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Research Article

Performance Assessment of a Turn Around Ranging in Communication Satellite Orbit Determination

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Abstract

Satellite operators utilize a two-stations turn around ranging (TAR) system to reduce the ground station measurement system's complexity and cost while having the same or better orbit determination accuracy for communication satellites orbit determination recently. This study investigates two stations' performance, four-way ranging on communication satellite orbit determination, operational conformance, and cost. The observation data sets are collected using traditional single station tracking (SST) and the new method TAR. The computed results using the Monte Carlo method encourage the satellite operators to use a four-way ranging system to observe and measure required data sets. TAR performance is evaluated, taking SST as a reference. The six classical orbital elements (a, e, i, RAAN, AoP, and TA) are compared for large numbers of observation data. The SST and TAR results are very close to each other. The worst-case calculated Euclidian distance between SST and TAR is 1.893 km at the epoch below the 6 km success criteria. The TAR observation method is appropriate to collect data sets for precise orbit determination. This work result indicates that satellite operators should consider deploying TAR stations to collect two-station range data sets and compute the orbit for nominal north-south station-keeping maneuvers (NSSK) and east-west station-keeping (EWSK) maneuver operations. The TAR method is superior to SST in terms of accuracy, operational conformance, and costs.

Keywords: orbit determination, turn around ranging, four way ranging, single station tracking, satellite orbit measured data set

1. Introduction

Satellite orbit is determined by the use of observation data obtained from ground-based or space-based systems. Observed and measured data sets are gathered from those stations. Technical properties and utilization type of the station influence orbit estimation accuracy. Satellite operators prefer reliable, high-performance, and cost-effective station solutions [1], [2].

Satellites in orbit are subject to external forces (such as sun, moon, non-uniform earth gravity), and those forces cause orbit perturbations. Satellite operators perform regular north-south station-keeping maneuvers (NSSK) and east-west station-keeping (EWSK) maneuvers to compensate perturbations and keep the satellite within a defined control window. The assigned window usually covers a range of ±0.10° in longitude and latitude, which the satellite should not violate, to avoid signal interference (or even physical contact) with neighboring spacecraft. The orbit of a satellite must be known precisely to perform the required maneuver efficiently and obey co-location rules if required. So, precise orbit determination is a critical factor in successfully keeping a satellite at the desired orbital location [3], [4].

The orbit determination of communication (or GEO) satellites uses many types of observations, data, and data processing methods [2]. Satellite laser ranging system uses laser light for range measurement [5]. Precise orbit determination of GEO satellites during orbit Maneuvering [6], autonomous orbit determination and orbit control for GEO satellite-based on a neural network [7], orbit determination of geostationary satellite during maneuver [8], sequential orbit determination for geostationary satellites operations [9] are most utilized orbit determination methods.

Orbit determination is the process of obtaining values of orbital parameters that entirely specifies the motion of a satellite. An accurate orbit estimator takes the measurement noise into account and determines an orbit that provides a "best fit" to the collected data. These data sets are subject to the dynamics of a satellite's orbital motion during the collecting process [10]-[12].

Precise orbit determination is necessary for the planning of orbit maneuvers and anticipating events such as eclipses.GEO satellite uninterrupted communication performance requires to keep the satellite within control windows. Communication satellite service availability requires a well-controlled satellite inside the defined window.

Single station tracking is the most frequently used ground station system for orbit determination of a communication satellite. Satellite operators alternatively select other types of tracking systems, such as turn around range measurement or four-way range measurement systems for NSSK and EWSK operations [13]. When selecting a system, the satellite operator's target is to improve orbit determination accuracy and decrease the system's operational complexity and cost.

Single station tracking method (SST) uses angle measurement of antenna and station to satellite range with a time tag. The antenna generally has mono-pulse tracking equipment, and mono-pulse tracking techniques are utilized to collect azimuth and elevation angle. When collecting angular values, mono-pulse antenna points to the satellite, and the antenna control unit reads out resolver azimuth and elevation values. A ground station transmits a ranging signal to a satellite TCR sub-system or a transponder, and a satellite transmits the received ranging signal back to a ground station to obtain range data. In this system, antenna misalignment, angular measurement accuracy, temperature fluctuation in day and night, wind load, and mechanical precisions are the primary error sources. Those errors affect the calculated orbital parameter accuracy [14].

In the turnaround ranging system (TAR), a four-way station to satellite range with a time tag is measured. TAR does not need an angular measurement. This simplifies antenna structure, and many sources of errors disappear. In addition to those advantages, the cost of the antenna significantly decreases. The measurement principle of TAR is that the ranging signal emitted from the ground station and a satellite transponder receives the signal and re-transmits to the ground; simultaneously, the remote station receives the transmitted signal from a satellite transponder. This signal uplinked to a satellite transponder, and the satellite transmits this signal back like the first signal. The main station (station A) ground system receives both re-transmitted signal and turn around (round trip) signal and processes the signals to obtain range data. This method uses a cost-effective and straightforward system compared to SST, to gather necessary data for orbit determination.

1. 1. Related Works

In literature, there are different works on the orbit determination of objects. Measat operational experience shows that TAR orbit determination accuracy is similar to classical ranging station performance. TAR makes ground station operations simplified [1].

Traditional antenna angle tracking can be improved by using an interferometer. This configuration provides more accurate orbit determination for geostationary satellites [3].

Satellite laser ranging (SLR) is another method to determine satellite orbits. It is an accurate method that provides sub-centimeter level range measurement. SLR enables a user to predict orbits precisely [5].

There are small changes in azimuth, elevation, and range of communication satellites. Single station tracking for orbit determination measures those three values. The study shows that elevation angle affects mostly the X variances, and the azimuth angle is more dominant in the Y variance. The range measurement effect is minimal and has the weakest effects on variations [14].

SST has azimuth and elevation bias error. Single station azimuth bias can be fixed by applying an estimated azimuth bias periodically. Three-sigma position accuracy of approximately 1.5 km can be achieved with the corrected azimuth bias for communication satellites [15]. In a satellite laser ranging, the received energy, the number of returned photons, the number of photoelectrons, and the Time-Of-Flight “TOF” affect the orbit determination accuracy [16]. The ground tracking and inter-satellite link is another method of orbit determination for the GEO satellite. Inter satellite link geometry and ground station clock errors affect calculated error in the cross-track or along-track direction [17]. Precise measurement and high precision time synchronization are necessary between ground stations to determine satellite orbits. Two-way satellite time and frequency transfer (TWSTFT) technology is commonly used among various time synchronization methods because of very high time transmission accuracy [18].

1.2. Ground-Based Satellite Observations

Satellite observation can be classified as optical observations, radio observations, and radio interferometry [2, 19]. Keplerian (classical) six independent elements describe a satellite's motion in space entirely. A tracking station aims to make observations from which these six motion elements can be deduced and an orbit computed.

Satellite orbit determination requires an input measurement data related to satellite position and/or velocity. Those observation data are obtainable from the ground-based tracking system or the sensors onboard the satellite. The transmitter and the receiver may be satellite onboard or ground station equipment.

Table 1 shows the most common ground-based observation and tracking methods and their measured values [19]. The following acronyms are defined; Deep Space Network (DSN), Satellite Laser Ranging (SLR), Total Count Phase (TCP), Time Difference of Arrival (TDOA), Frequency Difference of Arrival (FDOA), the time derivative of TDOA (TDOA dot), single differencing (SD), double differencing (DD), Tracking Data and Relay System (TDRS), Bilateral Ranging Transponder System (BRTS), and Dual Frequency (DF).

Table 1 Most common ground-based measurement for orbit determination

Method	**Measured Data Sets**
Traditional	Azimuth/Elevation, Right Ascension/Declination, Bistatic range, 2-way range,
DSN	3-way doppler, 3-way TCP, Dopler, TCP, Sequential range
SLR	Normal pointing range
Geolocation	TDOA, FDOA, TDOA dot, SD TDOA, SD FDOA, Ground TDOA, Ground
TDRS	BRTS Range, BRTS Doppler

Table 2 shows the most common space-based object (satellite) observation and tracking methods and their measured values. In this method, GNSS (Global Navigation Satellite System) measurements in the form of pseudo-range and doppler phase-count measurements from various GNSS constellations (GPS, Glonass, Galileo, QZSS, and Beidou) are processed to generate orbits.

Table 2 Most common space-based measurements for orbit determination

Method	**Measured Data Sets**
GNSS, GPS etc	Pseudorange (CA, L1, L2), SD and DD, Phase (CA, L1, L2, LA), SD and DD, CA and DF navigation solution (X, Y, Z)
TDRS	4-way range, 5-way doppler, 3-way return-link doppler
Space to Space	Range, Azimuth / Elevation, Right Ascension / Declination
Ephemeris	Position (X, Y, Z), Velocity (X dot, Y dot, Z dot)

Satellite operators (or orbit determiner) specifies the available measurement data sets of satellites depending on tracking systems. Satellites or objects may have a predefined set of allowable measurement types due to the ability of an observation system.

2. Methods of Observation and Data Collection

All orbit determination methods have their advantages and some shortages compared to others, as expected. The operators' trade-off among them, and select the best method and relevant system according to the needs and aims.

We use two types of observation (measurement) in this study. The first one is traditional angles and range observation called SST, and the second one has recently developed two stations, four-way range observation called TAR.

The measurement data are collected by a tracking system by means of electromagnetic wave propagation in this study because of existing ground system properties. Satellite measurement data has been collected in two different ways. The first one is classic traditional (conventional) topocentric coordinate azimuth elevation and range measurement, as shown in Figure 1(a). Large size antennas with a mono-pulse tracking system and ground-based measurement equipment gather necessary data precisely. This study utilized three mono-pulse tracking earth stations (station A, B, and C) and obtained azimuth elevation and range data for SST.

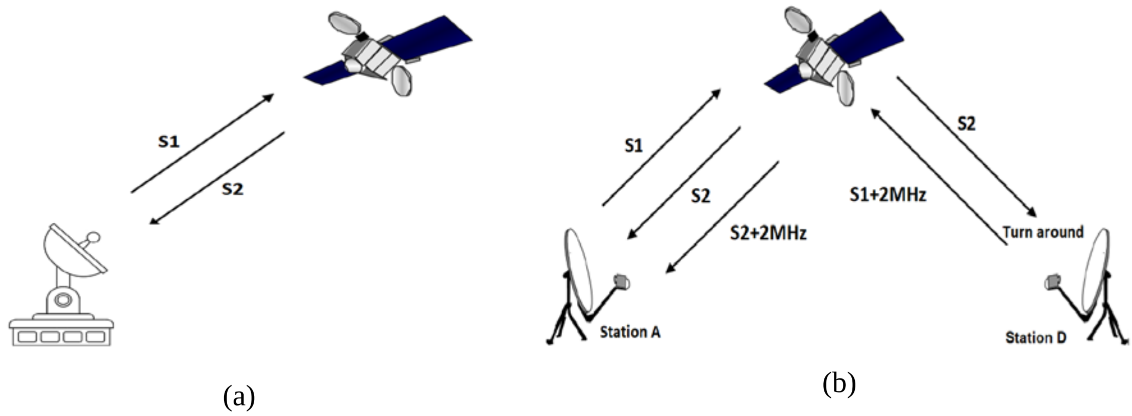


Figure 1 representation of (a) SST ground station and (b) TAR ground station

The second method is a four-way turnaround, only range measurement. In this method, two stations operate simultaneously. Generally, station D is an unmanned remote station. Both stations have 1.8 m or 2.4 m Vsat type cost-effective antennas in this method. These stations' costs are generally about 1/10 of SST type mono-pulse antenna system as of today's market conditions. Remote unmanned TAR site operational expenses are very low, and maintenance requires less effort than SST station since TAR does not need satellite tracking equipment and associated systems, large reflector, etc. In the TAR method to measure range, station A emits ranging signals S1 and the transponder onboard a GEO satellite transmits S2 (downconverted S1 signal), and the transmitted signals are received by the original tracking station to realize the distance measurement as shown in Figure 1(b).

Similarly, station D (remote station) receives the S2 signal and converts it to S1+2MHz and uplinks to the satellite. The satellite transponder onboard receives the signal and down-converts and re-transmits it as signal S2+2MHz. The ground station instrument processes both S2 and S2+2MHz signals and obtains station A to satellite range and station A to station D via satellite range data.

We utilize six earth stations (station D, E, F, G, H, J) to collect TAR data sets and evaluate two-station methods.

Both observation methods measure data every hour for two days. These duration (48 hours) is two periods of a geostationary satellite. TAR method collects 48 independently measured data sets at the end of the ranging campaign. Angles, azimuth, elevation, and range data sets are obtained for the SST method. Two station range data sets are obtained for the TAR method.

The distance from a ground station to a satellite can be defined in the following Equation 1.

$$\rho = |R_{SAT} - R_{GS}| + c.\tau_{delay} + 2\Delta D_{trop} + 2\Delta D_{ion} + \varepsilon \quad (1)$$

where; ρ:station to satellite distance, R_{SAT} : satellite position vector, R_{GS}: ground station position vector, c: speed of the light, τ: ground station and transponder time delay, ΔD_{trop}: tropospheric delay, ΔD_{ion}: ionospheric delay, ε: other errors

The instantaneous observation from a ground station to a satellite can be expressed in the following Equation 2 and 3.

$$t=(t_i+t_k)/2 \quad (2)$$

$$\rho=(t_k-t_i)*c/2 \quad (3)$$

Where t_i : time signal emitted from the ground station, t^k : time signal received at the satellite transponder, c is the speed of the light.

The antenna control unit directly reads angles (azimuth and elevation).

The following Equations 4, 5 and 6 are used to calculate satellite coordinates [13];

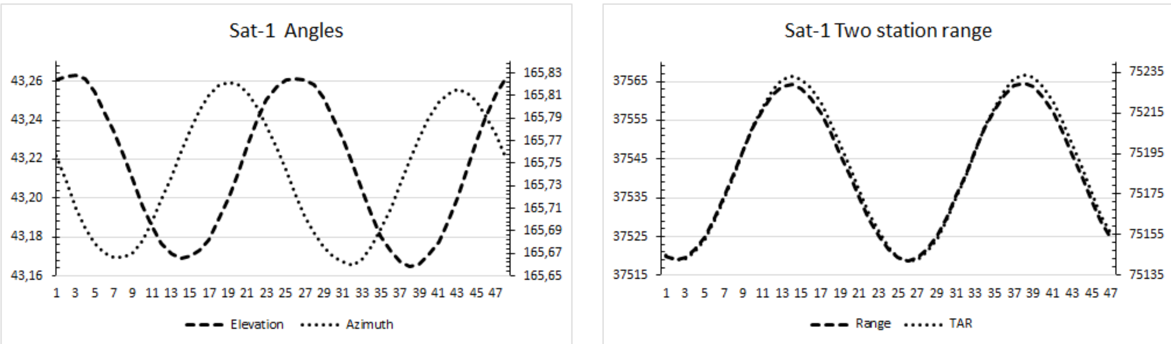
$$x=\rho\cos\beta\cos\alpha \quad (4)$$

$$y=\rho\cos\beta\sin\alpha \quad (5)$$

$$z=\rho\sin\beta \quad (6)$$

where, ρ is the range of the satellite, α: azimuth angle β: elevation angle, x, y, z : coordinate of the range between station and the satellite

Figure 2(a) presents azimuth and elevation measurement of a satellite, the left vertical axis shows elevation angle data, and the right vertical axis shows azimuth angle data; Figure 2(b) shows station to satellite range and station to station range via satellite measurement of a satellite, the left vertical axis provides station to satellite range in km, and the right vertical axis provides station to station via satellite range in km. The horizontal axis is the observation number from one to forty-eight. The graphs show one complete observation that takes 48 hours and contains 48 data sets.



(a) (b)

Figure 2 (a) Azimuth and elevation angle data from the mono-pulse antenna in degree (b) Station to satellite range and station to station via satellite range (TAR) in km

In this work, the overall orbit control strategy is based on a 14 days cycle. Initially, we performed a 48 hours ranging campaign to collect observation data sets, and then the NSSK maneuver is performed according to calculated orbit. After that, a 48 hours ranging campaign is performed to have the result of NSSK and prepare maneuver for EWSK. EWSK maneuver is performed after the next 48 hours, as it is necessary to wait the optimum E/W maneuver time. A 48 hours ranging campaign is then performed to confirm the orbit and provide accurate orbit parameters until the end of the cycle, as shown in Figure 3.

For one maneuver cycle of SST, three times 48 azimuth, elevation, and range measurements are gathered for a satellite. These data sets make 3*48=144 measurements to process for orbit determination for one cycle. Similarly, two stationTAR measurements produce 144 data sets. This work performed for two methods, three satellites and three cycles for 2*3*3*144=2592 measured values to process and evaluate orbits. The total duration of the work is 45 days, including data collection, processing, and maneuvering.

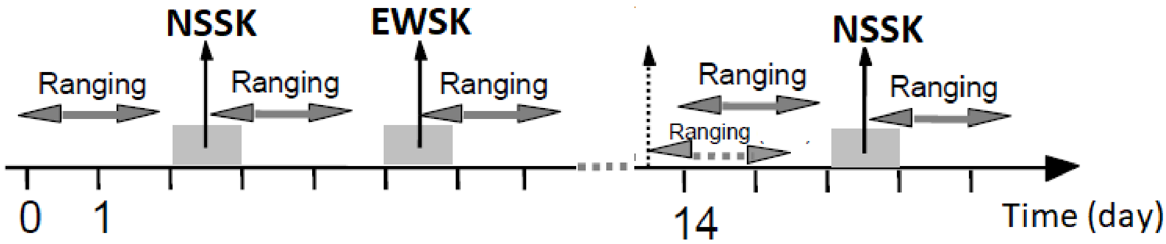


Figure 3 Geo satellite observation data collection and maneuver planning schedule

Those collected data are processed to determine the satellite orbits. This study utilizes focusgeo orbit determination software. The Orbit Determination software estimates orbital parameters from observed tracking (azimuth, elevation, range, and turn-around range) data collected from one or more tracking sites. The software is able to update the current orbit estimate based on a single new observation or process all observations.

The Orbit Determination software is able to predict the current orbit by using turn-around measurements.

The software proposes to accurately propagate an orbit into the future from a set of initial observations taking the various perturbations, as well as instrumentation errors into account. The orbit determination software estimates the six orbital elements which uniquely define the orbit, as well as maneuver delta-velocity components. In addition to the orbital elements and maneuver delta-velocity components, the software is capable of estimating tracking antenna azimuth and elevation biases, turn-around range bias, the range bias corrections to the solar force model, and maneuver performance calibrations. The software functions properly even during the absence of azimuth and elevation observations, assuming that turn-around range or range from a second, geographically remote site is available. The orbit determination software reads the initial orbit conditions from a data file specified by the user. The orbit propagator calculates the initial orbit to the time of each observation. The software provides orbit determination by using Monte Carlo methods. Using the iterative Monte Carlo method, the software outputs a summary to the user's, which indicates the level of convergence (e.g., residual, orbital element changes, etc.). The software calculates measurement residuals and orbit's determination residuals.

2.1. RMSE Method

A four-way TAR raging was conducted to explore the accuracy of communication satellite orbit by having range-range measurements. We propose to use the root mean square error (RMSE) method to analyze the performance of TAR measurement in this study. The RMSE compares the differences between values predicted by a model and the values computed by the other method. The RMSE is a measure of accuracy, to compare errors of different models for a particular dataset as shown in the following Equation 7.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T}(y1_{t-}y2_{t})^2}{T}} \qquad (7)$$

where $y1_t$: calculated parameters using SST, $y2_t$: calculated parameters using TAR, T: number of calculated results.

In this study, classical orbital elements (Keplerian parameters) of a geostationary satellite orbit are calculated using focus geo software. The first and the reference calculation approach is obtaining orbital parameters using azimuth elevation and range data with the Monte Carlo method. The second approach calculates the same epoch orbital parameters using two-station range data with the same Monte Carlo method. The epoch date and equations solving method Monte Carlo kept the same to compare the orbital parameters of two different observation methods. So, the difference in orbital parameters provides information about SST and TAR measurement model approach. Safe satellite operation requires a minimum 6 km inter-satellite distance in co-located satellites for the three-sigma separation confidence level. This 6 km requirement is selected as the success criteria of TAR orbit determination.

3. Results and Discussion

We have evaluated classical orbital elements of nine observation data sets from nine stations for every three satellites by using the SST and TAR method. We use the Monte Carlo method to solve the set of equations. The determined orbit results are in two formats, the first one classical orbital elements format and the second one earth-centered inertial (ECI) cartesian coordinate system format. Table 3 shows the orbital parameters of Sat-1 according to the first measurement of the cycle for SST and TAR measurement. Semimajor axis (a), eccentricity (e), and inclination (i) pairs' values are quite close to each other. Right ascension of ascending node (RAAN), argument of perigee (AoP) and true anomaly (TA) pairs' values have small differences. In Table 3, 4, and 5, a represents semimajor axis in km, e eccentricity unitless, i inclination in degree, RAAN right ascension of ascending node in degree, AoP is the argument of perigee in degree, and TA true anomaly in degree.

Table 3 Sat-1 initial orbital parameters

Classic orbital elements	SST	TAR	ECI (Cartesian)	SST	TAR
a (km)	42164.986	42164.9723	x (m)	-42155779.12	-42155979.71
e	0.000459	0.000453	y (m)	1396566.3770	1395363.0210
inc (deg)	0.049100	0.052900	z (m)	-17066.93322	-18001.92038
RAAN (deg)	136.0224	137.5415	Vx (m/s)	-102.7475618	-102.6198870
AoP (deg)	72.15160	70.01420	Vy (m/s)	-307.897254	-307.889126
TA (deg)	329.9286	330.4004	Vz (m/s)	-2.322385740	-2.14385019

SST method and TAR method computed a, e, i, orbital elements are shown in Table 4 for nine observations of Sat-1. It is recognized that the results are very close to each other. Similarly, Table 5 provides the results of the remaining orbital elements, RAAN, AoP, and TA. However, according to orbital parameters such as semimajor axis, inclination, etc. the variation is different.

Table 4 Sat-1 computed three orbital parameters pairs with SST and TAR observation for nine measurements. Station A for SST and station D & station E for TAR measurements

Obs #	a-SST	a-TAR	i-SST	i-TAR	e-SST	e-TAR
1	42164.98596	42164.97230	0.04910234	0.05286016	0.00045902	0.00045333
2	42165.26394	42165.26632	0.03666194	0.03887000	0.00045837	0.00045469
3	42166.78175	42166.78487	0.03892321	0.04268257	0.00054942	0.00054351
4	42164.85940	42164.83790	0.05037842	0.05065172	0.00045653	0.00045551
5	42164.81078	42164.81450	0.02874066	0.03054285	0.00045366	0.00045185
6	42166.34659	42166.34626	0.03056887	0.03293101	0.00045213	0.00044899
7	42166.22994	42166.23123	0.04153524	0.04233847	0.00036831	0.00036720
8	42165.44997	42165.45371	0.02146868	0.02114429	0.00041670	0.00041762
9	42167.20587	42167.20546	0.02554608	0.02653001	0.00049724	0.00049570

Longitude is not one of the six classical orbital elements, but it is calculated using some elements and provides information about satellite orbital location. Satellite operators keep a satellite in a defined longitudinal window, that's why longitude values of SST and TAR method are added to Table 5's column.

Table 5 Sat-1 computed four orbital parameters pairs with SST and TAR observation for nine measurements. Station A for SST and station D & station E for TAR measurements

Obs #	RAAN-SST	RAAN-TAR	AoP-SST	AoP-TAR	TA-SST	TA-TAR	Long-SST	Long-TAR
1	136.022429	137.541499	72.151565	70.014227	219.848164	220.254944	41.968486	41.970130
2	166.797524	166.036758	48.624112	49.110470	213.485476	214.114985	42.046363	42.045992
3	159.473316	158.897754	51.964912	52.119508	237.321082	237.742659	41.977561	41.978172
4	124.713056	126.761488	102.261324	99.807798	219.848164	220.254944	41.963148	41.964834
5	158.628444	162.762408	74.730430	69.967004	213.485476	214.114985	42.033573	42.033620
6	149.192599	152.585861	76.339560	72.339674	222.800639	223.407696	41.986209	41.986642
7	119.697845	118.149078	101.599432	103.519587	226.873536	226.502180	41.940869	41.940901
8	164.420003	165.718663	71.227446	69.842861	211.824073	211.909868	42.021552	42.021422
9	149.334633	150.615965	78.773232	77.314953	221.070292	221.247426	41.972284	41.972471

The difference in orbital parameters calculated by SST and TAR are provided in Table 6. The semimajor axis maximum difference is 0.4160 m in observation number 9, and the minimum difference is 0.0013 m in observation number 7. These values are very small and acceptable. The eccentricity difference is 5.91x10-6 and 9.2x10-7 for the maximum and the minimum values, respectively. Inclination maximum difference value is 0.00376°, and the minimum value is 0.00027°. RAAN and AoP differences are in the order of 1° to 5° and TA difference 0.6199° and 0.0858° for the maximum and the minimum, respectively. Those values are very close to each other and acceptable.

Table 6 Sat-1 calculated six orbital elements and their associated longitude difference for nine observations.

Obs #	Δa(km)	Δe	Δinc (deg)	ΔRAAN	ΔAoP	ΔTA	ΔLong
1	0.0136610	5.690E-06	-0.00376	-1.51907	2.137340	-0.61991	-0.00164
2	-0.002381	3.680E-06	-0.00221	0.760770	-0.48636	-0.27404	0.000370
3	-0.003123	5.910E-06	-0.00376	0.575560	-0.15460	-0.42158	-0.00061
4	0.0214990	1.020E-06	-0.00027	-2.04843	2.453530	-0.40678	-0.00169
5	-0.003723	1.810E-06	-0.00180	-4.13396	4.763430	-0.62951	-0.00005
6	0.0003330	3.140E-06	-0.00236	-3.39326	3.999890	-0.60706	-0.00043
7	-0.001282	1.110E-06	-0.00080	1.548770	-1.92016	0.371360	-0.00003
8	-0.003742	-9.200E-07	0.000320	-1.29866	1.384590	-0.08579	0.000130
9	0.0004160	1.540E-06	-0.00098	-1.28133	1.458280	-0.17713	-0.00019

Sat-1 calculated orbital elements with SST and TAR observation, and their differences are shown in Figure 4 - Figure 6. The left vertical axis shows the calculated value of the orbital element in two different colors. The right vertical axis shows the difference in the result. The horizontal axis is the observation number from one to nine. It is recognized that the magnitude of differences varies according to orbital elements. However, orbital element values are all within acceptable limits.

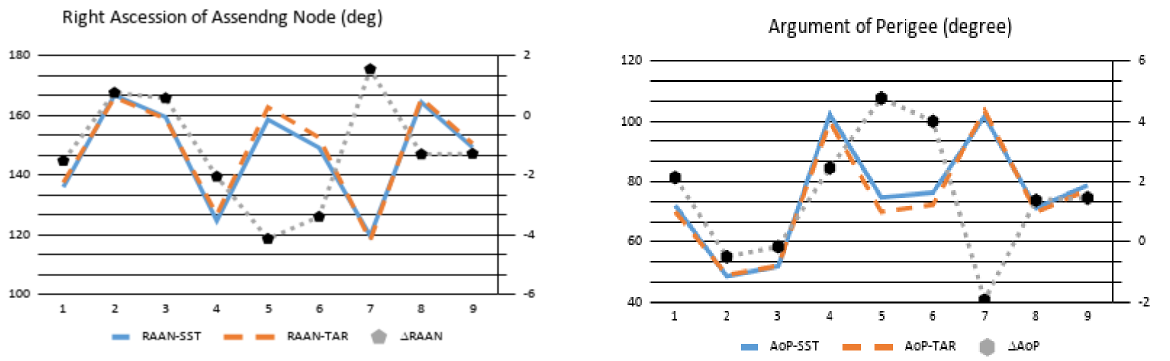


Figure 4 Calculated right ascension of ascending node, argument of perigee, eccentricity values from SST and TAR observation data and their difference for Sat-1 communication satellite.

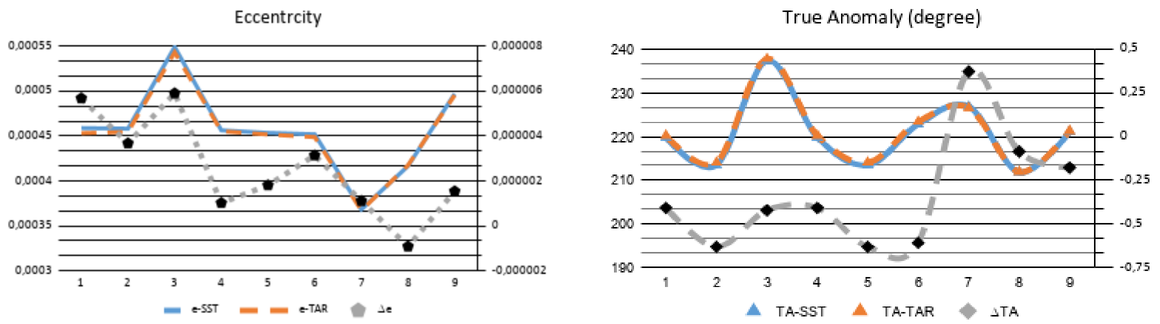


Figure 5 Calculated eccentricity, and true anomaly values from SST and TAR observation data and their difference for Sat-1 communication satellite.

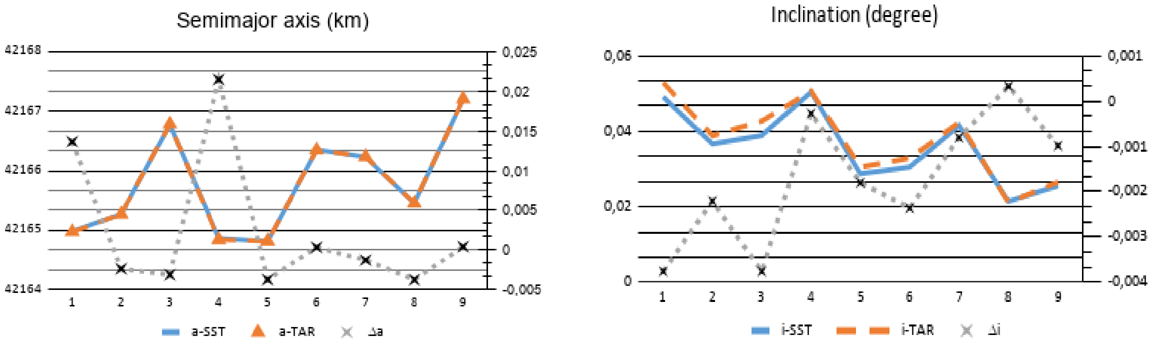


Figure 6 Calculated semimajor axis and inclination values from SST and TAR observation data and their difference for the Sat-1 communication satellite.

Table 7 shows SST and TAR observation Euclidien 3-D distance difference. This table provides results for three satellites and nine measurements. The maximum distance between SST and TAR orbit determination result is 1.893 km, and the minimum Euclidean distance is 0.2723 km. The velocity difference is 0.2307 m/s and 0.0247 m/s for the maximum and minimum value, respectively.

Table 7 Calculated Euclidean distance of three satellites for nine different SST and TAR observation data.

	Sat-1		**Sat-2**		**Sat-3**	
Obs#	Δ$\boldsymbol{\rho}$ [m]	Δv [m/s]	Δ$\boldsymbol{\rho}$ [m]	Δv [m/s]	Δ$\boldsymbol{\rho}$ [m]	Δv [m/s]
1	1537.043471	0.230717612	970.5935432	0.063792428	706.5908515	0.046583117
2	898.7939172	0.109295987	847.0846436	0.061467485	1026.124267	0.109127211
3	1361.035126	0.183722471	1111.038423	0.061053572	902.7798117	0.266153135
4	1342.749503	0.130285556	1274.088327	0.055727644	1506.889572	0.051774291
5	995.2406176	0.125742438	975.3496304	0.065700717	967.8471576	0.110689447
6	1188.324237	0.146028127	1342.10072	0.06924296	1098.628561	0.174532104
7	666.7779358	0.037654242	1696.844302	0.054849738	1893.410309	0.094463516
8	272.2957814	0.024368393	1159.273708	0.069173446	1539.522977	0.129045018
9	547.2337698	0.058411687	1296.835335	0.063771096	966.2989378	0.064260646

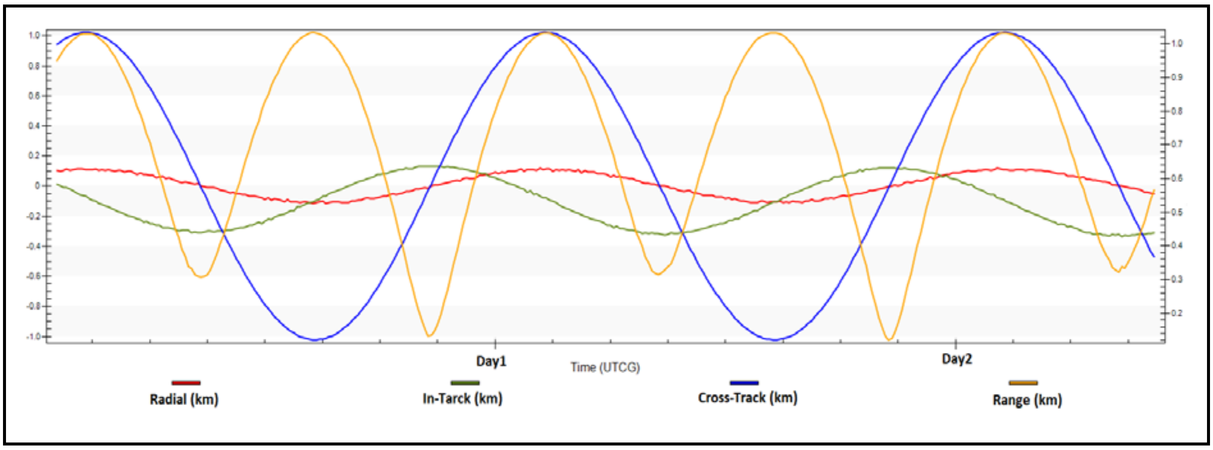


Figure 7 Cross-track, in-track, and radial position vector of Sat-1.

The position vector accuracy investigation in Figure 7 provides information that the maximum difference is in cross-track, which is about 2 km. The in-track difference is noticeably small and about 0.4 km. The radial distance is very low and less than 0.2 km.

Table 8 RMSE summary of six classical data for three satellites calculated by using SST and TAR measurement data

Satellites	Δa(km)	Δe	Δinc(deg)	ΔRAAN	ΔAoP	ΔTA
Sat-1	0.008781565	3.32454E-06	0.002204812	2.153668135	2.522529844	0.440205331
Sat-2	0.001183016	1.35181E-06	0.001524819	1.555173108	1.171455943	0.415063107
Sat-3	0.000328508	2.21273E-06	0.001540499	7.182120424	6.107330600	1.177065880

Overall, SST and TAR orbital elements differences obtained using RMSE are shown in Table 8. Semimajor axis difference is 8.78 m, eccentricity difference is 3.24x10-6, inclination difference is 0.022°, RAAn is 7.18°, AoP is 6.107°, and TA is 1.777° for the worst case. So the values are very close to each other.

Table 9 RMSE summary of position difference and velocity difference for three satellites

Satellites	$\Delta\rho$ [m]	ΔV (m/S)	ΔLong(degree)
Sat-1	1056.542946	0.132691565	0.000836586
Sat-2	1209.904997	0.062939317	0.000306716
Sat-3	1232.455060	0.133339923	0.000581840

Similarly, the result of all calculations in Table 9 shows that the worst distance between SST and TAR orbit determination is 1.056 km and the worst velocity is 0.1333 m/s. The longitudinal difference is 0.00084°. The computed orbital elements values for SST and TAR observation are quite similar.

4. Conclusion

GEO satellite orbit determination is conducted to assess the proposed method TAR performance. Classical orbital element calculations are carried out using real data from the tracking systems. The orbital element values are evaluated and compared for the SST and TAR methods. The results can be concluded as follows:

The position vector between SST and TAR as a Euclidean distance is about 1.056 km, for the worst case. The 48-h prediction in-track difference is about 0.4 km. The radial distance is noticeably very low and 0.2 km maximum.

Our study indicates that the new proposed method TAR results are usable, reliable, and acceptable for orbit determination operations. Satellite operators should consider TAR methods to collect the data. Consequently, satellite operators should direct more attention to deploy TAR stations.

Orbit determination using TAR measurement data is reliable and useful for maneuver operations and other calculations such as eclipses.

In summary, the TAR method is presented in this work, which solves operational complexity, multiple error source, and an investment and operation cost problem of the SST method.

This work may be extended to evaluate the TAR performance of different orbit determination methods and different filters.

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