Iterative Algorithm for Construction of Electron Density Mapping based on Beacon Satellite Observation Data

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Abstract: The observations of ionosphere layer can be observed by several ground-based equipment or satellite based. Some observation equipment procurement ionosphere layer of which requires a cost in a large amount. Therefore, one of related observation method has been developed in the last few years by the ionospheric researcher such as the use of beacon satellite signal for studying the variability of the electron density distribution in the ionosphere using the receiver system known as GRBR (GNU Radio Beacon receivers). In Indonesia, a similar receiver has been located and installed in separated parts of Indonesia such in Kototabang (0.204554S, 100.319990E), Sumedang (6.913047S, 107.837144E), Pontianak (0.003540S, 109.368398E), Yogyakarta (7.789792S, 110.363547E), Watukosek (7.563594S, 112.677585E), Manado (1.288394U, 124.913566) and Biak (6.9ºU, 107.84 ºBT). Those kind of receivers has produced some of the observational data since 2008. By utilizing the representative data and simple algebra iterative algorithm called Algebraic Reconstruction technique (ART) can produce a tomographic mapping area around the network scope of beacon satellite receiver. In this paper, will be discussed the introduction of iterative algorithm which is used to obtain ionospheric density. In closing, some example data used for the implementation of ART based on the beacon data in two different locations and the comparison value in this works raise around $1x10^4$ and $5x10^4$ of electron density in el/cm^3 qualitatively.
Key Words: ionospheric tomography, beacon experiment, iterative algorithm.

1. Introduction

The ionosphere layer has become one of the atmosphere layer that covering the Earth. This layer is formed by recombination of atoms into ions due to solar radiation such that the number density of electrons and others can be reduced or increased. The total of electron density is then can help the process of radio waves propagation to remote locations on the Earth's surface.

Characterization and parameterization of the ionosphere in equatorial regions and the lower latitudes are very difficult to obtain and require an instrument in large numbers. This problem can be overcome by using a computational technique known as ionospheric tomography computational techniques. This technique has the advantage that sufficient to provide coverage to an area along remote region that could not be excluded by the instrument coverage so that with this technique no longer requires instruments in large amounts relatively. The computational of ionospheric tomography techniques results a map of variety of distribution of the ionosphere in the spatial space both Latitude and Longitude by using data obtained from the beacon satellite receiver system. The receiver system had been installed throughout the region where will be made a mapping and were able to record a coherent signal from Low Earth Orbit satellites (LEO) simultaneously. The ionosphere tomography concepts already introduced in several times ago with 2D ionospheric mapping[3)]; as well as development and engineering modifications of tomography[4,5,6,7)].

A digital satellite receiver system based on GNU beacon has built in several time ago. A beacon satellite receiver system to measure the TEC in the ionosphere layer called the GNU Radio Beacon Receiver (GRBR)[8)]. This system produced some trajectory parameters of the satellite trajectory and some amount of the received satellite signal power and the absolute TEC. Those parameter values are stored in the file of ASCII format and saved to the server observational data automatically. These observation data can be used as an analysis and Ionosphere for further research such as estimation the spatial distribution of the TEC in Longitudinal[10)]; estimation the absolute value of TEC using data from radio beacons[2)]; the pattern of Large-Scale Wave Structure (LSWS) and Equatorial Spread F (ESF) based on data from GNU Radio Beacon Receiver (GRBR)[10)]. The use of data received from GRBR system can be developed for expansion study as the characteristics distribution of electron density in the ionosphere in the two-dimensional spatial space. The first tomographic around equatorial and Longitude India and tomographic analysis on Japanese territory[1,9)]. On the other hand,

particularly in Indonesia has been installed several GRBR systems in some areas thus forming the GRBR observation network of Indonesia.
The general problems in tomographic technique is the object reconstruction where could not be observed until such a condition or the characteristics approach of the observed object. Direct method and iterative method are the types of its algorithms that can be used for the object reconstruction. In this work, will be discussed an algebraic reconstruction techniques (ART) as one of the iterative reconstruction method that relatively easy to combine the object projection info into the reconstruction process.
This paper contains a brief introduction of tomographic reconstruction used in this work, a small implementation of tomographic reconstruction techniques in electron density distribution layer of ionosphere using ART and the observed data network GRBR Indonesia given in table 1.1. In closing, we discuss some results obtained tomographic mapping based on the algorithm used and the two data GRBR in the central region of Indonesia.

Table. 1.1. Distance between GRBR receiver in Indonesia

	EAR	PTK	SMD	YKT	WTK
EAR		1006	1119	1397	1596
PTK	1006		786.9	872.8	917.2
SMD	1119	786.9		295.2	538.8
YKT	1397	872.8	295.2		256.2
WTK	1596	917.2	538.8	256.2	

1.1. The Concept of computational ionospheric tomography

The distribution of electron density in the ionosphere layer can be mapped using tomographic techniques with ART algorithm. Many of the ART algorithm approach that has been done for giving the information of electron density distribution in the ionosphere[11)]. The results of experimental use of CRABEX receiver utilizing the Doppler frequency difference value of dual frequency which is emitted by the beacon satellite to determine TEC[1)]. The Doppler frequency differences correlated with STEC (Slant Total Electron Content) along ray path. The exact value of STEC are the basic data for tomographic inversion which can be defined as a linear equation as follows:

$$Y = Ax + E \qquad (1.)$$

Where, Y is an observation vector data TEC, x is the unknown parameter of electron, and A is the matrix of geometry and E illustrates the discretization error from measurement. Simple graphic illustration of ionospheric tomography techniques can be seen in Fig. 1.1.1. and Fig. 1.1.2.

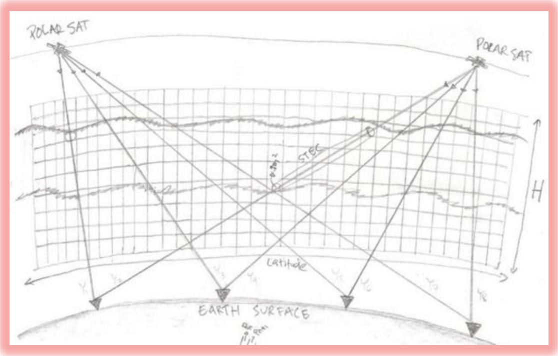

Fig. 1.1.1. Satellite ray path for ionospheric tomography reconstruction

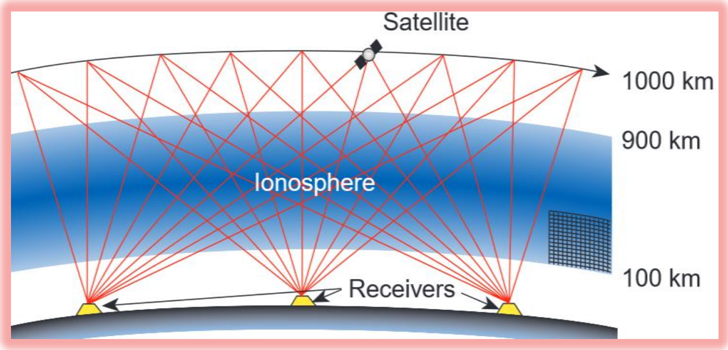

Fig. 1.1.2. The scheme of ionosphere grid reconstruction in ionospheric tomography

The satellite signals are received by the receiver system each time the satellite pass, satellite signals penetrate the ionosphere with a certain thickness. The satellite position and satellite signal parameter data stored in the observation database center can be computed to reconstruct the coverage area of the satellite signal shown in Fig. 1.1.1. A set of observed data, then to be formed a system of two-dimensional array in a matrix form that represents the geometry of ionosphere region as shown in Fig. 1.1.2. Details reconstruction techniques are discussed in the next chapter.

1.2. Algorithm Reconstruction Techniques (ART)

This technique is one of reconstruction technique using an iterative (looping) calculation process to solve the problems on multi linear equation. In detail, the ART is focused at reconstructing the content of each element of the matrix (*m x n*) formed from previous multi linear equation. The content of each element of this matrix reflects the value of the 2-dimensional density function. Outlining, the 4 (four) steps of ART are construction the initialization matrix, calculating the correction factor, reconstruction and testing of the convergence of the calculation results. Finally, the output of these technique is the numerical approximation which is calculated by the following equation:

$$f_j^{k+1} = f_j^k + \alpha \frac{p_i - \sum_{n=1}^{N} A_{in} f_n^k}{\sum_{n=1}^{N} A_{in}^2} A_{ij} \qquad (2.)$$

where the initial guesses f_j^o is determined from the global models of the ionosphere IRI represent the ionosphere background. Furthermore, at iteration k+1, the value of the parameter f_j^{j+1} can be obtained when it reaches the convergence conditions controlled by α, the projection results p_i and weight coefficient A_{ij}. Fig. 1.2.1. shows the flowchart of ART.

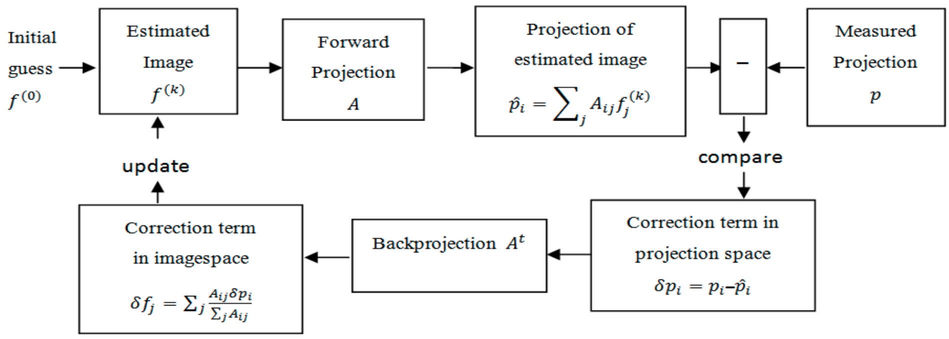

Fig. 1.2.1. The flowchart of ART

2. Tomography Reconstruction

The choose of two observation data from different locations used for the first time in data processing here besides generate the matrix of TEC background as an initial data. The global model of the ionosphere IRI-2012 is used to get the background of TEC. The next step, process the algorithm tomographic to construct the map as follow in the flow chart as shown below:

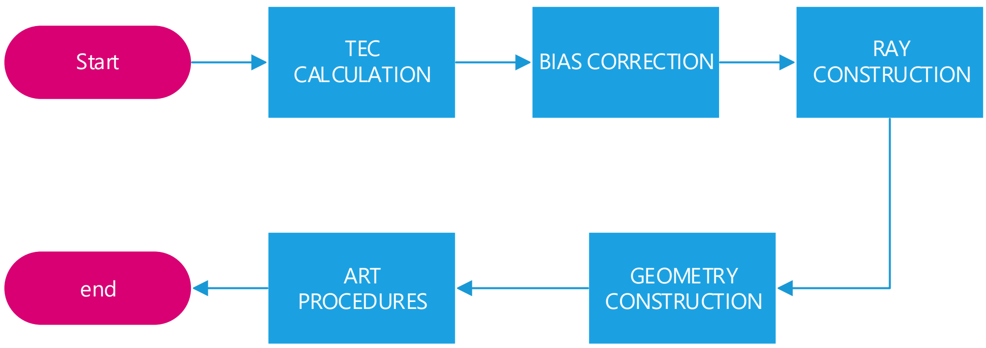

Fig. 2.1. The main flowchart of tomography

Before processing the main calculation of ART, IRI data and GRBR used in the process of reading the satellite trajectories data and STEC which will be used in the calculation of tomographic geometry and calculating the absolute value of TEC after corrected by using the technique of error bias correction to produce the absolute value TEC[12)]. Meanwhile, the TEC background initialization data will be used in the calculation process of ART to get the final results until meet the convergence state. On the other hand, the geometry of tomography matrix should be generated before taking out the ART procedures. This matrix can be generated by construct the ray path data from satellite ray path. The ray path data obtained from the calculation of trigonometric spatial in two dimension based on the satellite trajectory data. Furthermore, at the end of the process, the geometry matrix, the initial background and the absolute TEC data use in the ART procedures to approximate the final tomographic matrix based on the convergence state, as shown in Fig. 2.1.
Some of the tomography results need to be validated to check the accuracy of the calculation results. The validation can be done by comparing the tomographic reconstruction results with Radio Occultation, Ionosonde observation data and IRI2012. In this case, the IRI2012 data has been carried out to validate the tomography results. The maximum value of electron density (Nmax) reflecting the value of ionosphere layer critical frequency (foF2) obtained from tomographic reconstruction and compared with the IRI data. Using the same method, the data parameter maximum electron density in the ionosphere layer can also be compared with a variety of locally-time data RO. The 'Ionospheric slab thickness' τ as TEC comparison to the maximum electron density in the F2 layer (NmF2)[13)],

$$\tau = \frac{TEC}{NmF2} \quad (3.)$$

Or in the form of critical frequency in the F2 layer,

$$\tau = \frac{TEC}{1.24\times10^{-6}(foF2)^2} \quad \text{hence} \qquad (4a.)$$

$$\tau = \frac{TEC}{NmF2} = \frac{TEC}{1.24\times10^{-6}(foF2)^2} \qquad (4b.)$$

$$NmF2 = 1.24 \times 10^{-6}(foF2)^2 \qquad (5.)$$

$$foF2 = \sqrt{\frac{NmF2}{1.24\times10^{-6}}} \qquad (6.)$$

In this work, 10 data of tomography reconstruction and IRI data have been taken or selected for the validation process. For further data analysis, data linearization used as statistical calculation to obtain its parameters such as the correlation coefficient, standard deviation and gradient linearity of fitting data.

3. The Format of GRBR Data

The beacon satellite signals transmission 150 MHz and 400 MHz pass through the ionosphere which has a variability in plasma density. The resulting phase difference is proportional to the TEC along the ray path. Each ray path contains the location points of satellite trajectory and recorded into ASCII file given in Fig. 3.1. On the other hand, the signal processing has to be done to obtain both signal strength parameters and the TEC value included the error estimation. These results are also stored in ASCII file summary as shown in Fig. 3.2.

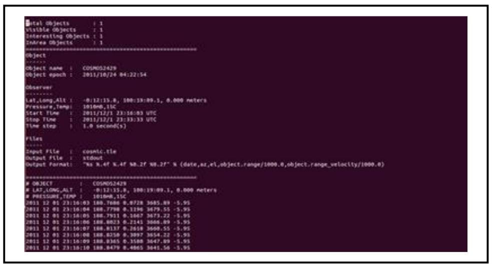

Fig. 3.1. Numerical data of trajectory file

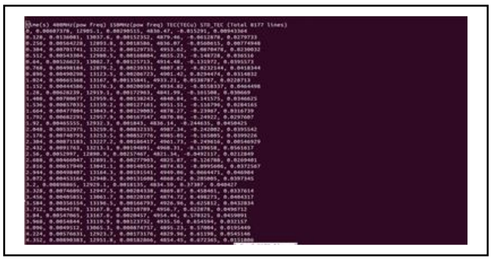

Fig.3.2. Numerical data of summary file

4. Results and Discussion

Categories of data that will be used in the tomography calculation is near spatially adjacent and within the same time relatively. Some results of the satellite trajectory, geometrical ray path, the IRI Data as initials background and tomographic results shown in this section.

Each satellite provides beacon signal or transmit both 150 MHz and 400 MHz simultaneously. Both of these signals will be received in the same time relatively in various locations of GRBR receiver system located in different geographic coordinates. The first thing that can be identified are the coordinates of the satellite trajectory passing tracks in the form of coordinates azimuth, elevation and conversions both coordinates into geographical coordinates of longitude and latitude. Fig. 4.1a and Fig. 4.1c shows the profiles of satellite trajectory passing over Yogyakarta on January 25, 2013 around 17UT and Fig.

4.1b and Fig. 4.1d shows the profiles of satellite trajectory passing over Pontianak on January 26, 2013 around 17UT. Back to the date on January 25, 2013 where formed the intersection of satellite trajectory in the range of geographical coordinates 105º-107º and -15º -15º. While the recorded data which is recorded in the next morning also shows the intersection of satellite trajectory in the range of geographical coordinates 106º – 108º and -15º – 15º.

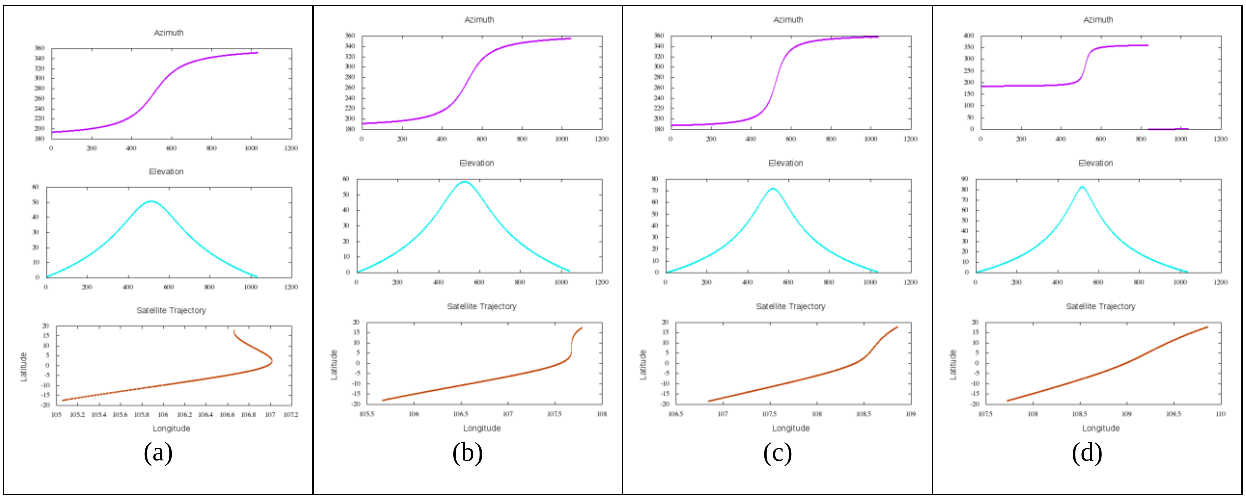

Fig. 4.1. Satellite trajectory profile received by GRBR system located in Yogyakarta and Pontianak.

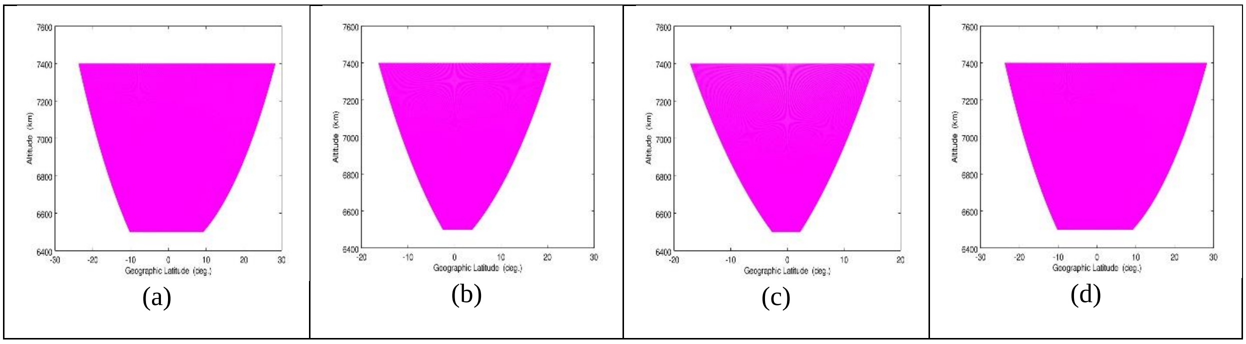

Fig. 4.2. Ray path geometry pattern from satellite trajectory

Using data of satellite trajectory, then it will be used to calculate the satellite ray path. The ray path will Fig. out the coverage area of tomography in two dimensional. Fig. 4.2a and Fig. 4.2c is the result of ray path based on data observed in Yogyakarta on 25-26 January 2013 at about 17 UT. While the Fig. 4.2b and Fig. 4.2d shows the scope of the ray path based on data observed in Pontianak on the same date and time as the Fig. 4.2a and Fig. 4.2c. The fourth picture shows the profile of coverage in the region of the ionosphere up to the height of satellites assuming the addition of long radius of the earth around 6400 Km. In addition, the left and right margins of the ray path pattern implying the curvature of the shape of the earth that projected into a 2-dimensional coordinate.

Furthermore, by combining the coordinate ray path data and TEC data, both data will be processed the calculation of tomography using the selected algorithm. However, the background of TEC data as the initialization in the iterative tomography calculation (ART) should be taken previously. The initial data are obtained from the global model data called IRI2012. The tomography of electron density profiles in the ionosphere are calculated based on the selected of relaxation value ($\lambda = 0.05$), and the minimum of tolerance ($\xi = 0.001$). The tomographic results obtained based on the observations data taken on January 25, 2013 shows in the Fig. 4.3. While the tomography results on the date January 26, 2013 shows in the Fig. 4.4. where the color bar is the value of the electron density in every altitude and latitude.

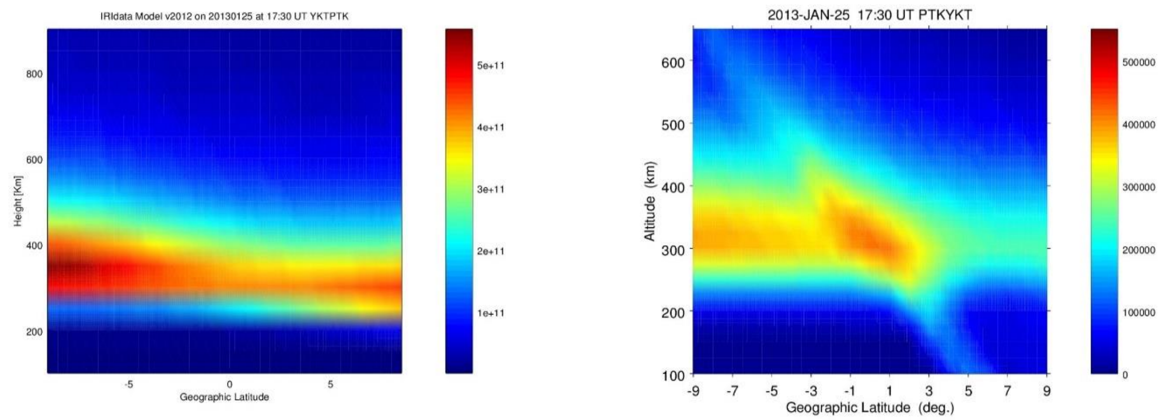

Fig. 4.3 IRI2012 data profile (ionospheric background) [left] and electron density tomography around 25012013:17:30 UT [right]

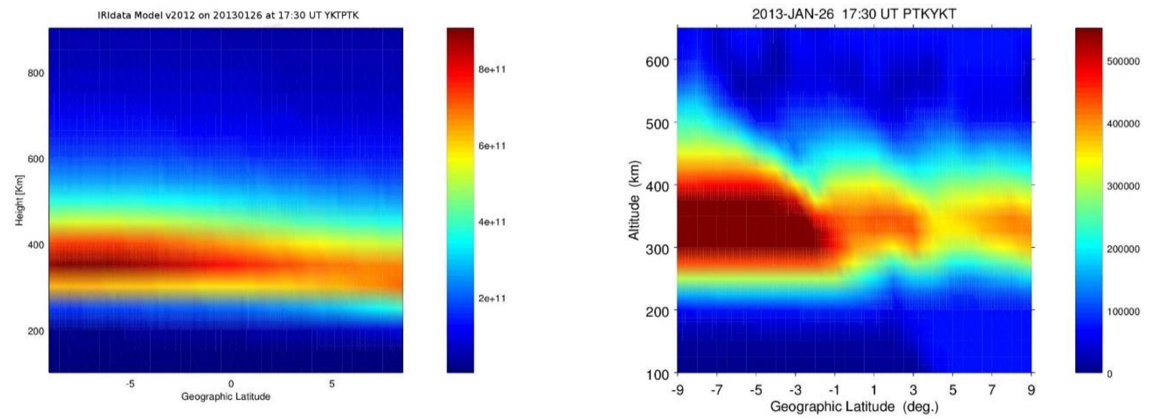

Fig. 4.4 IRI2012 data profile (ionospheric background) [left] and electron density tomography around 26012013:17:30 UT [right]

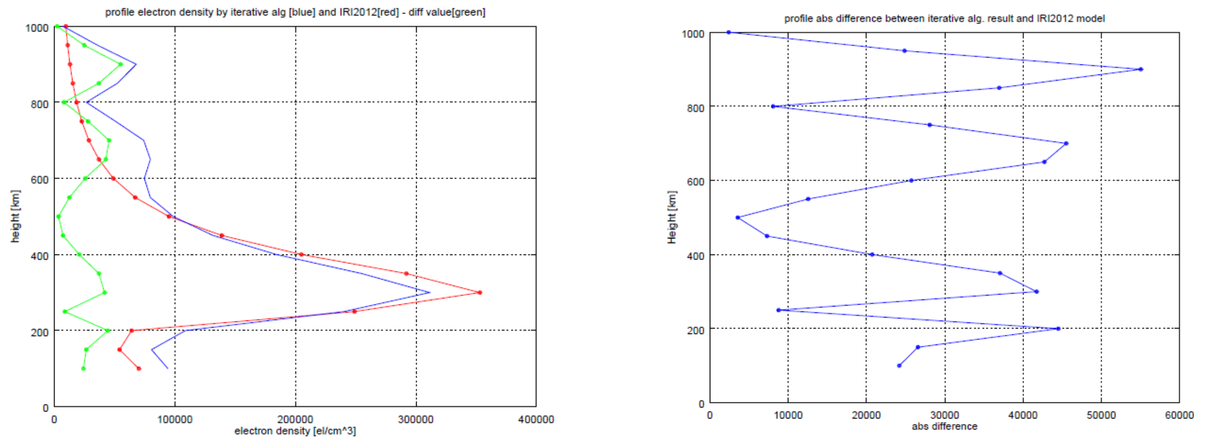

Fig. 4.5. Comparison of the electron density profiles derived from the ground-based GRBR iterative tomography reconstruction (blue line) nad IRI-2012 estimation (red line).

Fig. 4.5. is a comparison of the tomography reconstruction by iterative technique results at 17:30 UT on 26 January 2013, with the electron density profile from IRI-2012 model. It shows that the tomography reconstructed density profile has a range difference value raise up to the maximum number around $5x10^4$.

The comparison also shows that the IRI overestimates the densities at local time as shown the greater values shows in the peak of the curve.

5. Conclusion

The GRBR data observed in Indonesia can be applied for three-dimensional ionospheric monitoring. An example in 25-26 January 2016 shows the ionospheric tomography results based on GRBR data in Pontianak and Yogyakarta and the Algebraic Reconstruction Technique (ART) which is successful implemented as the first ionospheric tomography using Indonesian GRBR data. The intersection between each of satellite trajectory which is received in each GRBR receiver should be exist as the base of concept of tomography technique. The calculation process tomography in ART is determined by relaxation factor (λ) and the tolerance error (ξ). As the validation of the tomography results, the electron density profiles taken from IRI-2012 model data has been used for this purposes.

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