Orbit Determination Network System for Micro and Nano Satellites Using Low-Cost Ground Stations

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The number of micro- and nanosatellites has rapidly increased in recent years. The tracking of some satellites can be insufficient if orbits are not determined by the development institutions. This is especially true in the case of low-altitude satellites, in which the orbit frequently changes. In this paper, the activities of the international Orbit Determination Network (ODN) system are described, and the feasibility of tracking is quantitatively evaluated on the basis of simultaneous observations in two countries. The hardware and software architecture required for a conventional low-cost ground station to become a node of the network is also described in detail.

Key Words: Orbit Determination, Low-Cost Ground Station, Doppler Frequency

1. Introduction

The development of micro- and nanosatellites such as cubesats has advanced in recent years. The technology for developing micro- and nanosatellites is maturing, and applications for practical Earth observation missions are growing. Educational satellite projects are operated from ground stations located in universities. They depend on public orbital information released by USSTRATCOM (United States Strategic Command) and presented at the Space-Track.org web site. However, some satellites cannot be sufficiently tracked with only public orbital information. The microsatellite UNITEC-1 (UNISEC technological experiment carrier-1), developed by Japanese universities and the University Space Engineering Consortium (UNISEC), was launched in May 2010. It is a unique microsatellite on a deep-space trajectory to Venus with an orbit that must be determined without depending on USSTRATCOM. The nanosatellite KSAT (Kagoshima Satellite), developed by Kagoshima University, was launched together with UNITEC-1 and released into orbit less than 300 km from the Earth surface. The orbital information was released by USSTRATCOM, but the update frequency was not stable and often stopped for several days. Tracking the satellite using an estimate of the orbit was very difficult because of frequent changes due to strong atmospheric drag.

In previous studies, an orbit determination system using low-cost ground stations was demonstrated, which used only Doppler shift measurements of satellite beacon signals. The key component is a batch state estimation filter, which employs a classical analysis method to solve the state parameters from observations. The observational data are Doppler shift measurements of received radio signals, and the estimated states are the orbital elements of the satellite (position and velocity) with Earth-centered inertial coordinates. Three types of antennas were used in these experiments. The first is a 2.4-m diameter parabola antenna with a receiving gain of 32.2 dBi for 2.3-GHz S-band radio signals, shown in Fig. 1(a). The second is a commercial 10-element Yagi antenna with a gain of 11.6 dBi and an azimuth/elevation rotator, shown in Fig. 1(b). The third is a commercial mobile whip antenna with a length of 1.58 m and gain of 7.6 dBi, shown in Fig. 1(c).

Case studies using real satellite observations were carried out. The first case used the Yagi antenna for the nanosatellite CUTE-1, developed by the Tokyo Institute of Technology, with an approximately 435-MHz beacon transmitter. The second case used the 2.4-m parabola antenna for the 50-kg microsatellite SPRITE-SAT, developed by Tohoku University, with an approximately 2.3-GHz transmitter. The achieved position accuracy were 0.05 degrees (RMS, root mean square) in angle or 2.5 km (RMS) in distance for 435-MHz signals.

Fig. 1. Satellite tracking antennas at Tohoku University: a) 2.4 m parabola antenna for S-band radio signals, b) Yagi antenna with rotator for 435 MHz signals, and c) mobile antenna for 435 MHz signals.
and 0.55 degrees (RMS) in angle or 26 km (RMS) in distance for 2.3-GHz signals. This level of precision is sufficient for the purpose of satellite tracking, and the satellites can be continuously tracked without USSTRATCOM orbit information with this method. This method is especially effective for low-Earth orbit satellites with large Doppler shifts.

In this paper, an automatic data processing system for orbit determination, including observation and analysis, is shown to be an improvement over manual procedures. A case study for a real low-Earth orbit (LEO) satellite observed at a single ground station is shown. Simultaneous observations held in Japan and Germany in July 2012 are also reported. In the future, this system will contribute to the operation of micro- and nanosatellites for disaster monitoring and Earth sciences by using an increased number of ground network stations. Remarkably, the equipment cost for a single-node ground station is about USD 5000, allowing a large number of institutions around the world to participate.

An orbit determination method using Doppler shift and a batch state estimation filter was suggested 50 years ago. In practice, measurements of range and range rate (RARR) have been traditionally used, with a typical accuracy of 15 m and 1 mm/s, respectively. Measurements using the alternative of satellite laser ranging (SLR) systems enable us to observe the range with an accuracy of about +/- 1 cm, but the number of ground stations is not sufficient. Direct position measurements with on-board GPS receivers can be used for microsatellites with an accuracy of 10 m, but some nanosatellites are not equipped with a GPS receiver because of power consumption constraints.

The orbit determination methodology in this paper is not original, but a performance evaluation using real satellite observation data with an existing university-based low-cost ground station is not included in other studies. Special on-board instruments are not required for this method because Doppler shift measurements can be obtained for all LEO satellites. Many universities and institutions can easily adopt this method using their existing data communication ground stations.

This paper focuses on the system integration and the evaluation of observations of real satellite data. To shorten the calculation time, simpler orbital estimation model and filter are used. By combining other simulation-based methods, the performance of this system can be improved. The purpose of this system is to generate TLE (Two Line Element) records using newly defined procedures. A TLE is an instantaneous orbit at a specific time, usually when a satellite is passing over the equatorial plane. Using a recommended orbital estimator such as SGP4 (Simplified General Perturbations Satellite Orbit Model 4), the future and past orbit can be estimated at an arbitrary time. The error of the estimated orbit will increase as the propagation time is extended because of the orbital and the propagation model errors. In the case of cubesats, an analysis of real flight GPS data showed that the average error on SGP4 orbital estimations was 0.832 km after less than 3.5 days. To avoid this kind of error, another study suggested a method to generate more reliable orbit estimates by filtering multiple TLE records. This method can be integrated into the original TLEs generated by the system described here.

Our system uses only Doppler shift but can use other observational data, such as antenna directions. Sakamoto has suggested radio interferometers to determine the orbits of LEO satellites, which are sensitive to the tangential motion to radial direction. Combined with the Doppler shift, which is sensitive to radial motion, the precision of the determined orbit can be improved.

Needless to say, on-board sensors are more convenient for orbit determination than ground-based methods. GPS receivers are most common, but magnetic sensors are used in cubesats with a low power budget. From real flight data, a precision of less than 10 km in 24 hours has been shown with magnetic sensors.

2. Theory

When satellite signals are received at a ground station, the distance or range ρ between the satellite and the ground station is gradually changing, and the radio frequency experiences a Doppler shift. The position and velocity vectors of the satellite and the ground station can be calculated in the inertial coordinate system. From the relative position and velocity vectors p, ρ, the range-rate ˙ρ, which is the rate of change in range with respect to time, can be derived as

\[ \dot{\rho} = \rho \cdot \dot{p} / \rho \]  

If the carrier frequency of telemetry signals is f₀, and the speed of light is c, the Doppler frequency f can be defined by

\[ f = (1 - \dot{\rho} / c)f_0 \]  

The orbit is defined by a state vector X₀ = [x, y, z, dx/dt, dy/dt, dz/dt]ᵀ at time t₀, where each element is the position or velocity in an Earth-centered equatorial inertial coordinate frame. In some analyses, the carrier frequency f₀ can also be included as an estimated parameter because the transmitting frequency has a bias offset error from the nominal value caused by the unstable temperature of the oscillator. The observation vector Z is comprised of the group of measurements fᵢ at time tᵢ. In the orbit determination, X₀ is updated to decrease the residuals between the estimated Ž and the real Z. The orbit Xᵢ at time tᵢ and estimated measurement fᵢ are calculated from the initial X₀. The vector Xᵢ can be calculated by numerical integration of the differential equations of the orbital dynamics model. X₀ is recursively updated from the residual between the estimated fᵢ and the real fᵢ. When the RMS of the residuals has converged, the final value X is the determined orbit. This is a simple application of a general state estimation filter.

Adding the small (1 m or 1 mm/s) changes ΔX₀ to X₀, the small change ΔZ of the observational residuals can be derived by

\[ \Delta Z = H \Delta X_0 \]  

where H = ∂Z/∂X₀ is a sensitivity matrix. H is numerically calculated and updated when X₀ is changed. The error covariance matrix R is defined with its diagonal elements as the observational variance σ², and all other elements are zero. Finally, ΔX₀ can be calculated from ΔZ as follows. ΔZ is a residual vector between Z and Ž (ΔZ = Z − Ž). X₀ is
replaced by \( X_0 + \Delta X_0 \), and this sequence is repeatedly calculated until \( \Delta X_0 \) approaches zero;
\[
\Delta X_0 = (H^T R^{-1} H)^{-1} H^T R^{-1} \Delta \dot{Z}
\]  
(4)

The program ODEF (Orbit DEtermination Filter), developed by Sakamoto, can determine the orbit from the observations of Doppler shift and is used for real orbit observations in later sections of this paper.

3. Observation System

3.1. Hardware

In previous studies, the three types of antennas shown in Fig. 1 were used to observe Doppler shifts. From those studies, the most recommended was the mobile whip antenna. This antenna does not require rotation motors, which carry the risk of hardware defects. It can be set up easily with a commercial tripod without directional calibration.

The commercial radio transceiver, precise OCXO (Oven Controlled Xtal Oscillator), and normal-spec computer for the mobile whip antenna system are shown in Fig. 2. All instruments could be packed in a standard 60 L suitcase for conducting the experiment in Germany. The same can be carried out in any country as long as a power supply and internet connection are available.

3.2. Frequency measurement

The 430-MHz CW signals from a satellite are demodulated and down-converted to sound signals at around 800 Hz by a commercial radio receiver and are recorded by a computer with a normal-spec sound card, as shown in Fig. 3. The frequencies can be calculated at reasonable quality with noise on the order of several Hz using an FFT analysis.

The use of a commercial radio receiver instead of an expensive spectrum analyzer was proposed by Oda et al.\(^{12}\). The method described hereafter newly introduces a precise external OCXO with a stability of \( 1 \times 10^{-5} \) in order to decrease the measurement error by a factor of 1/50 because the frequency stability of typical transceivers is insufficient.

3.3. Automatic data processing system

The system was designed to record the orbital elements every time new observations are obtained. The set of orbital elements is defined as TU-TLE (Tohoku University Two-Line orbital Elements). It is possible to update the orbital elements more than 4 times per day for polar orbital satellites even if only one ground station is used. A comparison with US-TLE (USSTRATCOM TLE), updated once per day, is shown in Fig. 4. By increasing the update frequency, the orbital estimation error can be kept smaller than US-TLE.

The observational data is composed of the transceiver (A) and the peak-power frequencies computed by FFT (B). In each observation pass, two data files are generated. The software manages the start and finish times of each pass and automatically starts the orbit analysis procedure just after the observation pass finishes.

The transceiver frequency is changed at certain intervals to keep the signal (B) between 400 and 1200 Hz. The required automatic frequency control is based on the orbital estimation and the bias offset of the satellite’s on-board transmitter.

The four-step procedure described below and illustrated in Fig. 5 is carried out over several minutes. The settings in each step are examples in the case of tracking a 435-MHz satellite and would be modified for different target satellites or ground stations.

**Step-A1:** Combine the measurement data files and improve frequency observations by (1) eliminating data with no receiving signal (less than a threshold value calculated from the average of all the data), (2) averaging data in two-second segments to improve computational speed, (3) eliminating data with an error larger than 10 Hz compared to a polynomial approximation in each 30-sec segment, and (4) eliminating all data in a 30-sec segment when the RMS from the average value is less than 20 Hz, as these will be signals from other ground communication radios without a Doppler shift.

**Step-A2:** Process the single-pass orbit determination and eliminate bias frequency offset. The bias frequency offset, as well as the position and velocity orbital elements, can be determined by a state estimation filter and the observations are improved by eliminating offset values. In this step, only the determined frequency offset of each pass is adopted, while the other orbital elements are omitted because the orbital elements determined from a short time period have a large uncertainty. With this pre-processing sequence, the processing time of the subsequent multi-pass analysis can be shortened, and the convergence properties of post processing sequences are improved. The standard deviations (SD, \( \sigma \)) are calculated from frequency estimations and real observations in each pass, and observations with an error of 2.5 \( \sigma \) or more are eliminated for post processing. This is recursively calculated until these unnecessary data are completely removed.

**Step-A3:** Process multi-pass orbit determination and calculate the orbit. A maximum span, e.g., 3 days, is defined, and data older than this span are eliminated before new data are obtained. The epoch time is defined as the first datum of the last pass. After the state estimation process, the SD of the observations is calculated from the determined orbit. When the SD exceeds an unacceptable value, e.g., 30 Hz, all steps are canceled, and the data from the last observation pass are...
Step-A1: Calculate TU-TLE suitable for the determined orbit. The future estimated observations (a) are generated from the determined orbit using a precise orbital model. It is possible to include air drag models and high-gravity potential terms. The determined orbit is expressed by Keplerian orbital elements, and an initial value of the TU-TLE (TU-TLE') in which the air drag terms are all zero is generated. The TLE parameters are improved by a state estimation filter in which the estimated observations (b), calculated with the SGP8 orbital model, are compared to the data (a). The converged value is the TU-TLE.

4. Test I - Single Ground Station

In this test, the two nanosatellites CUTE-1 (822 km alt., 98.7 degree incl., 436.8375 MHz beacon signals) and KKS-1 (646 km alt., 98.1 degree incl., 437.385 MHz beacon signals) were observed at the Tohoku University ground station. The stability of the automatic processing system and the generated TU-TLE records was evaluated. The TU-TLE is updated with every new observation pass. The procedure to compare TU-TLE and US-TLE is as follows:

Step-B1: The estimated orbital values (azimuth, elevation, and Earth-centered inertial position) are calculated using TU-TLE in 5-sec intervals, while the elevation is limited to more than 5 degrees between the acquisition of signal (AOS) and loss of signal (LOS). TU-TLE records are updated in each pass, and the newest record is used in the estimation.

Step-B2: The estimated orbital values are calculated using US-TLE. The estimated values from TU-TLE and US-TLE are compared as shown in Fig. 6, and the maximum error and RMS value are calculated. The azimuthal data with elevation greater than 80 degrees are eliminated because of excessively large errors around the pole singularity.

The overlap analysis shown in previous studies was suitable for evaluating the error compared to the true orbits. Presently, US-TLE is normally used for the operation of micro- and nanosatellites developed by educational institutions. Therefore, the error statistics compared to US-TLE as well as the true orbit are suitable for the performance evaluation of new methods.

The observation spans were as follows:
- CUTE-1: 05:59:07 UTC on March 27, 2013 to 21:43:38 UTC on April 1, 2013, covering 33 passes (of which 10 passes were eliminated)
- KKS-1: 04:08:38 UTC on March 27, 2013 to 15:41:28 UTC on April 4, 2013, covering 48 passes (of which 17 passes were eliminated)

The evaluation results are listed in Table 1. Using the latest three-day observations, TU-TLEs were generated 3 days after the start of observation. For CUTE-1, the position error was 10.6 km (RMS), azimuth error was 0.33 degrees (RMS), and elevation error was 0.18 degrees (RMS). For KKS-1, the position error was 6.2 km (RMS), azimuth error was 0.24 degrees (RMS), and elevation error was 0.13 degrees (RMS). From these results, the new orbit determination system was suitable for continuous satellite tracking when the half-beam width was more than 1 degree. This agrees with previous studies, which showed an 11-km (RMS) position error for CUTE-1 from a 4-pass analysis.

5. Test II - Multiple Ground Stations

To evaluate the merit of using multiple ground stations in multiple countries, joint observations were carried out three
In this paper, an orbit determination system using Doppler shift measurements was shown, with the goal of constructing a feasible system for real satellite operations. Case studies for real satellite observations were presented using both single ground stations and multiple ground stations in different countries. Compared to simulations, real observations and data analysis require additional work in terms of hardware arrangement and developing stable software. The case studies shown in this paper are an important first step toward a future multi-point observation network system.

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References


Table 1. Evaluation of TU-TLE quality.

<table>
<thead>
<tr>
<th>Target</th>
<th>Error Evaluation of TU-TLE and US-TLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>position</td>
</tr>
<tr>
<td></td>
<td>of freq.</td>
</tr>
<tr>
<td>CUTE-1*</td>
<td>28 Hz</td>
</tr>
<tr>
<td>KKS-1**</td>
<td>26 Hz</td>
</tr>
</tbody>
</table>

* span = 2013/03/30 06:36 - 2013/04/04 15:41 UTC, freq. = 436.8375 MHz
** span = 2013/03/30 06:29 - 2013/04/04 15:41 UTC, freq. = 437.385 MHz
*** between real obs. and US-TLE estimation
**** only when el < 80deg

Table 3. Results of orbit determination and the error evaluation.

<table>
<thead>
<tr>
<th>Case*</th>
<th>Error Evaluation of determined orbit and US-TLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMS of freq.</td>
</tr>
<tr>
<td>a) TUGS only</td>
<td>33 Hz</td>
</tr>
<tr>
<td>b) IRS only</td>
<td>46 Hz</td>
</tr>
<tr>
<td>c) TUGS and IRS</td>
<td>43 Hz</td>
</tr>
</tbody>
</table>

* TUGS = Tohoku Univ., JP / IRS = IRS lab., Stuttgart Univ., DE

Table 2. Observation pass list used for orbit determination of CUTE-1.

<table>
<thead>
<tr>
<th>Pass</th>
<th>GS</th>
<th>First Data</th>
<th>Span</th>
<th>Total Span</th>
<th>Num. of Data***</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>TUGS</td>
<td>2012/07/04 07:38:06</td>
<td>10 m 41 s</td>
<td>0.0</td>
<td>174</td>
</tr>
<tr>
<td>P2</td>
<td>IRS</td>
<td>2012/07/04 16:06:54</td>
<td>11 m 28 s</td>
<td>0.4</td>
<td>230</td>
</tr>
<tr>
<td>P3</td>
<td>TUGS</td>
<td>2012/07/04 21:38:00</td>
<td>8 m 50 s</td>
<td>0.6</td>
<td>156</td>
</tr>
<tr>
<td>P4</td>
<td>IRS</td>
<td>2012/07/05 06:00:26</td>
<td>10 m 59 s</td>
<td>0.9</td>
<td>200</td>
</tr>
<tr>
<td>P5</td>
<td>TUGS</td>
<td>2012/07/05 08:58:11</td>
<td>8 m 27 s</td>
<td>1.1</td>
<td>108</td>
</tr>
<tr>
<td>P6</td>
<td>IRS</td>
<td>2012/07/05 17:26:41</td>
<td>12 m 25 s</td>
<td>1.4</td>
<td>180</td>
</tr>
<tr>
<td>P7</td>
<td>TUGS</td>
<td>2012/07/05 21:18:51</td>
<td>6 m 44 s</td>
<td>1.6</td>
<td>96</td>
</tr>
<tr>
<td>P8</td>
<td>IRS</td>
<td>2012/07/06 05:42:21</td>
<td>10 m 51 s</td>
<td>1.9</td>
<td>137</td>
</tr>
<tr>
<td>P9</td>
<td>TUGS</td>
<td>2012/07/06 08:38:26</td>
<td>9 m 14 s</td>
<td>2.0</td>
<td>123</td>
</tr>
</tbody>
</table>

* TUGS = Tohoku Univ., JP / IRS = IRS lab., Stuttgart Univ., DE
** obs. span is based on the first and last acquired data
*** num. of refined data after filtering

Fig. 6. Comparison of US-TLE and TU-TLE.

Fig. 7. Example of frequency measurements for CUTE-1 by two different stations (left: P1 at TUGS, right: P2 at IRS).


