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Development, Implementation and Testing of Algorithm to Detect Ionopause-Like Structure Using Parallel Processing in the Martian Atmosphere

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Abstract: ***This study assesses the Martian ionopause using MAVEN datasets between periapsis and 150-600 km. Ionopause is an abrupt reduction of the electron density with increasing altitude. It is also required to verify the simultaneous increase of the electron temperature and variability below 400 km. To address this issue, we have adopted a computational approach in determining the ionopause-like density structure of the ionospheric profile. From computing thermal & magnetic pressures, radial magnetic field components, ionopause-like density gradient are detected and stored. The ionopause (theoretically) is formed where the total ionospheric pressure equals solar wind dynamic pressure. The present algorithm consists of a comprehensive set of conditions to be performed on the dataset sequentially. These include datasets from various instruments simultaneously observed. The primary objective of the present study is to describe the implementation and testing of this algorithm for big datasets of the Martian ionosphere and extract ionopause-like density gradient using automation.***
Keywords: Ionopause, Mars, Remote sensing, MAVEN dataset, Parallel-processing

I. INTRODUCTION

Remote sensing is a scientific method of gathering and examining information from a distance. This is especially important for planetary science, where research is done about theoretical hypotheses. Still, remote sensing is also carried out in other fields, such as astronomy, weather monitoring, agricultural studies, and geology, to investigate ancient times. In everyday use, remote sensing has proven the most effective, in planetary science exploration, due to its advantage over other techniques [1]. Remote sensing can involve many different tasks, including surveillance or disaster track. Long-term weather reports, aerosol concentration, sea surface temperatures, and clouds covers have been studied on Earth. With the help of the digital era, researchers use various methodologies to pursue data analysis, such as big data, automation of routine datasets, advanced file systems, and other high-level data analyses. The current work demonstrates the development, implementation and testing of a new algorithm designed to detect ionopause in the atmosphere of Mars. This algorithm provides a unique technique to probe the atmosphere and ionosphere on a global scale using big datasets of remote sensing observations. Detection of ionopause plays a crucial role in monitoring the influence of space weather [2]. This paper presents a methodology for the algorithm utilising parallel processing. It is based on automation, meant to simulate any number of files for the end-user. In addition to discarded segment, the automation also produces its list. Parallel computing operates on the principle that significant problems can often be divided into smaller tasks, which are then solved simultaneously to save time (wall clock time) by taking advantage of non-local resources and overcoming memory constraints. The main aim is to showcase computational time on sequential and parallel codes, demonstrating the performance gain achieved through MATLAB® on the local machine using ©Parallel Computing Toolbox (Mathworks™) on four cores. The toolbox lets us utilise the processing power of multicore desktops by executing programs on workers (i.e. MATLAB computational engines) that can run locally (without CUDA and MPI) [3]. Further, PCT also allows to scale up the performance even further on High-performance clusters (HPC) with multicore processors and GPUs without recoding. An inbuilt optimisation function monitors the progress and reports the time taken to solve a process. The 'send(queue, data)' function records the processing time. The present work emphasises performance gain achieved from sequential and parallel execution. Our testing reports marginal performance gain over increasing RAM for parallel over sequential execution [4].

A. Dataset

With the space era, we can acquire a large number of datasets. The formation of ionopause in the planetary atmosphere is the fundamental problem. Out of a few available algorithms, only a few can study the long-term variability. A new algorithm is used in the proposed work and provides outstanding performance. As a result, the computational times decrease, and overall performance increases over many files. In the present work, we have used datasets from NASA's MAVEN mission to Mars. The MAVEN mission is a spacecraft orbiting Mars to study the atmosphere of Mars, sent by NASA [5].

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It is an acronym for Mars Atmosphere and Volatile Evolution. The orbit of MAVEN is elliptical with ~75 inclination, with an orbital period of ~ 4.5 hours with a periapse altitude of ~ 170 km. Categorically speaking, MAVEN has (i) Particles and Fields instrument suite, (ii) Remote Sensing instrument suite, and (iii) an eponymous suite. The Langmuir probe and waves (LPW) measures Solar fluxes, Electron Temperature & Density [6]. LPW measurements have minimum & maximum values which acts as the quality flag in data filtration. Neutral Gas and Ion Mass Spectrometer (NGIMS) measures abundances of neutral and ions [7]. These datasets carry % error provided as quality flags. Magnetic field investigation (MAG) is a magnetometer that measures the magnetic field environment [8]. The MAG instrument provides a magnetic field along the B_X, B_Y, and B_Z in MSO coordinates and Magnetic Field RMS BRMS Deviation. The Solar Wind Ion Analyzer (SWIA) measures solar wind characteristics around Mars [9]. Solar wind dynamic pressure, solar is computed on the SWIA ground from density and velocity moments, assuming 100% protons by SWIA. Quality flags are 0/1 (bad/good). NASA maintains the Planetary Data system (PDS), an online archive that identifies, collects, and examines data to the worldwide community of planetary science researchers (https://www.pds-ppi.igpp.ucla.edu). The data labelled as 'insitu-Calibrated/Level-2' encompasses fully processed data from the Particles and Fields package and NGIMS, together with ephemeris information in 'TAB' delimited files. Headers of tabulated data are available with attached 'XML/label' files for the required data. These data are in physical units and available in uniform timestamps. First, algorithm checks for data duplication and eliminates duplicate copies (retaining the latest version) of data from local storage. Above mentioned process is a scalable process, and in our testing, it does not affect the overall storage/processing structure. Then algorithm computes the theoretical parameters of the density gradient, magnetic field components, thermal and magnetic pressures and ion and electron temperatures and examines relationships between these parameters.

B. Analysis

Following are the steps of the analysis [10]:

1) *Segmentation:* Segmentation divides the process into different segments (based on orbit number) and each segment can contain a set of orbits upon which same functions will be applied. It is a pre-processing practice used to diminish the chance of any errors.

2) *Processing:* In order to maintain consistency in identification of an ionopause from segment, after feeding it to the operation, certain criteria are followed. The ACID approach is applied to the output of the process.

a) *Atomicity*: This checks whether all four processes occur simultaneously. Each process upon completion returns an integer (0 or 1) along with the output. A predefined *4×1* integer vector is used to store the output. The integer '1' is returned when the segment satisfies the conditions and '0' otherwise. A possible detection of ionopause requires all process to return integer '1'. This involves the following two operations.

- *Abort*: If any process returns '0', the segment is discarded and the algorithm calls next segment.
- *Commit*: If all process returns '1', the processed segment undergoes further scrutiny. Atomicity is also known as the 'All or nothing rule'.

b) *Consistency:* This module checks the integrity so that the database is consistent before and after the process. The number of row elements are checked for the correctness of a database. The total amount of segment elements before and after the processes must be maintained. If segment is consistent, the processed segment undergoes further scrutiny.

c) *Isolation:* This ensures that even after every process can occur concurrently without modification of the segment. This safeguards that the implementation of process will result in a state that is equivalent to a state achieved these were executed parallelly in same order. The orbit number is marked and extracted.

d) *Durability:* This ensures that once the process has completed execution, the updates and modifications to the segment are stored and written to collection for redundancy, in case a system failure occurs. Data is checked for a potential ionopause detection. If the gradient is less than an order of magnitude, we mark it as an ionopause pattern. If not, then we discard all the information gained by these processes and iterate over next orbit/segment from scratch in an incremental way. Before discarding the data, this algorithm avoids stores it, in so doing, it achieves a running time of () which is optimal in the worst

3) *Detection Criteria:* Our selection criteria require sharp decrease in the total ion and electron densities by an order of magnitude with altitude range less than 50 kms. Such a sharp density gradient is a classic signature of an ionopause. Simultaneously, a sudden decrease and increase in the electron density and temperature, with increasing altitude is required, respectively. Based on recent literature, we also condition that horizontal magnetic field must be larger than radial field ($B_H > B_R$). Finally, the ionopause must coincides with significant thermal pressure reduction with increasing altitude.

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II. LITERATURE SURVEY

Mars does not have any dipole magnetic field. Therefore, the solar wind unswervingly interacts with its atmosphere and ionosphere. The ionopause is the uppermost region where the ionosphere ceases. Studies have revealed that the ionopause-like feature was consistent with observations at Venus [11]-[13]. The Viking 2 probe detected ionopause at about 300km altitude during the entry of the Viking 2 probe [14]. Later, the Mars Global surveyor observed the median altitude of ionopause ~ 360 km for the daytime [15]. However, ionopause for nighttime may lie between 300 and 500 km with ionopause thickness between 10-20km [16],[17]. Luhmann et al. [18] defined 'a layer' where the currents split the cold-dense ionospheric plasma from the hot, tenuous and magnetised solar wind as ionopause and photoelectron boundary (PEB). The ionopause is an abrupt break in the ionospheric electron density [19] whereas, photoelectron boundary (PEB) is a reduction of CO_2-photoelectron fluxes in the electron energy spectrum [20]-[22]. From Local electron density profiles, the ionopause altitude increased at locations with crustal magnetic fields. A mean ionopause altitude is relatively constant, around 390 km, along with a mean thickness is 37.5 ± 20 km, associated with ion cyclotron frequency [23].

Han et al. [24] Discrepancy between ionopause and photoelectron boundary determined from Mars Express measurements. Two indicators usually recognise the interface: the ionopause identified from ionospheric density profiles and the photoelectron boundary (PEB) determined from the electron energy spectrum at higher energies. Vogt et al. [25] studied 86 ion density profiles using an automated routine to search Ionopause-like density gradient. They suggested the presence of a magnetic field. Their selection criteria required decreased ion density by at least an order of magnitude. The altitude of ionopauses lies between 270 to 464 km, with an average value of 344 km. Recently, after analysis of using more than 6,000 orbits of Mars Express RADAR datasets, the average ionopause altitude of 363 ± 65 km was reported, and strong crustal magnetic fields restricted its formation [26]. Recently Mars' Ionopause was studied in the light of solar wind Pressures [27]. The total ionospheric pressure (thermal + magnetic) becomes equivalent to the solar wind dynamic pressure using the specific data provided from the MAVEN Deep Dip campaign (when spacecraft orbit reaches an altitude of about 120km). Electron temperature has also been considered a new parameter. The major drawbacks of these studies were the lack of unification, and the limited dataset was studied. Different studies focused on different parameters due to a lack of simultaneous observations. From the literature, it is clear that automation has been utilised in recent years. However, the Martian ionopause is still not completely understood because of its formation, location, impact of magnetic field, range of altitudes, and structure. Therefore, it allows investigating from a fresh perspective.

III. PROBLEM FORMULATION

The Martian ionopause is studied from different orbiter observations. The ionosphere model and data suggest that orbital bias, uneven sampling. Moreover, solar wind conditions can affect ionopause detections. Past studies have revealed many comparisons among the ionopauses at Mars and Venus. Few recent studies suggest that horizontal magnetic fields may play an essential role in forming the ionopause-like structure in the upper ionosphere in the daytime. These studies required many files to analyse, classified into two categories, i.e. magnetised region and non-magnetised regions of Mars. Observational studies have verified that sharp decreases in the electron density occur at ionopause and increase at locations with strong crustal magnetic fields. However, the process that controls the formation of the ionopause at Mars is not entirely known. We have applied our sequential and parallel code to MAVEN orbit segments as shown in Fig. 1, which orbit 8986 measures at day time at latitude 20° at altitudes below 400 km. The case 1 for single orbit, case 2 for a segment, and case 3 as monthly data was tested.

IV. PROPOSED WORK

In this section the implementation setups used for detection of ionopause using the algorithm are described.

A. Implementation Procedure

As discussed in literature survey, there is a problem of processing of data in sequential, which is the main challenge in data forensics. So, there is a need for improvement in the data security techniques for better efficiency and more efficient algorithm for enhancing security.

The following method is implemented on MATLAB. Following are the steps taken:

1) *Step 1:* Read data
2) *Step 2:* Data Segmentation into unique orbits, check quality parameters (error, uncertainty, quality flags), starts iteration over orbits. Different orbits can have different size of array, depending on their size. This reduces the bigdata into smaller chunks sent to parallel processing workers and will it take less time to process.
3) *Step 3:* Each orbit is then sent into four parallel processes: (i) the density gradients, (ii) magnetic field components (iii) electron temperature (iv) Magnetic and thermal pressures, are computed using eqs (1-4), returns 1 or 0 upon completion.

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4) *Step 4:* If all process returns '1', an event is detected and orbit processed for further processing. Otherwise, it is registered as discarded and algorithm jumps to the next orbit.
5) *Step 5:* In this step, the data volume is checked. Orbits with consistent and sufficient datapoints are considered. If the data is scattered/sparse then the algorithm will register and discard the orbit and jumps to the next orbit.
6) *Step 6:* Here pattern analysis is performed. A typical ionopause is formed when a balance of magnetic and thermal pressures occurs. Once this criteria is fulfilled, and ionopause is considered to be detected. Otherwise, it is registered as discarded and algorithm jumps to the next orbit.
7) *Step 7:* Iteration is completed. The final parameters from the results are visualised. It is stored in the memory.

Although the algorithm is robust and works accurately in out testing, we also perform visual inspection to eliminate any chance of computational error. We name our algorithm as the YAILDA (Yet-another Automated Ionopause-like Detection Algorithm) developed to detect ionopause from MAVEN datasets.

B. Implementation Setup

The software used to implement our proposed algorithm is MATLAB. MATLAB, developed by *MathWorks* is a high-level language which provides a wide variety of toolboxes to develop algorithms, graphically visualize data, create computational models and applications. It has built-in math functions which helps us to test multiple approaches and find resolution faster than with spreadsheets or conventional programming languages, such as C/C++ or Fortran. We chose MATLAB because of the following reasons:

1) Well-known language for numerical computation and visualization
2) Parallel processing environment for iterative study and problem solving
3) Scalable for HPC for maximizing performance
4) Built-in graphics for visualizing data and can make custom plots In the present algorithm various functions from MATLAB toolboxes used as follows:
5) Parallel Computing Toolbox
6) Statistical Toolbox

V. METHODOLOGY

A. Methodology Used

This section describes a methodology and its related parameters, experiment factors.

1) *System Parameters:* The experiments are conducted using Intel quad Core 64-bit Intel i7 processor with 8 GB RAM disk size of 500 GB. The implementation is done in the MATLAB. In this report, the algorithm has been implemented on Sequential and Parallel processing of the above configuration in three different cases.
2) *Experimental Parameters:* In order to evaluate the effectiveness of the proposed technique in the ionopause-detection. The two parameters are must be determined.

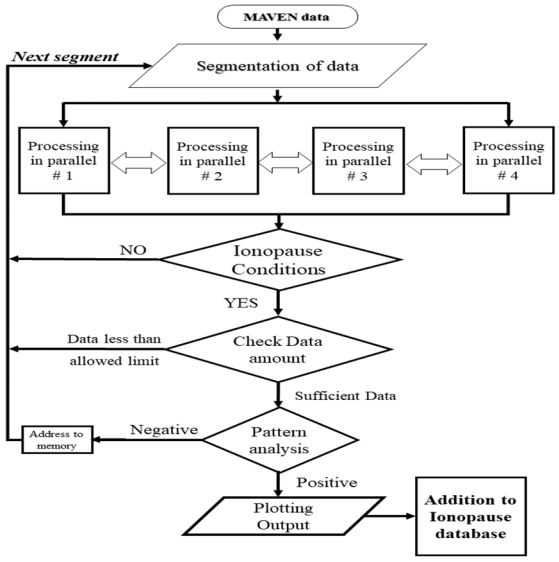


Figure 5.1: The Flowchart explaining Data processing by YAILDA

B. Detection

Our selection criteria require sharp decrease in the total ion and electron densities by an order of magnitude with altitude range less than 50 kms. Such a sharp density gradient is a classic signature of an ionopause. Simultaneously, a sudden decrease and increase in the electron density and temperature, with increasing altitude is required, respectively. Based on recent literature, we also condition that horizontal magnetic field must be larger than radial field ($B_H > B_R$). Finally, the ionopause must coincides with significant thermal pressure reduction with increasing altitude. The following equations are used to estimate the physical quantities and each calculation returns either '1 or 0'.

1	Density Gradient	$(\Delta n) = n_b - n_e$
2	Thermal Pressure & Magnetic Pressure	$(P_{th}) = N_e k_B (T_e + T_i)$ *(units dyn.cm^{-2})* $(P_{mag}) = B^2/\mu_0$ *(units dyn.cm^{-2})*
3	Electron temperature	$(\Delta T_e) = T_b - T_e$ *(units Kelvin)*
4	Magnetic field component	$B_R = B_X(X/R) + B_Y(Y/R) + B_Z(Z/R)$ $B_H = \left(\lvert B\rvert^2 - B_R{}^2\right)^{1/2}$ $B_T = \left(B_X{}^2 + B_Y{}^2 + B_Z{}^2\right)^{1/2}$ *(units nT)*

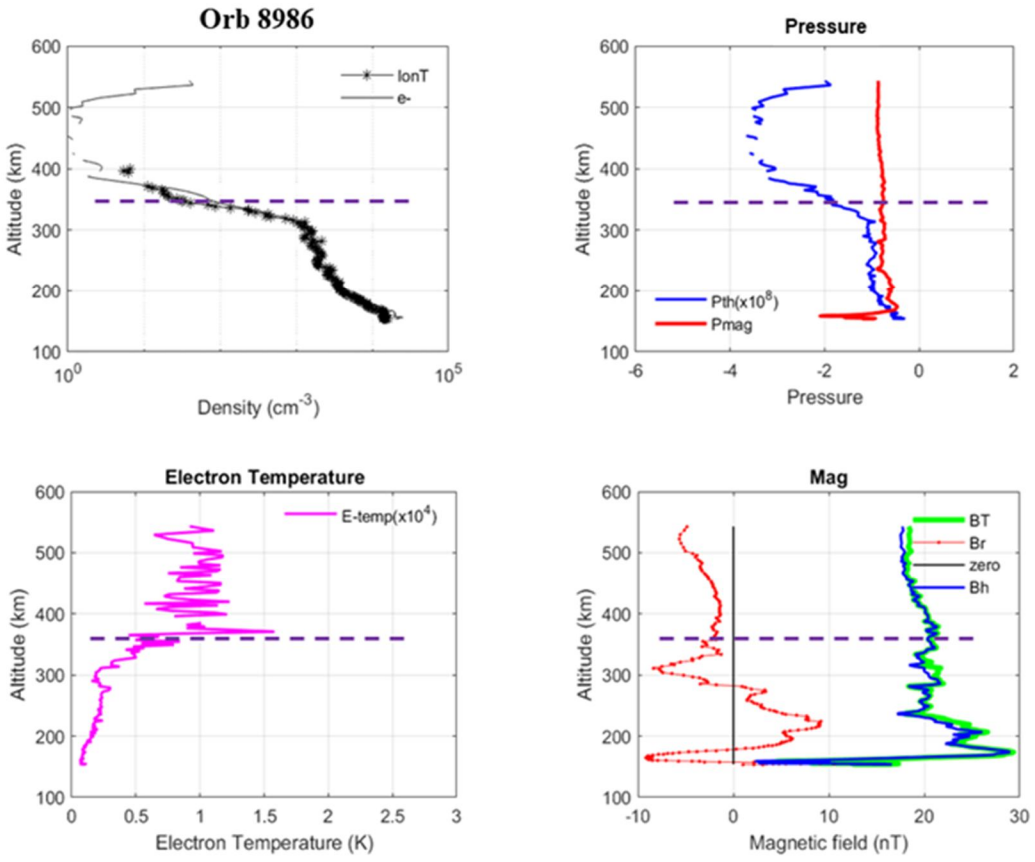


Fig. 5.2 Orbit 8986 Altitude profiles of the (a) Total ion and Electron density (b) Magnetic and Thermal pressure (c) Electron Temperature and (d) Magnetic field components. The ionopause is marked with dashed line.

Our conditions to recognize the ionopause is seen as simultaneous changes in both the Fig 5.2. The predicted ionopause is marked as dashed-line. The sudden electron density decrease, coincident with electron temperature fluctuations of least a factor of two, and magnetic field criterion. We have combined quantitative approach. As shown in Figure 5.2, the horizontal magnetic field is larger than radial field ($B_H > B_R$) at altitudes below 200 km which is also marked.

C. Time Processing

The time processing is defined as the two sets of functions for measuring absolute elapsed time: clock and e-time. For sequential run 'tic/toc' functions are applied. For the parallel run, to track elapsed time, a small function is added.

VI. RESULTS ANALYSIS

In this section, we present an evaluation of the proposed method's significance by using the parameters. We have generated the charts of our proposed method by using two parameters first is time processing, second is file size involved. In these graphs, we have several files which are to be processed. The Runtime returns the execution time required to compile MATLAB components. The Self Time gives the amount of CPU time spent executing that function, excluding any other functions that it calls. Thus total time is calculated by subtracting the self-time from run time. We have shown all processes and time taken by them as individual cases. In sequential and parallel processing, testing is carried out on single orbit, segment, and monthly data. The performance achieved is reflected in the table shows shown below.

A. Case 1 (Single Orbit)

In this scenario, single orbit is processed in sequential and parallel. In sequential processing files take about 10% much more time to process. There is a marginal advantage of processing of as the orbit data is very small.

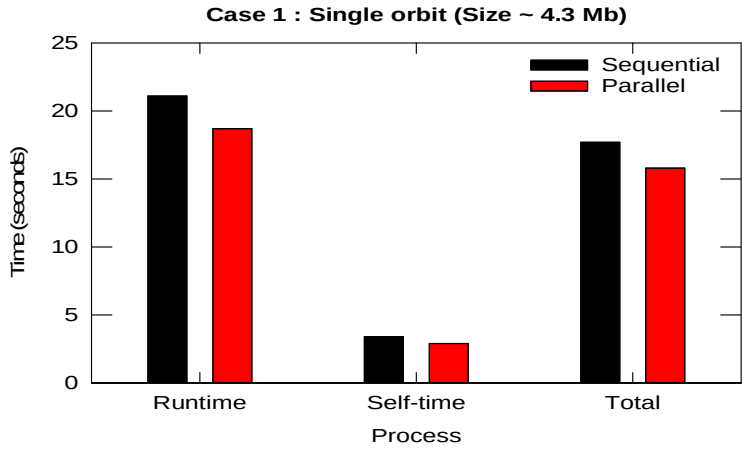


Fig. 6.1 Time taken to process single orbit in sequential (black colour) and parallel (red)

B. Case 2 (Segment)

In this scenario, a segment is processed in sequential and parallel. We can clearly see from the figure 6.2 that parallel processing has a little advantage. In this case, parallel processing of a segment is about 15% faster compared to sequential. There is a marginal advantage as the algorithm starts to register the discarded orbits in the segment.

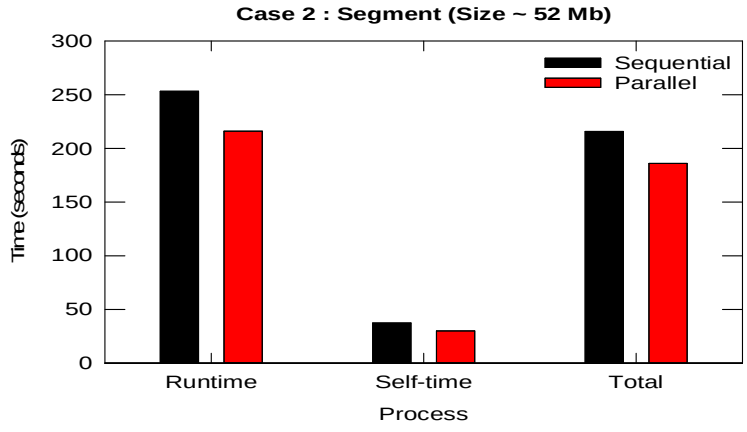


Fig. 6.2 Time taken to process Segment in sequential (black colour) and parallel (red)

C. Case 3 (Monthly Data)

In this scenario, a monthly data is processed in sequential and parallel. We can clearly see from the figure 6.3 that parallel processing has a great advantage. In this case, parallel processing of a segment is about 25% faster compared to sequential. There is a clear advantage as the algorithm performs way better and also registers the discarded orbits in the segment.

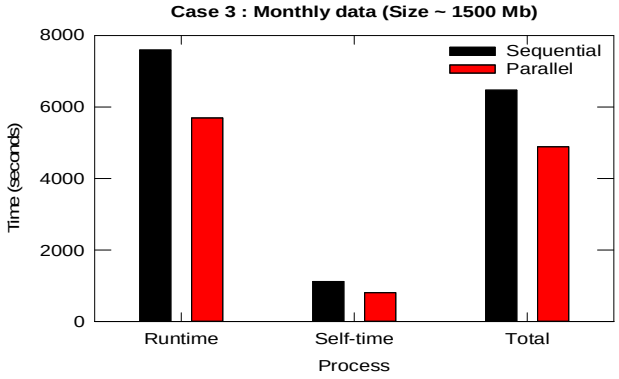


Fig.6.1 Time Taken to Process Monthly Data in Sequential (Black Colour) and Parallel (Red)

VII. CONCLUSION

In this paragraph, the proposed algorithm result is displayed in table A. The simulations have improved upon the time factor that tested. Earlier, only selective parameters were considered due to limited datasets and computational limitations. However, this is the first step to utilise automation, combined with parallel processing instead of sequential processing, to reduce the overall time required to process the data. The proposed algorithm presents a novel technique to detect ionopause more efficiently. Results of the parallel processing have been much better than the previous results.

TABLE I: Time Consumed in Sequential and Parallel Processing

	Sequential Processing		
	Case #1	Case #2	Case #3
Runtime	21.1	253.2	7596.0
Self-time	3.4	37.4	1122.0
Total time	17.7	215.8	6474.0
	Parallel processing		
	Case #1	Case #2	Case #3
Runtime	18.7	216.0	5697.0
Self-time	2.9	30.0	807.4
Total time	15.8	186.0	4889.6

VIII. FUTURE SCOPE

PRL's Computer Centre has Vikram-100 High-Performance Cluster having 100TF sustained performance. The use of HPC in the assessment of Martian ionospheric response using advanced computational analysis is an emerging field of research that can unravel new insights that were not possible earlier. Although being extensively studied, the Martian ionosphere is not understood completely. There are several opportunities due to the growing wealth of data from spaceborne observations. In our approach, we have presented a unique solution to identify ionopause-like structures from the concurrent ionospheric database of the MAVEN mission. To fully understand the formation of the ionopause at Mars, we will revise our algorithm to understand the response of solar input. In future, we plan to expand this technique for long term datasets to harness the Vikram-100 High-Performance Compute Cluster capabilities [28, 29].

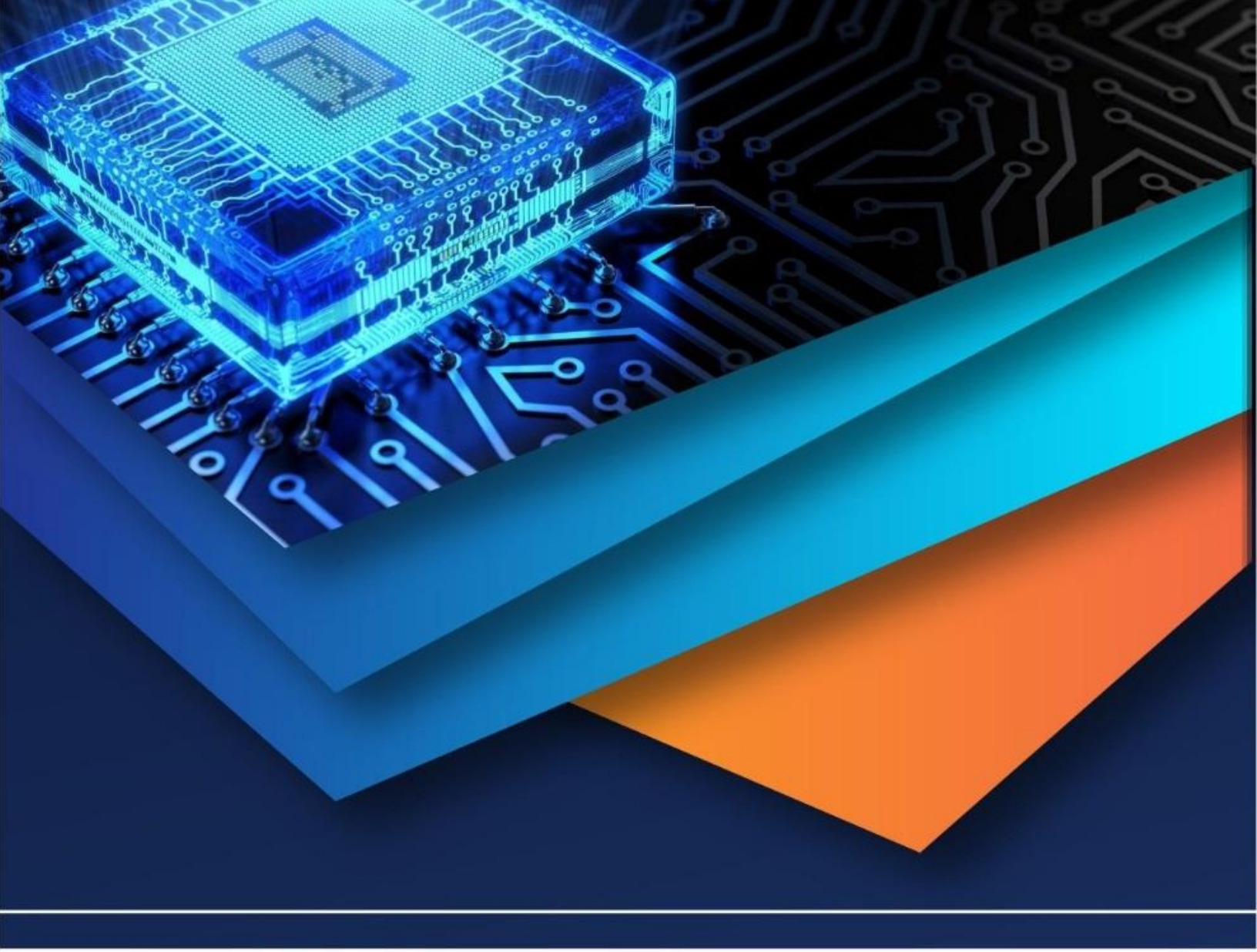
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IX. ACKNOWLEDGEMENT

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