The Heart of NavIC-Navigation with Indian Constellation

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ABSTRACT

Global Navigation Satellite System (GNSS) has become indispensable for various applications worldwide. Regional navigation satellite systems cover the regions up to 1500 km^2 providing the Positioning, Navigation, and Timing (PNT) solutions. Navigation with Indian Constellation (NavIC) is such a regional system, now having its own indigenously developed space atomic clock - the Indian Rubidium Atomic Frequency Standard (IRAFS) that was launched onboard NVS-01 providing services to the Indian subcontinent. This paper provides an overview of the successfully developed IRAFS technology and its performance capabilities meeting the stringent space clock requirements for NavIC, and provides directions for the future aspects that could improve the technology further.

Keywords: NavIC, GNSS, Rubidium, Atomic Clock, IRAFS, Satellite, Positioning, Navigation, Timing (PNT).

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INTRODUCTION

You are visiting New Delhi for the first time and do not know to navigate on your own. It is raining heavily, and you want to reach your hotel soon as you can. Booking an Uber to reach your destination is the best option – in this scenario, both you and the Uber driver need to locate each other first – to pick you to start your journey towards the destination. How does the Uber app know your and the moving car's exact locations? What is the technology behind this which enables such useful applications? Well, the satellite technology behind this is known as Global Navigation Satellite System (GNSS).[1] GNSS is a combination of various navigation systems, such as Global Positioning System (GPS) of the United States of America, Galileo Navigation System of the European Union, Global Navigation Satellite System (GLONASS) of Russia, and COMPASS/BeiDou of China. Two regional satellite systems can be added to the GNSS; the Navigation with Indian Constellation (NavIC) of India and Quasi-Zenith Satellite System (QZSS) of Japan.

Accurately knowing one's position (or location) means, there must be accurate time behind this, as per the relation, velocity = distance/time. As the velocity of light (or electromagnetic radiation or signals) can be accurately determined traversing in any medium as per its refractive index, to estimate precise position, *precise time* is the key factor. With the maximum velocity of light of 300 million meters per second, one nanosecond (one billionth of a second) corresponds to 30 cm of positioning accuracy. Therefore, we need precise clocks for navigation purposes, and such clocks are known as Atomic Clocks or Frequency Standards – which form the heart of any navigation system. The other well-known applications of the atomic clocks (or GNSS) are telecommunication network synchronization, power grid synchronization, aviation, high-speed internet, banking, stock markets, astronomical observations with wide-band array of telescopes (eg. imaging of blackholes), accurate weather predictions, scientific experiments, autonomous vehicles, Unaided Ariel Vehicles (UAVs) and many more.[2] In general, any aspect that requires accurate time down to nanoseconds and better simply cannot ignore *the atomic clocks*. There are various kinds of atomic clocks, that can be broadly categorized as the ground-based atomic clocks and the space-based atomic clocks.[3] The ground clocks include the cesium beam clocks, the cold atom fountains, and the active hydrogen masers, whereas, the Rubidium (Rb) clocks, passive hydrogen masers and mercury clocks are in the space clocks category. For the space clocks, the Size, Weight, and Power (SWaP) are the important factors to be considered – because sending just one kilogram of mass to space typically cost about 100,000 dollars (or 80 lakh rupees). Therefore, each space clock costing up to half million dollars. Due to the strategic and ubiquitous applications, atomic clock technology is a valued asset of any country. Only a handful of countries know how to build the space clocks; the US, Russia, Switzerland, China, and now, India has proudly joined these elite nations. The first ever Indian space clock, also known as Indian Rubidium Atomic Frequency Standard (IRAFS) was developed at the Space Applications Center

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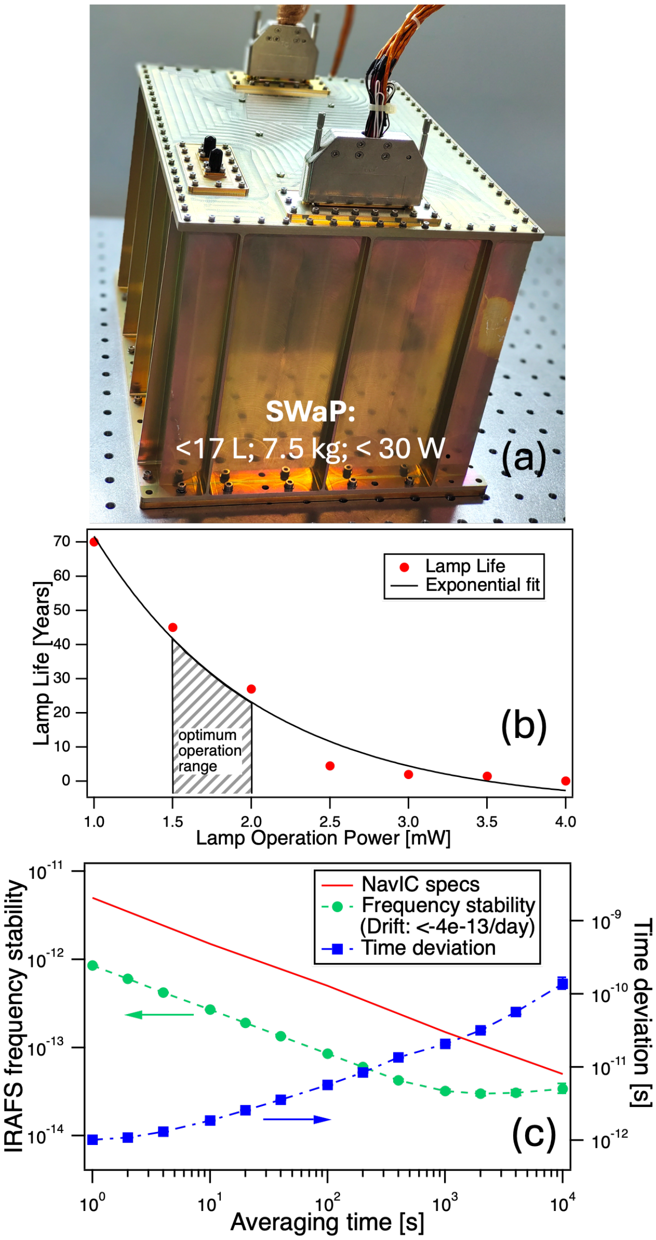

Figure 1: (a) Indian Rubidium Atomic Frequency Standard (IRAFS). A similar Flight Model unit was flown onboard NVS-01; (b) is an estimated Rb lamp life as a function of its RF operation power, ideally operating between 1.5 to 2 W of power ensures a longer life up to 40 years, and (c) shows the typical frequency stability of IRAFS and the time deviation over an averaging period of 10,000 s.

(SAC) of the Indian Space Research Organization (ISRO) and has been successfully launched onboard the Navigation satellite (NVS-01). The Rubidium Atomic clock works on precisely measuring the quantum energy transitions between the ground states of the Rb atoms at 6.8 billion oscillations in a second, thereby using this atomic signal to discipline a quartz oscillator operating at 10 MHz,[3,4] therefore the eventual atomic clock output is at 10 MHz. The IRAFS has been in continuous operation since July 2023 providing the accurate timing signals for the precise navigation operations, as part of the NavIC (Navigation with Indian Constellation) system.

Figure 1a shows a typical space qualified IRAFS with Size, Weight, and Power (SWAP) values of <17 liters, <7.5 kg and <30 W, respectively. Figure 1b shows the estimated optimum operation power of Rb lamp for long-term operation in space up to 40 years, and 1c shows the typical frequency stability performance and the time deviation down to 0.2 ns over 10,000 s of averaging time. Due to the clocks continuous visibility in the regional system, these units are synchronized within 10,000 s period to the stable ground segment clocks such as active hydrogen masers, thereby ensuring the timing errors are well with in 1 ns.

At first, the Rb atomic clocks were procured for the initial satellites, but having the indigenous technology gives India the needed independence and space prowess in the field of navigation. The IRAFS has shown performances better than the previously procured clocks, with stabilities of $<1e\text{-}12\ \tau^{-0.5}$ down to <5e-14 at one day time periods.[5] Thanks to the visionaries of ISRO and the excellent technical team, and the dedicated and focused technical leadership, which made this complicated technology indigenously possible as a gift to the India's technological growth by empowering the vision of Aatmanirbhar Bharat.

CONCLUSION AND PROSPECTS

Complex space clock technology has been successfully realized in the form of IRAFS for NavIC, strengthening it as an independent satellite navigation system. The performances of IRAFS meeting the stringent specifications in its maiden attempt is an excellent feat. The long-term performances over a day could be further bettered by improving the thermal behavior of the clock. Furthermore, the conventional Rb lamp technology for optical pumping could be replaced with laser module, thereby tapping the full potential of the excellent Rb Physics Package to reach the performance levels closer to the shot-noise limit of $5e\text{-}13\ \tau^{-0.5}$.

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Dr. Thejesh N. Bandi is an Associate Professor at the Department of Physics & Astronomy and Principal Investigator of the Quantime: Precision Navigation, Timing and Frequency (PNTF) Lab [Quantime.ua.edu], at the University of Alabama, USA, and he is an IEEE senior member.

Dr. Bandi with 18+ years of research experience has contributed to precision spectroscopic studies, compact ground, and space clocks – the recent being successful first ever Indian Rubidium clock onboard NavIC constellation which he led the design and development at the Indian Space Research Organisation (ISRO) as Head of the clocks division. His background, achievements and contributions were covered by Zeroing-In podcast series that appeared during December 2023 on various social media platforms.

Dr. Bandi has a PhD from University of Neuchâtel, Switzerland, and was a postdoctoral fellow at NASA's Jet Propulsion Lab (JPL) / Caltech, USA. His research interests span from basic atomic and ion spectroscopy to its novel implementation methods with the atomic and optical clocks; quantum metrological studies; time scales and synchronization schemes; and Artificial Intelligence (AI) novel methods for time and frequency metrology and safe GNSS. Dr. Bandi is also active in training the next-generation skilled manpower for the sustenance and growth of the PNT field.

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