across various layers of the ionosphere with more than 85% accuracy.

This paper will also discuss the Social Goal of the Project. Pratham will be transmitting onboard data when it passes over India. With a low-cost ground station, students from other universities will also be able to detect the beacon signal and measure TEC. Workshops on making low-cost ground stations have been held at IITB for students from other universities. Moreover, the simulations developed for Pratham are being made available online in a Virtual Laboratory for the benefit of students all over the world. The entire documentation of Pratham, TEC data and the Virtual Laboratory will be freely available at www.aero.iitb.ac.in/pratham. We hope these will serve as stepping stones for future missions.

Key Words: **TEC, polarization, tomography, ground station, social goal**

I. INTRODUCTION

Over the past couple of decades, student satellites have brought about a revolution in serving as an excellent means of educating students in the field of space systems engineering and design. Students from the Indian Institute of Technology Bombay (IITB) started embarked on the process of building their first student satellite ever (hence the name Pratham, which means 'the first' in Sanskrit) towards the end of the year 2007. The goal of the mission is

1. Enabling students to gain knowledge and experience in the field of Satellite and Space technology.
2. Empowering the Satellite Team with the skills to develop the Satellite through various phases of Design, Analysis, Fabrication and Testing until the Flight Model is made.
3. Launching the satellite into orbit and measuring Total Electron Count (TEC) of the Ionosphere.
4. Involving students from other universities in our Satellite mission by building ground stations in their universities.

The satellite being built is a 260 mm cube and weighs nearly 10kg. The team has gone through various phases of design reviews and the satellite is slated for launch through a PSLV in the fourth quarter of 2010.

In this paper, we present the payload and the social goal of Pratham with a focus on describing the procedure adopted for measurement of TEC. In section 2, we give an introduction to TEC, its significance and the methods used for its measurement. We then describe the ground station setup and onboard equipment for TEC measurement followed by the in-house algorithm developed for performing ionosphere tomography. In section 3, we describe our social goal and conclude in section 4 with a synopsis of our mission design.

II. PAYLOAD

A. Introduction to TEC

Total Electron Count or TEC is defined as the number of electrons in a column of unit cross sectional area, extending from ground all the way up to the end of the ionosphere. Units of TEC are electrons/m^2. If this column is vertical, then the TEC is referred to as Vertical TEC (VTEC) and otherwise it is referred to as Slant TEC (STEC). When referring to the TEC at a location, we usually mean the VTEC, unless otherwise stated. One must remember that since the ionosphere virtually extends to large distances from the earth, only 95% of the ionosphere is covered between the earth and our satellite.

TEC values are of great importance to the scientific community. The Indian subcontinent being close to the magnetic equator is rich in phenomena such as the Equatorial Ionization Anomaly (also known as the Appleton anomaly), the Equatorial Spread F (ESF) and the Equatorial ElectroJet (EEJ).

The understanding of the dynamics of the TEC has gained significant commercial importance since the uncertainty in TEC values cause uncertainties in group delays for single frequency GPS receivers, leading to inaccuracies in position measurement.

Recent efforts made by the scientists from IPGP in France suggest that TEC measurements can serve as precursors for seismic activity in the earth's interior. The gravity waves upon interacting with the ionosphere cause fluctuations in the TEC distribution and monitoring them might lead to the development of a robust prediction mechanism for future prediction of earthquakes under an ocean which will help us to detect a Tsunami before its arrival. There are various techniques for measurement of TEC from LEO satellites:

1. Measurement of Faraday Rotation
2. Measurement of Group Delay of received signals

3. Measurement of Doppler shift of received signals due to ionospheric fluctuations
4. Measurement of amplitude scintillations of received signals.

We decided to opt for the Faraday Rotation technique after performing a trade-off with all the possible techniques. The primary advantage of Faraday rotation technique is its simplicity which is of immense importance for a student satellite mission.

Faraday Rotation

When a linearly polarized radio wave passes through an ionized medium with a magnetic field in the direction of propagation, the plane of polarization rotates. This effect is called Faraday rotation [9].

$$\Delta\varphi = 4.87 * 10^{-4} * f^{-2} \int_{h1}^{h2} NBcos(\theta)dl$$

Where N – electron density, B – magnetic field of earth, θ – angle between the magnetic field and the direction of propagation of the radio wave, $\Delta\varphi$ – is the change in angle of polarization, f – frequency of the wave

Based on this principle, the TEC over a region can be measured by transmitting linearly polarized signals and measuring the change in their polarization angle.

Modifying the equation by averaging the Magnetic field over its path gives us

$$\phi_f - \phi_i = 4.87 * 10^{-4} * f^{-2} * B_{avg} * (TEC)$$

where Φ_f – final angle of polarization, ϕ_i – initial angle of polarization. This averaging assumption isn't too bad since the magnetic field doesn't vary much along the path of propagation of the radio waves transmitted from the satellite

Need for two frequencies

Except for the ϕ_i and TEC, other quantities are known. To eliminate the need of ϕ_i, we are using two frequencies to determine TEC and it is determined as follows

$$\phi_{f1} - \phi_i = 4.87 * 10^{-4} * f^{-2} * B_{avg} * (TEC)$$

$$\phi_{f2} - \phi_i = 4.87 * 10^{-4} * f^{-2} * B_{avg} * (TEC)$$

$$\phi_{f3} - \phi_i = 4.87 * 10^{-4} * f^{-2} * B_{avg} * (TEC)$$

Irrespective of the method used for measurement, current standards require electron content distribution (which will be determined from tomography discussed later) values up to an accuracy of 10-15%. This requires us to determine TEC up to an accuracy of 1TECU and the polarization angle up to an accuracy of 2degrees.

n-pi ambiguity

The difference in measurement of Polarization made at the Ground Station does not give us exactly the difference in rotation of two waves as it would not be accounting for the number of 360 degree rotations. It only gives us the offset that lies between [0,360).This is the n-pi ambiguity that we have to deal with.

We propose to resolve this using the Leighteinjeir method. For this we would need simultaneous measurements at two Ground Stations which are separated by a distance of at least 5Km. Here, we use the approximation that the ionospheric electron distribution is in a thin shell of uniform density. Obviously, this is a very bad approximation, but it is enough to determine the n-pi ambiguity to the nearest integer. Under this approximation, we can write $T_{i,1}\sin(\theta_1) = T_{j,2}\sin(\theta_2)$

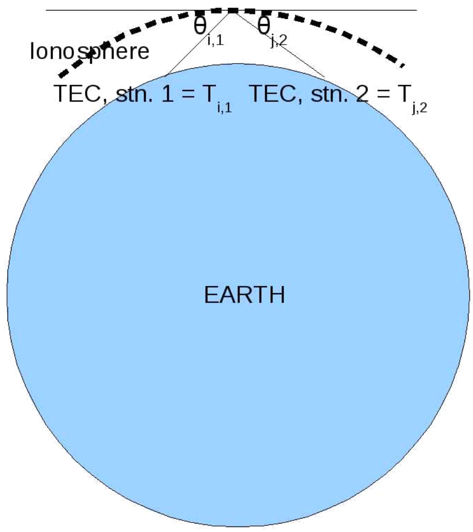

Fig.I: Two station method

With several values of $T_{i,1}$ and $T_{j,2}$, we can fit a straight line to equation (3) for all values of i, j and we can then get least squares estimates of n1 and n2.

B. Measurement of TEC at IITB

In order to radiate linearly polarized waves from the satellite, we plan to use monopole antennas. We will be measuring the angle of polarization at the ground station by using a crossed Yagi antenna and measuring the intensities of the signals at the two feeds. The ratio of these intensities will give us the polarization angle.

We plan to measure relative intensities of the radio waves by using an Analog Devices chip AD8302. This IC takes two inputs INPA and INPB and gives a voltage o/p proportional to the level ratio of these signals in dB. In addition, the pin VPHS gives the phase difference between the signal s at the INPA and INPB.

$$v = 0.9 + 0.6\log_{10}(|tan\theta|)$$

For each output voltage of AD8032, there are two angles which satisfy the above equation and are supplementary to each other. To resolve this ambiguity, we need to use the phase difference information.

The radio wave which will be received at the ground station will not be perfectly linearly polarized due to mainly two reasons:

a) Polarization purity of the monopole antenna: The wave emitted by the monopoles onboard the satellite will not be perfectly linearly polarized because the monopoles will have a finite radius and other such factors. This will introduce a circularly polarized component into the waves and thus the measurements made at the ground station will be faulty [5]. Considering the requirement of measuring polarization angle at the ground station up to an accuracy of 1degree, the monopoles on the satellite transmit radio waves with a polarization purity of 99.9%.

b) Ellipticization of wave: When a linearly polarized EM wave passes through a medium with a transverse magnetic field and plane of polarization neither parallel nor perpendicular to the magnetic field, another effect known as Faraday ellipticization also takes place, by which the EM wave becomes elliptically polarized [6].

For a frequency of 433 MHz, the minimum length needed to traverse in order to get an axial ratio of even 20dB (very weakly elliptically polarized) is of the order of 10000 km, which is far greater than the expected radius of our orbit.

For a frequency of 145MHz if the initial angle between plane of polarization and earth's magnetic field is considerably away from 45^0, the receiving wave at the Ground Station could be considered linearly polarized as its axial ratio would be greater than 20dB.

C. Ionospheric Tomography

TEC gives us information about the integrals of electron density in various directions from the IIT Bombay ground station. From these integrals, we can derive the values of the electron densities at various positions of the ionosphere. This technique is called ionospheric tomography.

For our technique we would need ground stations on same longitude [2]. It is very difficult to extend this method for ground stations over different longitudes because the temporal and spatial variations in TEC would then get mixed up. We hence need the ground stations to receive signals from the satellite continuously.

For tomography, we divide our atmospheric domain into small pixels and the electron density is assumed to be constant in each of the pixels. TEC information as said could be viewed as an integral and can be expressed as a linear combination of these pixel values [1]. Solving this system of linear equations, we get a solution which is a vector of electron densities associated with each pixel, which could be processed to obtain a picture of the electron density function.

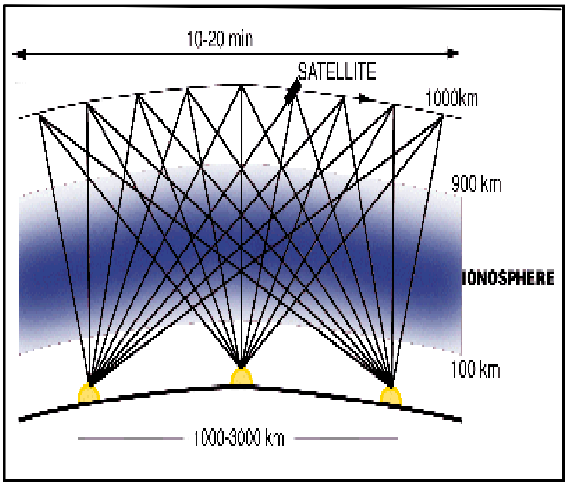

Fig. II: Geometry for Ionospheric Tomography

Mathematically, let the column vector consisting of the values of the electron density at various pixels be [x_i]. Also, let the column vector consisting of the components of the integrated electron density values at various elevation angles and at various stations be [y_j]. Then, the relation between [x] and [y] is given by:

$$y_i = A_{ij}x_j$$

Where, A_{ij} = length of the intercept at the i^{th} pixel by the j^{th} ray. But now the problem with inverting A is it is highly rank deficient because of the geometry of the problem. There are infinite solutions to this matrix equation. So we treat this as a minimization problem also assuming a model electron density x_0 [10] we also place the constraints that the neighbouring pixels shouldn't differ much by using Tikhonov Matrix. This is called Tikhonov Regularization. We seek to minimize the objective function

$$f(x) = ||Ax - y||^2 + \alpha||x - x_0||^2 + \beta||Tx||^2$$

Where α, β are variable parameters which are fixed on the basis of our relative confidence on the TEC data. We used the ILOG CPLEX package to minimize this function.

D. Simulation Procedure

The simulation was carried on a part of the ionosphere above a certain longitude, spanning certain fixed ranges of latitude and altitude. This two-dimensional space is divided into a grid consisting of equally spaced radial lines at 1 degree separation and circular arcs at 10 km. Further, five ground stations were considered, each of which has a fixed field of view. Assuming the satellite is at a fixed orbital height, we calculate the TEC values received by the ground stations along a large number of paths. In order to do so, the length matrix is first calculated in the following manner.

We work in a two-dimensional polar co-ordinate system, with the centre of the earth as origin and the radial line at the equator as the pole. To obtain the (i,j)th entry of L, i.e. the length of the intercept made by the i th ray in the jth cell of the grid, we proceed as follows. The ray is represented by an equation of the form

$$r \sin\theta = mr\cos\theta + R(m\cos\lambda - \sin\lambda)$$

Where R = radius of the earth, λ =latitude of the ground station, m = slope of the ray =tan(φ) and φ is the angle between the ray and the local vertical. Each cell in the grid is represented by its bounding curves. We solve for the intersection of the ray with each of the bounding curves of a particular cell, and determine if the ray does intersect the cell. If so, we calculate the distance between the two points of intersection and enter this as L(i,j). Else we enter zero. Thus the length matrix, L is constructed. We then obtain the TEC vector.

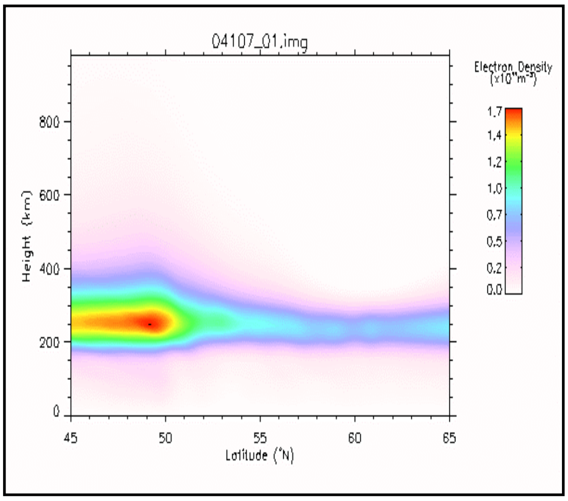

Fig. III: Tomography plot from simulations

E. Ground Station Details

We classify the ground stations as follows:

a) Central Ground Station(IIT Bombay)

b) Link Ground Station (for n-pi ambiguity)

c) Type I (same longitude as Central GS)

d) Type II(which do not share same longitude with central GS)

Ground Station elements:

a) 2 crossed Yagis (145MHz and 437MHz)

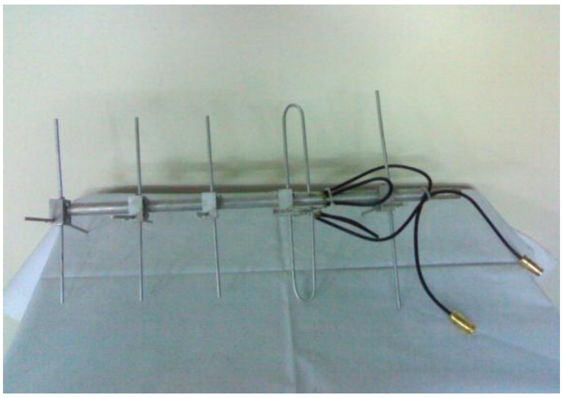

Figure IV:Yagi at 437 MHz at IITB Groundstation

Fig. V: Yagi antenna at 145 MHz at IITB Ground station

b) 16 Low Noise Amplifiers

AD 8302 chip has a lower sensitivity cut off at 60dB, but the receiving signal has strength of -130dB. So to raise it above -60dB, we'll need to use 4LNA's of gain 20dB each [4].

c) 2 AD 8302 chips

Logarithmic amplifiers in AD8032 chip bring about the level ratio of intensities of two inputs in dB.

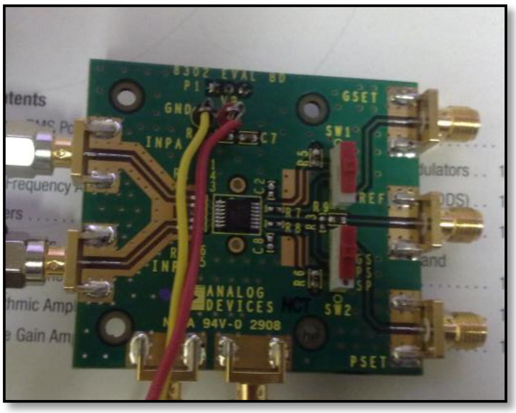

Figure V: AD8302Module

d) Low pass filters of cut off frequency 5 KHz

Small signal envelope bandwidth of AD 8302 is 30MHz but our micro-controller has a clock frequency of 10 KHz. To satisfy the Nyquist criterion and block the noise due to higher frequency components, we are using a Low pass filter. The data is then passed through ADCs and stored in dedicated servers [8].

Figure VI: Groundstation at IIT Bombay

III. SOCIAL GOAL

The Social goal of Pratham represents the belief of the team that knowledge gained in the field of satellite technology is an important constituent of mission objectives and mission success when it comes to student satellites. It is with this in mind that Pratham decided to involve other universities in the project by inviting them to build a ground station for the satellite. The idea was to disseminate knowledge gained by the team in the field of satellite technology and at the same time make them a part of the mission. Thus, we started a series of Groundstation workshops, each focusing on a different area of Groundstation fabrication and setup. The Social goal took a step further with the setting up of Virtual Labs under a project initiated by the Ministry for Human Resources Development, Government of India. We describe each of the above in detail in the sections below.

A. Groundstation workshops

The Groundstation workshop series was started keeping in mind the principle of CDIO (Conceive, design, Build and Operate). The participants were given an overview of the status of the Central Ground station at IIT Bombay and were given a set of tasks at the end of each workshop. The tasks were to be completed before the next workshop and generally involved concepts covered in the workshop session. There was no selection criterion for participating in the workshop and anyone who was interested in satellite communication, from students to professionals, could participate in the workshop.

The first Ground station workshop dealt with the conceptual design of the Central ground station. The concept of Payload and different types of Groundstations were discussed in the workshop and a problem statement related to the design of the Yagi Antenna was given to the participants. The participants were asked to decide the location of their Groundstation and study the behaviour of different types of antennae to linear and circular polarisation. The participating universities/individuals were given a rough estimate of the budget for Groundstation fabrication and setup. The entire cost of setting up a Groundstation was less than 500 USD.

The second Groundstation workshop focused on the simulation and optimisation of the crossed yagi antenna using 4NEC2 software. The software is freely available and was used by Pratham team for its Groundstation antenna design. The participants were given rudimentary parameters to start with their design and then had to do several iterations before achieving an antenna design with the desired performance characteristics. The second task allotted to the universities was to fabricate the Groundstation antenna and characterise them before the third Groundstation workshop.

The third Groundstation workshop involved presentation by the Universities who had already fabricated their Antennae and a discussion on their characterisation result. The workshop included a demo of satellite tracking and reception of signals and a detailed analysis of data storage and analysis after reception. The entire process of measurement of TEC after data has been stored by various Groundstation was explained to the students and professionals by the Payload team. We also had scientists from Vikram Sarabhai Space center (VSSC) and National Atmospheric Research Laboratory (NARL) present for the third phase of the workshop. The third workshop was also attended by Ham amateurs who were interested in setting up data -points for measuring TEC. The task given to the participating institutions involved fabrication of mounts and setting up of data storage facility at their Groundstations.

Following is the picture of the Yagi manufactured by one of the participating universities,

Fig. VII: Crossed yagi at 437MHz made by BVCOE Mumbai, India

Currently, IITB is collaborating with 11 different universities, including one in France where ground stations are being setup for TEC measurements. The satellite has an onboard GPS which will enable it to transmit the linearly polarized radio waves over the regions of interest where our ground stations are setup.

B. Virtual Labs

Pratham has provided valuable learning opportunity to large number of students of IITB. Part of this learning happened through the use of a set of simulation softwares that were developed as part of their project. We intend to extend this learning opportunity to a wider segment of student community outside of IITB. Virtual Laboratory in Satellite Modelling & Simulation offers distance learning opportunity in Satellite Technology through online experiments. In this laboratory, students can perform experiments with the same tools that helped the Pratham team to learn about Satellites; these are the same tools that helped our team in designing Pratham. These simulations interfaces can be accessed at *www.aero.iitb.ac.in/pratham* [7]

IV. Synopsis

In this paper, we have described the details of carrying out TEC measurements using the simple Faraday Rotation technique. The algorithm for generating tomograms from the TEC data was also presented. We finally, describes the social goal of Pratham and how we have gone about incorporating several other universities into our mission. We hope our efforts serve as stepping stones for larger successes in the future.

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