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RESEARCH ARTICLE

TDOA BASED TRACKING MEASUREMENT FOR GEO SATELLITES ORBIT DETERMINATION: EVALUATION FOR THE SATELLITE OPERATORS

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ABSTRACT

The satellite's orbit determination has recently evolved with new tracking data and data processing methods and algorithms developments. The satellite operators need the current and future motion of the satellites for operational purposes and use various methods to measure the tracking data. This study investigates the time difference of arrival (TDOA) based ground data measurement and processing of these tracking data to obtain orbital parameters and the communication satellite operators' use of the method. First, a conceptual ground station network was established to collect TDOA based tracking data. Then these data were processed to determine the orbits using a sequential process (SP) filter method. The results were analyzed by comparing radial, in-track, and cross-track positions and velocities for three satellites at different orbital locations. The mean root mean square error (RMSE) differences of radial, in-track, and cross-track (RIC) position values of three satellites are about 19 m, 5 m, and 1 m, respectively. Similarly, the mean RMSE differences of RIC velocity values are about 0.8 cm/s, 0.15 cm/s, 0.05 cm/s respectively. These values are below the success criteria that are satellite typical flight dynamics requirements. The estimated communication satellites orbit with TDOA based observation data are fully consistent with truth orbit parameters. The satellite operators can utilize the proposed TDOA measurement method with its benefits to estimate satellite orbit.

Keywords: TDOA measurement, Tracking data, Orbit determination, Communication satellite

1. INTRODUCTION

The satellite's orbit determination (OD) has been evolved over the decades with new developments in observations and data processing techniques. The satellite's orbit is the satellite's motion's knowledge in a specified coordinate system. The classical orbit determination relies on earth or space-based observation and gathering desired data, and then processing the data with various algorithms and methods. The orbital parameters obtained as a result of the orbit determination effort provide knowledge about the satellites' position in orbit with respect to time.

The estimation of the future motion of a satellite in the dynamical system requires a set of parameters. The minimum set of satellite orbit determination parameters in the orbit determination problem is the position and velocity vectors at the epoch. The prediction accuracy of OD can be improved by expanding the minimal parameters, including dynamic and measurement model parameters. However, the initial position and velocity vectors are not exactly known, and the exerted forces are only defined by approximation in mathematical modeling. This situation causes errors in the actual motion to deviate from the predicted model [1].

The satellite position can be determined by data of the observing or tracking stations whose locations are known flawlessly. The observed data usually consist of range, range rate, angles (azimuth, elevation), frequency difference of arrival (FDOA), time difference of arrival (TDOA), or other observable quantities. Unfortunately, these sets of data are subject to some errors, which affect the

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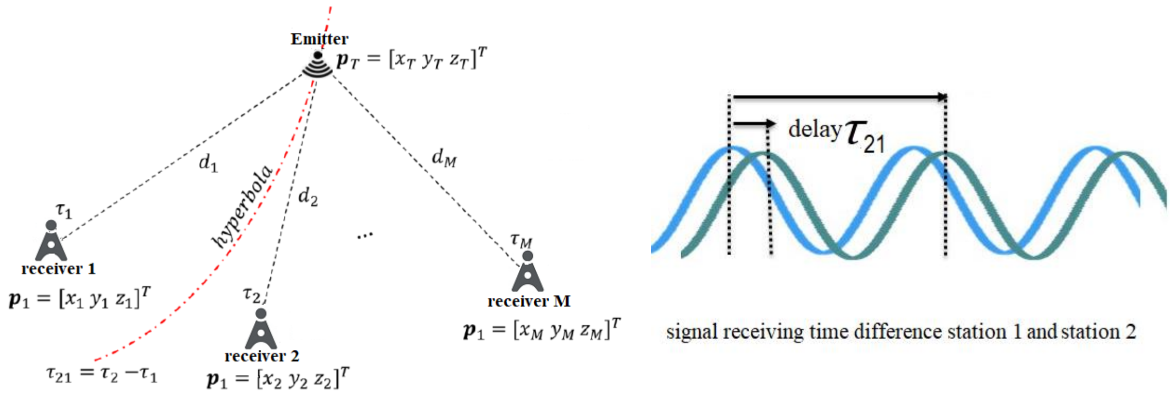
estimated orbit accuracy. The state variables (position and velocity) are not observable but non-linear functions of observed data. The aim of the orbit determination effort is to have a better estimation. The observed data and evaluation methods have both systematic and random errors. Consequently, the estimated orbit is not exact and has some deviation from the actual orbit.

The problem of state estimation is observation data of the satellite, which has an unknown initial state, random and systematic error effect, inaccurate mathematical model. The predicted orbit values of the satellite's ephemeris data (position and velocity components as a function of time) differ from truth ephemeris due to the following effects; inaccuracies in the calculated state vector (position and velocity vector), error in the mathematical model, errors in the observations, errors in the computational procedure. Other sources of errors are the dynamical model and computer truncation, and round-off. Consequently, since the satellites are moving, the process of observation and orbit evaluation must be repeated continually. Furthermore, the orbit determination accuracy can be increased by calibrated station biases, the precise location data of tracking stations, and well-adjusted station clocks [2,3].

In the ground-based TDOA measurement, the signal is generated by a static ground-based transmitter, and received by a communication satellite, and re-transmitted to the coverage area. Ground stations receivers, as shown in Figure 1(a), receive the re-transmitted signal. Figure 1(b) shows TDOA spectrum illustrations. The station distance difference (d_2-d_1) causes the late arrival of the signal at station 2 [4].



(a) (b)

Figure 1. TDOA based (a) general emitter receiver configuration measurement implementation (b)spectrum illustration of signal arriving at station 1 and station 2.

The difference in signal reception times between two ground stations are directly related to the distance of each ground station from the satellite. The acquired measurements can be expressed in the following Equation (1) [5].

$$\begin{aligned} d_i^2 - d_1^2 &= (d_1 + c\Delta t_{1i})^2 - d_1^2 = 2d_1 c\Delta t_{1i} + c^2\Delta t_{1i}^2 \\ &= x_i^2 + y_i^2 + z_i^2 - x_1^2 - y_1^2 - z_i^2 - 2[x_T(x_i - x_1) + y_T(y_i - y_1) + z_T(z_i - z_1)] \end{aligned} \quad (1)$$

where;
d_i : distance of the i-th station from the satellite, Δt_{1i} :measured time difference between the signal received at the first (reference) ground station and the i-th ground station, c: the speed of light, [x_T, y_T, z_T]: coordinates of the satellite (target) and [x_i, y_i, z_i] : the coordinates of the i-th ground station.

The TDOA equation in a linear system can be expressed in Equation 2 by taking the first station as a reference, and performing all the time and distance difference calculations according to the first station.

$$-2\begin{bmatrix} (x_2-x_1) & (y_2-y_1) & (z_2-z_1) & c\Delta t_{21} \\ (x_3-x_1) & (y_3-y_1) & (z_3-z_1) & c\Delta t_{31} \\ & \vdots & & \\ (x_M-x_1) & (y_M-y_1) & (z_M-z_1) & c\Delta t_{M1} \end{bmatrix}\begin{bmatrix} x_T \\ y_T \\ z_T \\ d_1 \end{bmatrix} = \begin{bmatrix} c^2\Delta t_{21}^2 - x_2^2 - y_2^2 - z_2^2 + x_1^2 + y_1^2 + z_1^2 \\ c^2\Delta t_{31}^2 - x_3^2 - y_3^2 - z_3^2 + x_1^2 + y_1^2 + z_1^2 \\ \vdots \\ c^2\Delta t_{M1}^2 - x_M^2 - y_M^2 - z_3^2 + x_1^2 + y_1^2 + z_1^2 \end{bmatrix} \quad (2)$$

The positions of a target can be estimated by solving the above Equation 2 by various methods.

In the literature, Time Difference of Arrival TDOA has a wide variety of applications, especially in the field of target (source) localization. TDOA networks support launch vehicle orbit determination and space missions. The sensor network design suitability can be estimated for spacecraft orbit determination. The dilution of precision (DOP) is a very useful operator that provides an accuracy of TDOA using relations between the receivers' time accuracy and the position errors [5].

Target localization using a group of sensor nodes with known locations has been widely utilized. TDOA method has been extensively studied in wireless communication, navigation, civil and military fields, and orbit determination. The TDOA method can achieve higher positioning precision and require fewer sensor nodes to gather the measurement data than FDOA [6].

The three satellites TDOA is a convenient method to locate the interference location source in satellite communication. The interference source determination via the intersection of the TDOA lines of position (LOP) may have two mirrored intersection points. The mirrored point can be eliminated based on a multi-moment measurement method [7].

Passive source localization estimates the positions of the source or emitters by having the receivers' data. Some of the well-known passive localization methods are analyzed, and the results are compared [8].

TDOA based method's accuracy vastly depends on the target sensor geometry. TDOA and FDOA measurements provide valuable information to estimate spacecraft orbit. In order to improve the accuracy of geostationary satellites orbits and the geolocation solution, solar radiation pressure estimation must be precise. The Fourier solar radiation pressure coefficients can be precisely obtained using FDOA and TDOA measurements [9].

TDOA measurements require exact data of the receiver locations to localize sources. The receiver location errors can cause a noteworthy decrease in source location precision. An algebraic solution can improve the source location prediction. [10].

The dual satellite geolocation system's performance can be improved using the TDOA method. When the geolocation error covariance matrix and the ephemeris error covariance matrix are combined, the results show better estimation [11].

TDOA localization method can be utilized to detect VSAT (very small aperture terminal) interference. VSAT earth stations can be deployed quickly and with minimum infrastructure, and one can reach rural areas easily. However, misaligned VSAT may interfere with the other satellite, and finding the source of interference is very difficult. The TDOA algorithm described in [12] shows promising results for determining the location of the source of satellite interference.

TDOA method overcomes the problem of positioning multiple target nodes in the presence of unknown turnaround times. Cramér–Rao lower bound (CRLB) can be used to estimate the performance of the method. The results provide that the cooperation technique has considerable improvements in positioning accuracy, especially for low signal-to-noise ratios [13].

TDOA international network can be utilized a geostationary communication satellite's passive correlation ranging. Tracked satellite's orbital parameters can be determined using measured values of the TDOA for different models of satellite motion. The results provide operationally applicable values [14].

TDOA based passive ranging for geostationary satellites and the classical tone-ranging comparison in terms of accuracy and operational complexity shows that TDOA ranging provides better orbit accuracy and reduced technical and operational processes to Eutelsat satellite operator. The developed cost model shows 43% less workforce, and cost reduction can be achieved. [15].

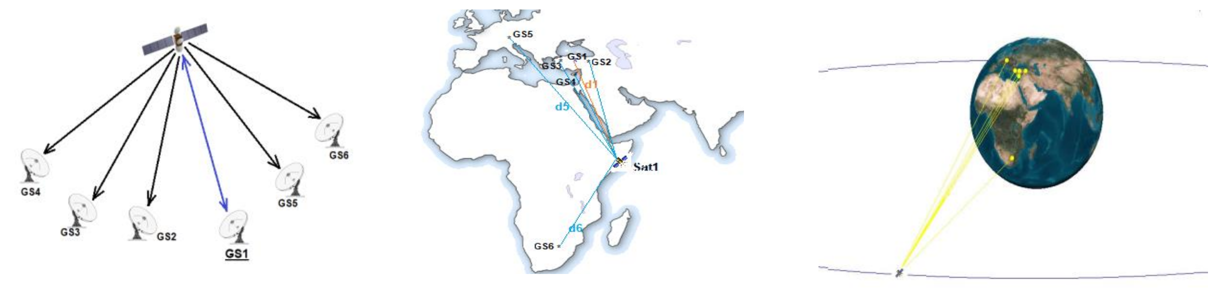
Satellite observations to collect data can be categorized as RF observations, optical observations, and radio interferometry. The ground-based tracking systems or the receiver's onboard the satellites gather these observed data. The transmitter and the receiver's equipment for tracking may be onboard satellites or on the ground stations. There are various types of ground-based radio observation such as azimuth, elevation, range, range to rage, turn around range, range rate, TDOA, and FDOA [16].

The satellite operators use orbit determination software to predict the satellite orbits after collecting the observation data. The orbit determination software predicts the six classical orbital elements which define the unique orbit. The estimation of observation antenna elevation and azimuth biases, turn-around range bias, the range bias corrections to the solar force model, and maneuver performance calibrations are general capabilities of the orbit determination applications. In addition to these, the software can propagate an orbit precisely into the future from a set of initial observations taking the various instrumentation errors and perturbations into consideration. The software processes the data to estimate the orbits using the methods such as Weighted Least Squares and Sequential Processing [16].

2. PROPOSED TDOA METHOD TO GATHER TRACKING DATA

We propose TDOA based tracking measurement for a geosynchronous satellite. The target of this study is to estimate the communication satellite's orbit. The goal was achieved by measuring time differences of signal arrival time in six ground stations.

In the ground-based TDOA measurement, the signal is generated by a fixed ground-based transmitter, and received by a communication satellite, and re-transmitted to the coverage area. Dedicated ground stations receive the re-transmitted signal. The application of this method for one communication satellite and six ground stations is shown in Figure 2.



(a) (b) (c)

Figure 2. (a) TDOA based satellite tracking data measurement implementation of emitter receiver configuration. The ground station deployment for TDOA type data collecting (b) Two dimensional view (c) 3-D view

TDOA type observations provide measured data of the difference in distance traveled along two distinct signal paths. The signal paths originate from the same emitter and end at different receivers. In this study, the signal originated from the same emitter and was received from six different ground station's receivers. The ground stations (GS1, GS2, GS3, GS4, GS5, and GS6) with precisely known location information are distributed over the earth within the visible arc of the satellite. We will refer to the six paths as signal path 1, signal path 2, and signal path 6 and assume that the reference for the observation time tag is the time of receipt of signal on path 1 (at GS1). The difference measurement algorithm is formed in the sense of time of arrival on path 2 (TOA2) minus the time of arrival on path 1 (TOA1); similarly, other paths difference measurements are formed in by taking path 1 as reference i.e., TOA3-TOA1, TOA4-TOA1, TOA5-TOA1, and TOA6-TOA1.

The proposed TDOA observation method measures data with thirty minutes' interval for forty-eight hours. Data collection duration (two days) is two periods of a geostationary satellite. The method collects 96 data sets measured independently at the end of the campaign for each ground station.

Table1 provides TDOA based measurement data in seconds. GS2-GS1 column data means TDOA of signal between GS2 and GS1, abbreviated as TDOA21 or TO21. The other columns show the data of other ground stations. The total number of measurement data is 480 samples for five stations.

Table 1. Sat1 TDOA tracking sample data for 48 hours observation from six-ground station

Date UTCG	GS2-GS1	GS3-GS1	GS4-GS1	GS5-GS1	GS6-GS1
01 Jul 2021 09:00:00	3.24670236E-04	-1.85179421E-04	-1.13588639E-03	4.30621100E-03	-2.75935335E-03
01 Jul 2021 09:30:00	3.24846356E-04	-1.85011778E-04	-1.13592027E-03	4.30670740E-03	-2.76308209E-03
01 Jul 2021 10:00:00	3.24976584E-04	-1.84894009E-04	-1.13599066E-03	4.30714861E-03	-2.76669168E-03
..	..	..	..	..	..
03 Jul 2021 08:30:00	3.24875483E-04	-1.85209216E-04	-1.13562237E-03	4.30638631E-03	-2.75609244E-03
03 Jul 2021 09:00:00	3.25053360E-04	-1.85039817E-04	-1.13564567E-03	4.30687387E-03	-2.75972136E-03

The orbital parameters of three communication satellites at different orbital slots (42.0°E, 31.0°E, 50.0°E) were estimated to investigate the validity and applicability of the measurement. The communication satellites used in this work are assumed to have 2150 kg weight and 30 m^2 solar pressure area. The satellite's orbit epoch is July 1st, 2021, 09:00.0000 in Gregorian universal time code (UTC). The satellite orbital motions are stimulated with the value of the classical element (semi major axis SMA, eccentricity, inclination, right ascension of ascending node RAAN, true anomaly TA, argument of perigee AoP) given in Table 2. The satellites were propagated for 48 hours with a high-precision orbit propagator. The generated ephemeris data is taken as a reference truth orbit to compare the Sequential Processing (SP) filter method orbit determination results for TDOA based observation data.

Table 2. Sat1, Sat2 and Sat 3 initial orbital states in classical orbital parameters

	SMA (km)	Eccentricity	TA (deg)	Incl (deg)	RAAN (deg)	AoPer (deg)
Sat1	42165.3000	0.00004815	13.1819	0.049900	96.364400	4.28920100
Sat2	42165.1488	0.00005485	35.3602	0.049830	85.389484	324.668710
Sat3	42165.14879	0.00004699	355.711	0.049840	104.389079	346.793038

The ground stations are named GS1, GS2, GS3, GS4, GS5, and GS6, as shown in Figure 2(b). The selected ground station profile matched well with the practical satellite operators' facility properties in terms of ground station operations, satellites, and orbit determination sample size.

The observation data were collected with a convenience sample of time-synchronized six stations by using the TDOA method. The observation data gathering campaign takes 48 hours and contains 96 sampling data for each station. The measured data were processed prior to the start of orbit determination. The ground station equipment delay, tropospheric and ionospheric delay, satellite transponder delay, and other sources of errors are taken into consideration while processing the measured data.

In measurement modeling, a single range difference mathematically can be expressed as shown in Equation 3.

$$\rho_{i1} = |R_{sat} - R_{GSi}| + c\tau_{delay} + \Delta d_{trop} + \Delta d_{ion} + \varepsilon \quad (3)$$

where;
ρ_{i1} : i^{th} station to satellite distance , R_{sat}: satellite position vector, R_{GSi} : i^{th} ground station position vector, c: speed of light, τ : ground station and transponder time delay, Δd_{trop} :tropospheric delay, Δd_{ion} : ionospheric delay, ε : other errors.

TDOA and signal phase observation must be corrected for the errors shown in Equation 3 during the measurement processing. These error sources are tropospheric delay, ionospheric delay, and ground equipment and satellite transponder delays [17].

The signal at each ground station has a different delay due to the ionosphere. The RF signals propagating propagation through the ionosphere differ from those in free space. The vertical group delay can be expressed approximately in Equation 4.

$$\rho_{ion}(f) = \frac{40.3\ 10^{16}\ TEC}{f^2} \quad (4)$$

where; TEC: the total electron content (in units of 10^{16} electrons/m^2) and f: frequency in Hz.

The troposphere measurement delay consists of two main components; the dry component r_{dry} and the wet component r_{wet} . The delay can be expressed in Equation 5.

$$\rho_{trop} = \rho_{dry} m_{dry}(\alpha) + \rho_{wet} m_{wet}(\alpha) \quad (5)$$

where; α is the elevation angle, m_{dry} and m_{wet} mapping function.

The 90% of total tropospheric delay is the dry delay. The dry delta is approximately 2.2 m (7.3 ns) for zenith delay. The wet component is equivalent to 10 cm to 15 cm (0.3 ns to 0.5 ns), which amounts to about 10% of the total zenith delay. [17].

In this study, ground station data collecting methods were selected as TDOA based measurement systems to determine the orbits of communication (geosynchronous) satellites.

2.1. Satellite orbit determination Sequential Processing (SP) Filter Methods

In this study, the collected TDOA measurement data from the satellites are processed with the SP filter method to determine the orbit. The SP method is commonly selected to determine orbit in the most flight-proven softwares utilized by the satellite operators.

The SP filter method uses observation data with ground station precise locations data, prior position and velocity estimates, and a prior state-error covariance matrix. SP methods provide refined position and velocity estimation. The following approach was utilized to estimate orbit using the filter method [1].

$$\Delta X = A(t) X \Delta t + B(t) \Delta \beta \quad (6)$$

where;
A(t): nxn time dependent matrix (measurement data), Δt: time increment, *B(t):* nx3 time dependent matrix, β: Brownian motion

The solution of Equation 6 provides orbital elements of satellites. The results are in various time and coordinate systems. These systems can be converted to each other. Classical orbital elements and UTC have common usage among satellite operators.

3. RESULTS AND DISCUSSION

This work shows orbit determination of a communication satellite with the TDOA measurement method. The TDOA method results are compared with truth orbit results. Truth orbit is defined as the simulated orbit of the satellites with flight-proven software utilized by the satellite operator.

Eumetsat orbit determination accuracy from the flight dynamic system requirement is 1500 m, 500 m, and 50 m, in in-track, cross-track, and radial direction, respectively. Since the satellite operators' operational requirements are close to each other, these values are taken as success criteria. Similarly, velocity accuracy requirement is 100 cm/s, 10 cm/s and 1cm/s for in-track, cross-track and radial direction [18].

Table 3 provides information about the satellite's radius and tangential velocity at epoch obtained using SP Filter and truth orbit. The radius differences and velocity differences are about 0.043 km, and 0.000002 km/s, respectively. These pre-results show good agreement with truth orbit.

Table 3. Truth orbit and SP filter r and v values and differences for 3 satellites

	Truth orbit		**SP Filter**		**delta Truth orbit and SP**	
	r (km)	**v (km/s)**	**r (km)**	**v (km/s)**	**r (km)**	**v (km/s)**
Sat1	42163.219527	3.074765	42163.262312	3.074767	0.042785	-0.000002
Sat2	42163.261456	3.074762	42163.304241	3.074764	0.042758	-0.000002
Sat3	42163.219527	3.074765	42163.262312	3.074767	0.042785	-0.000002

Figure 3 shows Sat1's position and velocity differences between the SP Filter method and truth orbit in radial, in-track, and cross-track directions. The position average deviation of Sat1 are about 3.3 m, 0.44 m, and 0.16 m for radial, in-track, and cross-track, respectively. Similarly, the velocity average deviations are in the order 0.12 cm/s, 0.01 cm/s and 0.007 cm/s for radial, in-track, and cross-track, respectively. The results are in accord with the simulated truth orbit.

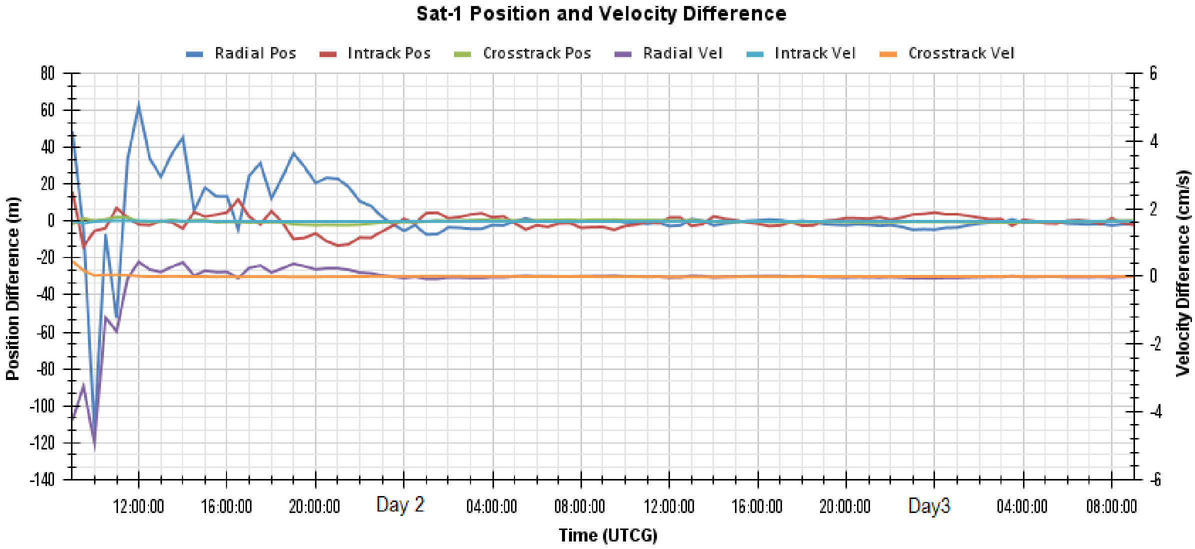


Figure 3. Sat1 radial, in-track and cross-track position and velocity differences between Truth orbit and SP Filter for 48 hours

Figure 4 shows Sat2 satellite's radial, in-track, and cross-track position and velocity average deviations between the SP Filter method and truth orbit. The position average deviations of Sat2 are about 4.5 m, 0.75 m, and 0.2 m for radial, in-track, and cross-track, respectively. Similarly, the velocity average deviations are in the order 0.1 cm/s, 0.01 cm/s and 0.007 cm/s for radial, in-track, and cross-track, respectively.

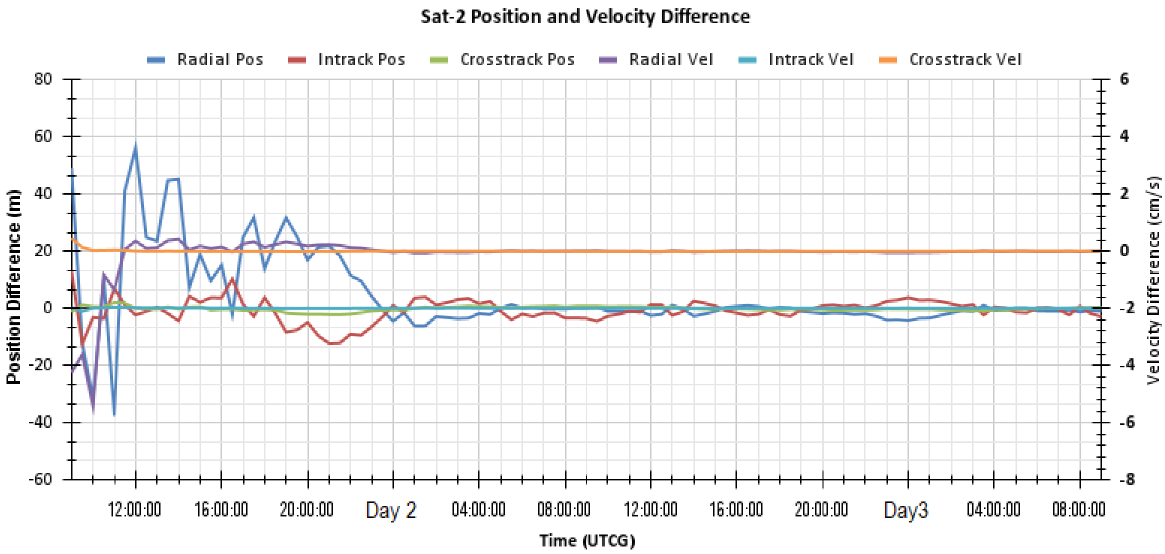
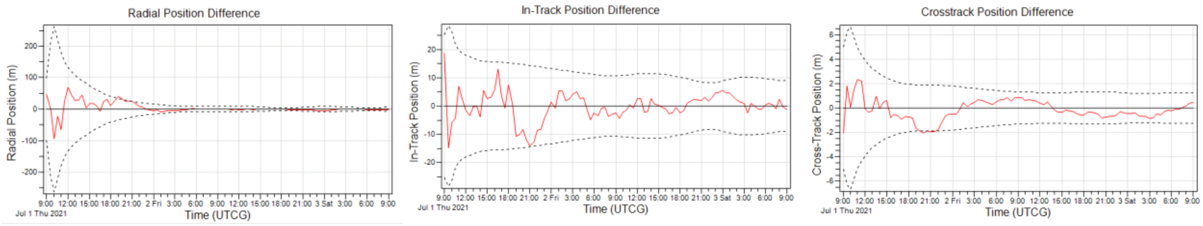


Figure 4. Sat2 radial, in-track and cross-track position and velocity differences between Truth orbit and SP Filter for 48 hours

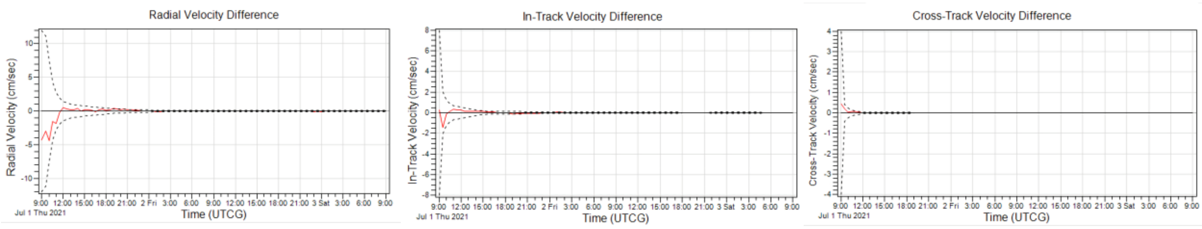
Figures 5(a), (b), and (c) show Sat3 radial, in-track, and cross-track position average deviations between the results of the SP Filter solution and truth orbit. The position average deviations are about 3.22 m, 0.15 m, and 0.16 m for radial, in-track, and cross-track, respectively.



(a) (b) (c)

Figure 5. Sat3 radial in-track and cross-track position differences for 48 hours

Figures 6 (a), (b), and (c) show Sat3 radial, in-track, and cross-track velocity average deviations between the results of SP Filter solution and trut orbit. The velocity average deviations are about of 0.12 cm/s, 0.05 cm/s and 0.008 cm/s for radial, in-track and cross-track respectively.



(a) (b) (c)

Figure 6. Sat3 radial in-track and cross-track velocity differences for 48 hours

The results show that velocity differences are less than position differences. All results are in line with truth orbit values.

Sat1, Sat2, and Sat2 position and velocity differences are less than acceptable error values, and therefore the proposed method provides excellent results.

Table 4 provides results of TDOA measurement-based orbit determination for three orbital slots. The results are compared based on average differences. The radial average position difference is about 4 m, and in-track and cross-track differences are less than 1 m for all three satellites. The velocity differences are quite small, and the average radial differences are in the order of 0.1 cm/s. The in-track and cross-track differences are in the order of 0.01 cm/s for all satellites. It can be concluded that communication satellites orbit successfully determined with TDOA measurement data.

Table 4. Truth orbit and SP filter radial, in-track and cross-track position and velocity average differences for 48 hours

Satellite	**Position Average Differences (m)**			**Velocity Average Differences (cm/s)**		
	Radial	**In-track**	**Cross-track**	**Radial**	**In-track**	**Cross-track**
Sat1	3.263	-0.442	-0.158	-0.118	0.009	0.007
Sat2	4.420	-0.748	-0.173	-0.117	0.014	0.007
Sat3	3.229	-0.136	-0.162	-0.116	0.005	0.008

Table 5 provides root mean square error (RMSE) of SP filter results and truth orbit results for three satellites. The maximum position RMSE is in radial and less than 20 m. The in-track position RMSEs are about 5 m, and the cross-track RMSEs are less than 1 m for three satellites.

The velocity RMSEs are less than 1 cm/s, the in-track and cross-track RMSEs are about 0.1 cm/s and 0.05 cm/s respectively.

Table 5. RMSE of Truth orbit and SP filter for radial, in-track and cross-track position and velocity values.

Satellite	Position Differences (m)			Velocity Differences (cm/s)		
	Radial	**In-track**	**Cross-track**	**Radial**	**In-track**	**Cross-track**
Sat1	15.0888	4.1685	0.7954	0.8142	0.1318	0.0495
Sat2	19.3276	4.5935	0.8201	0.7753	0.1481	0.0510
Sat3	19.2271	5.0305	0.8514	0.7392	0.1644	0.0526

The RMSE comparison results show that position and velocity differences are very small, like previous results.

This study investigated the potential use of the TDOA measurements method in orbit determination. The findings mentioned above indicate that TDOA method provides almost the same results as currently utilized flight-proven software results. The results suggest that the use of TDOA tracking data for orbit determination of geosynchronous satellites is an alternative way with additional benefits.

4. CONCLUSION

The shift towards evolution in tracking systems and data processing methods has forced the satellite operators to alternative orbit determination methods. Providing accurate orbit parameters is no longer sufficient; satisfying satellite operators require unceasing measurement, a cost-effective system, and independence from satellite commanding and ranging subsystem. The satellite operators and manufacturers recognize the importance of alternative tracking data collecting methods for orbit determination. The results of this research suggest that TDOA provides not only unceasing measurement but also a cost-effective solution compared to single station tracking. TDOA method has the advantage of satellite payload utilization and independence from satellite telecommand and ranging subsystems. This study investigated the potential use of TDOA observation data for communication satellite orbit determination. In three different satellite orbital locations, the results indicate that the satellite operators can utilize TDOA based tracking data for orbit determination efforts. The results are in line with actual orbit parameters.

The results are highly sensitive to ground station clock errors. Although we do not explicitly analyze the effect of ground stations locations other than the parameters in the model, a potential explanation might be that location geometry affects the obtained orbital parameters. The number and distribution geometry of ground stations affect the accuracy of the determined orbit. In general, our results indicate that valid observation data provides reliable orbit estimation. Moreover, our study validated that the TDOA measurement data are enough to process and obtain orbital parameters. Our study indicates that TDOA based orbital data are important drivers of orbit determination in the proposed method.
Finally, our study validated that the TDOA based observation data can be utilized to determine communication satellite orbit accurately.

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CONFLICT OF INTEREST

The authors stated that there are no conflicts of interest regarding the publication of this article.

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