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Developing a network time server for LEO optical tracking

Tu Tran Anh, Thuc Nguyen Van, Huy Le Xuan
Vietnam National Space Center, Vietnam Academy of Science and Technology, Hanoi, Vietnam

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ABSTRACT

In 2021, to enhance the Vietnam's capability in space situational awareness, Vietnam National Space Center started to develop a space surveillance and tracking system using optical telescopes. An important part of the system is getting accurate timing to guarantee high quality astrometry measurements. A time server was self-developed to meet the demand. The device takes reference time from global navigation satellite system (GNSS) and synchronizes the time to all computers in the network using network time protocol (NTP). GNSS antenna, GNSS receiver module, and Raspberry Pi 4 were used to build a simple stratum 1 NTP time server. The device works smoothly, the synchronization is accurate and stable in both the server and the clients.

Corresponding Author:

Tu Tran Anh
Vietnam National Space Center, Vietnam Academy of Science and Technology, Vietnam
VNSC Building (A6), 18 Hoang Quoc Viet, Hanoi, Vietnam
Email: tatu@vnsc.org.vn

1. INTRODUCTION

With the rapid increase of the number of satellites and space debris in orbit nowadays, a space surveillance and tracking (SST) system needs to be established so that a space agency can monitor the satellites and predict potential collisions [1]–[5]. In 2021, Vietnam National Space Center (VNSC) has started a project to build an SST system for Vietnam. As a new player in the field, VNSC first focuses on tracking objects in low earth orbit (LEO) using optical telescope instead of radar, as the system is simpler and less expensive to develop [5], [6]. A network of optical telescopes located in observatories across Vietnam are utilised to take images of the objects. The images will then be processed and analyzed using Artificial Intelligence to determine the orbital elements of the objects. The results will be cross-checked with available data to identify the object.

To track LEO objects using this method, a big challenge is rapid movement of orbital object. A satellite in LEO typically has the velocity around 7.6–7.9 km/s [7]. This rapid movement causes two main problems when taking image: long streak in the image if the exposure time is long, and astrometric error if the timestamp is inaccurate [8], [9]. In [10], [11] calculated a time error of 0.02 s causes 30 arcsecond residuals on the object along-track path, and recommend the time error not higher than 1 ms.

At VNSC, the computers controlling the telescopes are currently time-synchronized using the internet via public time servers. For this project, this setup has several problems such as low accuracy, low stability due to the internet connection, and security risks in opening port to the public servers [12], [13]. Therefore, a private time server should be equipped at each observatory. The devices will synchronize directly to a common accurate time source, then provide the time for the computers via local network. With this configuration, all computers will be time-synchronized with high accuracy, stability, and safety.

Time server has been used in many observatories, as well as SST project [14]–[18] to provide accurate timing with high security. However, the devices are commercial products and installed without dedicated study. In this paper, we aim to deliver a complete study and self-development of a time server for an SST system. The paper is structured as; section 2 provides the calculation of the timing requirement for the system. Section 3 and 4 presents the selection of time source and time protocol. Section 5 presents the procedure of building the device using commercial-off-the-shelf (COTS) components. The results are shown in section 6, and conclusions are given in the last section.

2. CALCULATION OF TIMING REQUIREMENT

Consider a satellite operating at the altitude of 400 km. Its velocity is derived from the formula [19]:

$$v_s = \sqrt{\frac{\mu_E}{R}} \tag{1}$$

where: μ_E: gravitational parameter of Earth, μ_E=398 600 ($km^3.s^{-2}$)

R: distance from the Earth's center, R=6378 + 400=6778 (km)

With these numbers, v_s=7.69 km/s. When taking photo of object moving at such high speed, if the exposure time is long, the object will cross more than 1 pixel during that time, resulting in a long streak. To determine the exact location of the satellite at the acquisition time, the exposure time must be very short so that the satellite crosses only one pixel. For a satellite at zenith, the exposure time t_E is calculated using the following formula [18]:

$$t_E = \frac{p_x H}{f v_s} \tag{2}$$

where: px: detector's pixel size. For the FLI-16801 camera using at VNSC, the pixel size is 9 µm [20]

H: orbital height of the satellite. H=400 km

f: focal length of the telescope. For the RC500 telescope at VNSC, f=4 m

vs: orbital velocity of, vs=7.69 km/s

With these values, the exposure time t_E equals 1.17×10^{-4} s. In practice, slightly longer exposure and small streaks are acceptable, but the time of exposure beginning and end must have the resolution of millisecond to guarantee good image quality. Another need for high timing accuracy is satellite orbit determination. Higher timing accuracy leads to more precise estimation of the orbit, but the technical work of achieving this accuracy will become more challenging. To set the acceptable orbit estimation error as project requirement, the proposed standard of ESA researchers in [21] were referred. The acceptable astrometry error of LEO satellite is selected to be 7 arcseconds RMS. To find the related timing error, the angular velocity of satellite needs to be calculated. For a ground observer, the apparent angular velocity is different with respect to the satellite position in the sky. When the satellite first appears at the horizon, the geometry is described in Figure 1.

In 1 second, the satellite moves 7.69 km, corresponding to the angle θ_h. To find θ_h, we need to find horizontal range D_h, distance from telescope to satellite after 1 second D, and angle α. Using basic geometry laws, we have:

$$D_h = \sqrt{(6378+400)^2 - 6378^2} = 2294\ (km) \tag{3}$$

$$\alpha = \frac{\pi}{2} - arcsin\left(\frac{6378}{6378+400}\right) = 0.345\ (rad) \tag{4}$$

$$D = \sqrt{{D_h}^2 + 7.69^2 - 2 \times D_h \times 7.69 \times \cos(\alpha)} = 2287\ (km) \tag{5}$$

$$\theta_h \approx sin\,\theta_h = \frac{7.69}{D}\sin(\alpha) = 0.00114\ (rad) \approx 0.065^o \tag{6}$$

The angular velocity is 0.065 (degree/s), or 0.235 (arcsecond/ms). When the satellite is at zenith, the range becomes the altitude of the satellite, as described in Figure 2.

In 1 second, the satellite moves 7.69 km, corresponding to the angle θ_z.

$$\theta_z \approx tan\,\theta_z = \frac{7.69}{400} = 0.019225\ (rad) \approx 1.1^o$$

The angular velocity is 1.1 (degree/s), or 3.96 (arcsecond/ms), about 17 times faster than the value at the horizon, and this is the worst-case scenario. The angular velocity means that if the time of image acquisition has an error of 1 ms, the position of the satellite in the image will have an error of 3.96 arcseconds. Therefore, to have good data for orbit determination, the timing accuracy should be within 7 (arcsec)/3.96 (arcsec/ms) ≈ 2 ms.

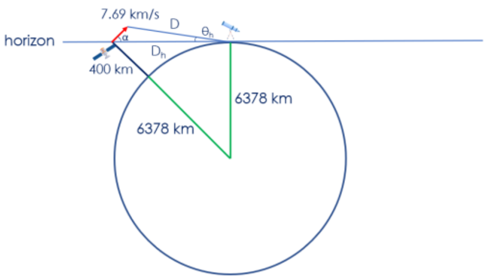


Figure 1. Satellite angular velocity at horizon

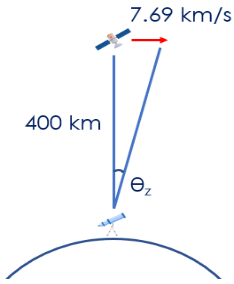


Figure 2. Satellite angular velocity at zenith

3. SELECTION OF REFERENCE TIME SOURCE

To meet the timing requirement and allow collaboration between observatories, all time servers need to refer their time from a common reliable source, which is the atomic clock [22]. However, the atomic clock itself is very expensive and needs specialists to be properly operated. Fortunately, the time signal from atomic clocks in other infrastructures is widely transmitted, via two means: radio signal from physics labs (such as MSF signal from NPL, WWVB signal from National Institute Of Standards And Technology NIST), and GNSS signal. The Table 1 compares the two options.

Table 1. Comparison between reference time sources

Criteria	Radio	GNSS
Source	Physics labs (NPL, NIST…)	GNSS satellites
Method of reception	Using corresponding antenna and receiver module	
Timing accuracy	< 30 ms [23]	< 40 ns [24]
Main affected factor	Topography	Surrounded tall buildings
Development cost	Less expensive	More expensive
Coverage	Regional	Worldwide

From Table 1, the GNSS signal, even though more expensive to develop, provides very accurate timing and worldwide coverage. Radio time signal does not meet the requirement, and also not available in Vietnam. Therefore, the GNSS is selected as the time source.

4. SELECTION OF TIME PROTOCOL

To synchronize time from reference source to all devices in a network, a time protocol must be specified. Two most popular protocols in use today are network time protocol (NTP) and precision time protocol (PTP). Table 2 provides brief comparison between the two.

Table 2. Comparison between NTP and PTP

Criteria	NTP	PTP
Timing accuracy	~ 1 ms [25]	< 1 µs [26]
Primary error source	End device	Routing, switch, port contention, devices
Mode of operation	Clients pull time from server	Master pushes time to slaves
System complexity	Simpler	More complex
Availability	Free standard, widely available	Paid standard, require specific components
Estimated cost to build using COTS components	Stratum 1 server: 650 $	Grandmaster: 2400 $

Even though PTP can provide very high accurate timing, its complexity and high development cost make it not a suitable choice in this project. NTP, on the other hand, is simpler and less expensive to develop, and its timing accuracy still meets the demand. Therefore, NTP is selected as the time synchronization protocol in the network, and a stratum 1 server will be built to provide the accurate time to other devices.

5. BUILDING A GNSS NTP TIME SERVER

5.1. System description

A GNSS NTP time server could be constructed following the schematic in Figure 3. There are three main parts in a time server: GNSS antenna, GNSS receiver module, and processing board. The antenna receives signal from GNSS, then transmits it to the receiver module to convert it to usable information. The receiver module provides two outputs to indicate the time: national marine electronics association NMEA data and a pulse per second (PPS) signal. NMEA data is the series of sentence which contains GNSS position, time value in UTC, and other information. However, it alone does not provide stable update rate for two reasons:

- The NMEA sentence which contains the time value are sent after the beginning of a new second along with other sentences. However, there is no fixed order in which these sentences are sent. So if the processing board receives a time value, it does not know exactly when the data was sent during this second.
- The GNSS receiver often sends NMEA data over universal asynchronous receiver-transmitter UART serial interface, which has transfer latency, depending on the length of the message and the communication speed.

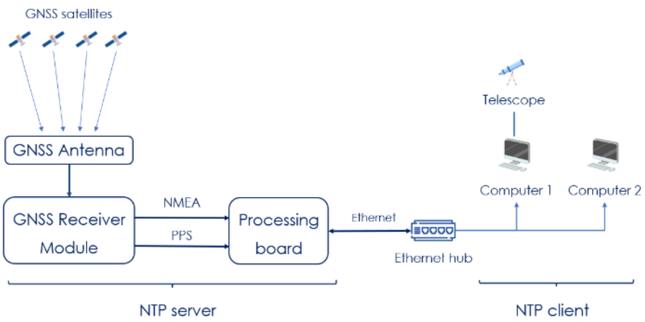


Figure 3. GNSS-based time synchronization system architecture

Therefore, a second output, PPS signal is required. PPS is an electrical signal that has a width less than 1 second and a sharply rising or abruptly falling edge that repeats exactly after 1 second, with error from 1 ns to 1 µs per second [27], [28], depending on the quality of the module. Normally the rising edge of PPS is used to mark the beginning of a second. The processing board takes the absolute time value from NMEA data, and use PPS signal to count the second, hence achieving accurate and stable timing. It will sync time to other computers in local area network LAN via Ethernet hubs and cables.

5.2. Hardware

The main components used to build the time server are:

- PCTEL 40 dB GPS timing reference antenna
- Ublox ZED-F9T 00B, a GNSS receiver module offering 5 ns timing accuracy [29], with temperature compensated crystal oscillator TCXO to maintain short-term stability.
- Raspberry Pi 4 model B, a single-board computer with integrated Ethernet port for LAN, general-purpose input/output GPIO pins for UART and PPS, and running Linux-based operating system with useful tools such as PPS supported kernel, GPS Daemon, NTP Daemon.

The connection between GNSS receiver module and the Raspberry Pi is shown in Table 3. A time server is built and set up in Nha Trang observatory, Khanh Hoa as depicted in Figures 4(a) to (c).

Table 3. Connection between GNSS receiver module and Raspberry Pi 4

GNSS receiver module pin	Raspberry Pi 4 GPIO pin
3V3	17 (3V3)
GND	39 (GND)
RX	14 (TX)
TX	15 (RX)
PPS	18 (PCM_CLK)

(a) (b) (c)

Figure 4. Time server in Nha Trang observatory (a) GNSS antenna, (b) telescope system, and (c) time server in the network

5.3. Software

Figure 5 presents the overview of software configuration to turn a Raspberry Pi 4 into a GNSS NTP time server. Three main steps are performed as:

a. Configure serial port

The GNSS module sends NMEA sentences over UART serial port at 38400 baud. On Raspberry Pi 4, the hardware UART by default communicates at 9600 baud, and is used for Bluetooth and to log in from other consoles. Therefore, to connect two devices, bluetooth, login shell and console login need to be disabled, and the communication speed of Raspberry Pi 4 is set to 38400 baud to match with the GNSS module.

b. Set up PPS and GNSS

To receive PPS signal, two works need to be done: enable the Linux special kernal support for PPS, and install *pps-tools*, the PPS standard package. To interpret data from NMEA and PPS, *gpsd*, the most popular GNSS service daemon would be installed and configured.

c. Set up NTP

For time server application, NTP is compiled from source code. The final, and also the key process is to feed time sources to NTP Daemon. From Figure 4, the NTP Daemon takes time data from two drivers: shared memory driver (SHM), and PPS clock discipline. The SHM receives its time info from a shared memory segment, which contains NMEA and PPS data from GNSS Daemon. This driver alone is enough to make NTP work. However, since PPS signal has a specific supported driver called PPS clock discipline, it is best to put this driver into NTP daemon as well. The selected NTP daemon is *ntpd*, and the configuration code is shown in Figure 6.

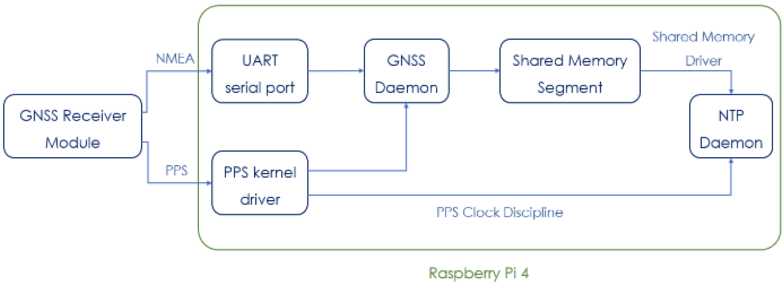


Figure 5. Conceptual overview of software configuration

```
#PPS Clock Discipline source
server 127.127.22.0 minpoll 4 maxpoll 4
fudge 127.127.22.0 flag3 1 flag4 1 refid PPS

#Shared Memory Driver source
server 127.127.28.0 minpoll 4 maxpoll 4
fudge 127.127.28.0 flag1 1 time1 +0.067 refid GPS

server 127.127.28.2 minpoll 4 maxpoll 4 prefer
fudge 127.127.28.2 flag1 1 refid SHM2
```

Figure 6. NTP configuration

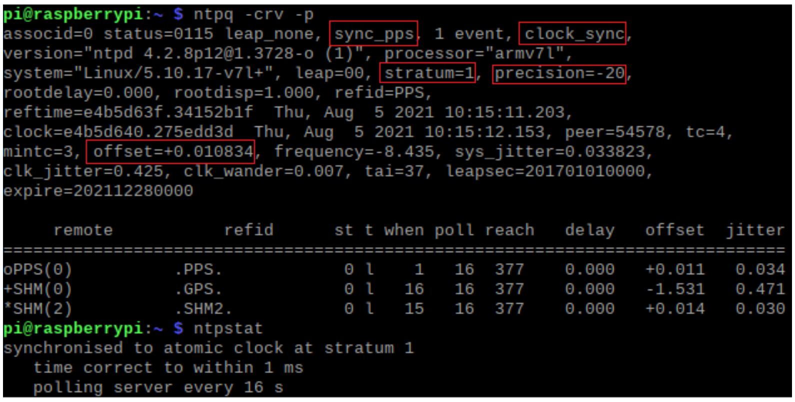
The first three lines configure PPS clock discipline, which is at address 127.127.22.0 (PPS 0). The minpoll 4 maxpoll 4 command tells NTP to poll data every 2^4=16 second. Flag3 1 enables kernel PPS discipline, while flag4 1 enables recording of PPS offset each second, which is useful to construct Allan deviation plot. Since this driver cannot number the seconds, an auxiliary source is required (SHM in this case), and this source should be specified as the prefer peer.

The rest of the code configures SHM. The NMEA data is at address 127.127.28.0 (SHM 0), the polling interval is also set to 16 seconds. flag1 1 tells NTP to skip difference limit check, which is used in case the real-time clock RTC backup cannot keep time over long period without main power, and the SHM clock must be able to force long initial jump. time1 +0.067 is the compensated time offset for the delay in UART, -0.067 s. This value is different for each receiver module, and it is determined by trial and improvement: The time1 value was initially set equal to 0, then the time server is let running for several hours, and the mean delay is calculated from the statistics log file. The last two lines configure PPS data from shared memory segment, which is at address 127.127.28.2 (SHM 2).

6. RESULT

6.1. Time server status

The quality of a time server is specified by its accuracy and stability. Accuracy describes how close is the time compared to UTC, while stability means how well a device can maintain its accuracy over a given time interval. The accuracy of the time server is shown in the status in Figure 7. In this status, two messages sync_pps and clock_sync imply that the device is now time-synchronized to the PPS signal from PPS clock discipline. The precision of the source is estimated to be 2^{-20} s. The device serves as NTP stratum 1, the system offset is 0.011 ms. A small jitter, the network latency of 0.034 ms is regarded. In general, the device is syncing to atomic clock source and the accuracy is within 1 ms. To check the stability, the device was let running for five days, the data were recorded and plotted in Figure 8.



```
pi@raspberrypi:~ $ ntpq -crv -p
associd=0 status=0115 leap_none, sync_pps, 1 event, clock_sync,
version="ntpd 4.2.8p12@1.3728-o (1)", processor="armv7l",
system="Linux/5.10.17-v7l+", leap=00, stratum=1, precision=-20,
rootdelay=0.000, rootdisp=1.000, refid=PPS,
reftime=e4b5d63f.34152b1f  Thu, Aug  5 2021 10:15:11.203,
clock=e4b5d640.275edd3d  Thu, Aug  5 2021 10:15:12.153, peer=54578, tc=4,
mintc=3, offset=+0.010834, frequency=-8.435, sys_jitter=0.033823,
clk_jitter=0.425, clk_wander=0.007, tai=37, leapsec=201701010000,
expire=202112280000

     remote           refid      st t when poll reach   delay   offset  jitter
==============================================================================
oPPS(0)          .PPS.            0 l    1   16  377    0.000   +0.011   0.034
+SHM(0)          .GPS.            0 l   16   16  377    0.000   -1.531   0.471
*SHM(2)          .SHM2.           0 l   15   16  377    0.000   +0.014   0.030
pi@raspberrypi:~ $ ntpstat
synchronised to atomic clock at stratum 1
   time correct to within 1 ms
   polling server every 16 s
```

Figure 7. NTP status of the time server

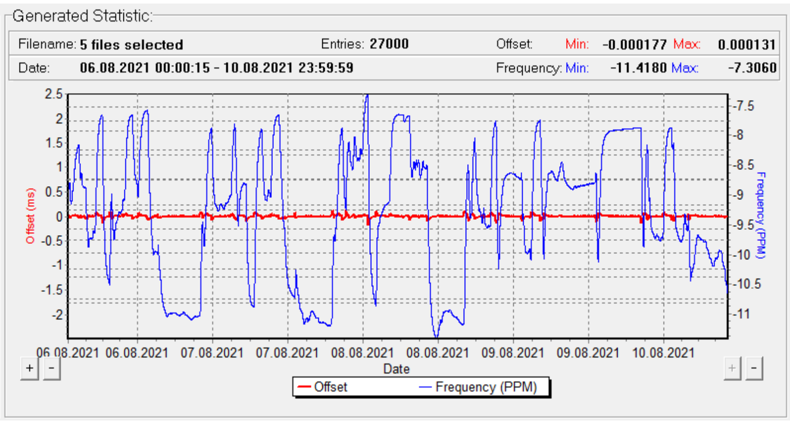


Figure 8. Variation in clock and frequency offset of time server

In Figure 8, the clock is found to be both accurate and stable, with mean offset=0.00026 ms and the variation is within ±0.2 ms. The stability is quantified using allan deviation instead of standard deviation because this tool is less affected by noise. It is calculated by comparing the time offset between consecutive measurement period. The allan deviation plot of the device is shown in Figure 9.

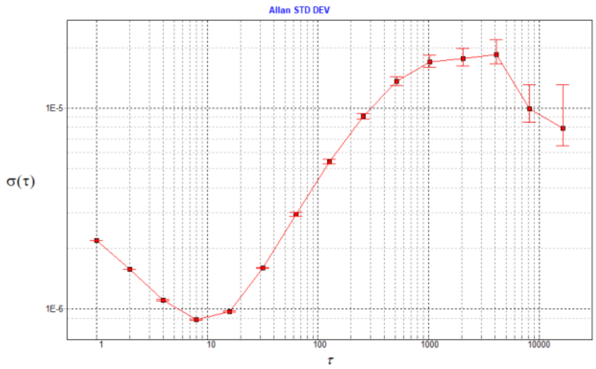


Figure 9. Allan deviation of time server

With short sample time τ=1s, Allan deviation $\sigma_y(\tau)=2.2\text{x}10^{-6}$. With longer τ, $\sigma_y(\tau)$ decreases because the noise has averaged out. The stability is best when the allan deviation is calculated with τ=8 s, $\sigma_y(\tau)=8.86\text{x}10^{-7}$. However, as τ becomes larger, $\sigma_y(\tau)$ starts increasing again, implying that the clock frequency is gradually drifting due to many factors such as temperature change, aging. The error bars get larger with τ because for large τ, it takes a lot of time to gather the data.

6.2. Sync with computer

A computer running Windows 10 is connected with the time server via 2-meter ethernet cable. After installing and configuring NTP on the computer, time synchronization is established, as shown in Figure 10. The computer now becomes NTP stratum 2, syncing directly to the time server at IP address 169.254.177.76, with offset=-0.088 ms and jitter=0.156 ms. A 0.344 ms delay is expected, as the effect of Ethernet cable. The stability of stratum 2 synchronization is plotted in Figure 11. It can be seen that the offsets are within ± 1ms, and the frequency varies very little from 2.281 to 6.351 ppm. In total, the time error of stratum 2 computer to GNSS clock is less than 2 ms, which meets the project requirement.

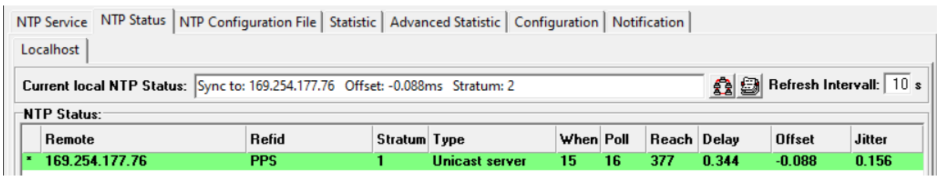


Figure 10. Time synchronization between computer and time server

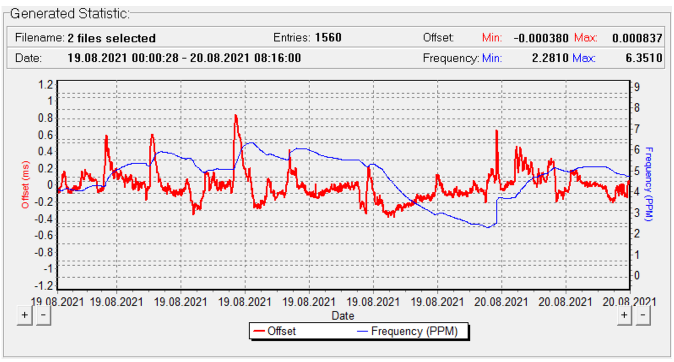


Figure 11. Offset and frequency stability of stratum 2 synchronization

7. CONCLUSION

A network time server has been successfully developed after a decent study. The device has an offset within 0.2 ms to GNSS clock, the Allan deviation at τ=1 s is 2.2x10^{-6}. It becomes a time source for another computer, the synchronization error is less than 1.5 ms. The computer therefore is able to synchronize its time to the GNSS with accuracy better than 2 ms, which is adequate to capture image of LEO object as it passes by. The device is currently being used in the observatories across Vietnam in the SST system. In the future, we plan to improve the accuracy and stability further, with maximum offset between computer and GNSS less than 1 ms, to improve the quality of the data.

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BIOGRAPHIES OF AUTHORS

Tu Tran Anh received MSc. Degree in Space: Earth Observation – Astrophysics – Satellite Technologies from University of Science and Technology of Hanoi (USTH) in 2021. Since 2018, he has been working at Vietnam National Space Center as researcher at Space System Design Department. His research are in the fields of satellite attitude and orbit control system (AOCS), GNSS technology and GNSS-based device. He can be contacted at email: tatu@vnsc.org.vn.

Thuc Nguyen Van received M.Eng Degree in System Design and Management from Keio University in 2015. Since 2013, he has been working at Vietnam National Space Center as a researcher at Satellite Assembly, Integration and Testing department, then Space systems Research and Development department. His research are focused on Command and Data Handling for nano, micro satellites engineering, high positioning accuracy GNSS receiver and its applications. He can be contacted at email: nvthuc@vnsc.org.vn.

Huy Le Xuan received Ph.D. Degree in Mechanical and Aerospace Engineering from Tokyo Institute of Technology in 2014. He has been working at VNSC since 2011 at Space Systems Design Department. Currently, he is the Vice Director General of VNSC. His research interests are development of small satellites for Earth observation, system engineering, satellite attitude determination and control, optimal estimation of dynamics systems. Involved projects: PicoDragon (1-kg satellite of VNSC), MicroDragon (50-kg satellite of VNSC), NanoDragon (4-kg satellite of VNSC). He can be contacted at email: lxhuy@vnsc.org.vn.