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Automatic tracking system for weather satellite image reception

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Abstract

We present a tracking ground system for low Earth-orbiting (LEO) satellite image reception composed of a software part and a material part.

The developed prediction software (LAAR-TRACK) ensures an efficient satellite orbit determination. It is based on the simplified general perturbations model (SGP4) used by the North American Aerospace Defense Command for generating orbital elements.

LAAR-TRACK gives the azimuth and the elevation needed for the antenna to signal, in real time, LEO satellites during their passage above the ground receiving station. The software is loaded on a computer directly connected, via the parallel port, to the tracking interface that we developed, which will be detailed in this paper. The proposed tracking system is composed of a simple hardware interface structure that can be easily technically reproduced without any programming. The cost of the proposed tracking interface is lower than that of the other proposed realizations.

Key Words: *LEO satellites, ground station, two-line elements, SGP4 model, satellite tracking interface*

1. Introduction

Several autonomous orbit determination methods for low Earth-orbiting (LEO) satellites have been proposed over the last 2 decades using several methods [1-3].

Satellites such as those in the National Oceanic and Atmospheric Administration (NOAA) series particularly need accurate prediction and localization to have high-quality received images without cuts in the reception, which cause black horizontal lines on the images [4-7].

General perturbation element sets are generated by the North American Aerospace Defense Command (NORAD) for all resident space objects. These element sets are periodically refined so as to maintain a reasonable prediction capability for all space objects, and they can be used to predict the position and velocity

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of Earth-orbiting objects [8]. When orbital elements are generated from observations, a particular model is used. The elements released are the mean elements and are meant to be used with a particular model. Blindly converting to a different format or using a different model results in decreased accuracy. The best accuracy is achieved when using the same model as used to generate the elements [9].

As we are interested in the reception of high resolution picture transmission (HRPT) images of NOAA satellites with an altitude of approximately 850 km, we chose to implement a simplified general perturbations model (SGP4), applied for near-Earth satellites [10], for our prediction software, taking into consideration all of the external perturbations that affect the satellite's trajectory.

The orbit determination problem consists of 2 basic parts: propagation of the state estimate forward in time and the updating of the state estimate based upon new measurements of parameters that are functions of the states.

2. The prediction models

Satellite orbits around Earth are not the perfect ellipses of Newtonian mechanics. The oblateness of Earth, the irregular gravitational field, the atmospheric drag, the pull of the Moon and Sun, and the solar light pressure have effects on satellite trajectories. Accurate models take into consideration these perturbations to predict the exact position of the satellite [11].

The simplified perturbations models are a set of 5 mathematical models (SGP, SGP4, SDP4, SGP8, and SDP8) used by the National Aeronautics and Space Administration (NASA) and NORAD for calculation of the orbital state vectors of satellites and space debris relative to the Earth-centered inertial (ECI) coordinate system [12].

These models predict the effect of perturbations caused by Earth's shape (spherical harmonics), drag, radiation, and gravitational effects from other bodies such as the Sun and Moon [13].

The accuracy of element sets depends on time. The perturbations change the orbit in nonpredictable ways over long periods of time. This means that the accuracy of the predictions from an element set decrease over time. The best accuracy requires the obtaining of fresh element sets.

Atmospheric drag is the least predictable factor; it could slow down the motion of a satellite when its orbit is low enough to be affected by the friction of Earth's atmosphere [14]. This has more of an effect on lower satellites and makes their orbits less predictable, which means that the elements need to be updated more frequently to be accurate.

2.1. The SGP4 propagator

SGP4 is a NASA/NORAD algorithm of calculating near-Earth satellites. Any satellite with an orbital time of less than 225 min should have this algorithm applied. Satellites with orbital times greater than 225 min should have the SDP4 or SDP8 algorithms applied. Two-line element (TLE) data should be used as the input for the SGP4 algorithm. The accuracy of SGP4 is typically 0.1° longitude and 0.1° latitude from the ground. TLE data older than 30 days are considerably inaccurate due to perturbations in the orbit.

To summarize, SGP4 uses a geopotential model of the fourth order:

$$V = -\frac{GM}{r}\left(1 - \sum_{n=2}^{4} J_n \left(\frac{r_e}{r}\right)^n P_n(\sin\phi)\right), \tag{1}$$

where V is the geopotential, G is the gravitational constant, M is the mass of Earth, r is Earth's mean radius, Φ and r_e are respectively the latitude and the radius of the observational point, P_n is the normalized associated Legendre function, and J_n represents the zonal terms.

This model takes into consideration:

- The equatorial pad of Earth (J_2),
- The pear form of Earth (J_3),
- An additional deviation (J_4).

It also models the atmospheric trail, which slows down satellites on their trajectories.

3. Two-line elements

Data for each satellite consist of 3 lines: 1 line containing the satellite's name, followed by the standard 2-line orbital element set format identical to that used by NASA and NORAD.

3.1. Decoding the TLEs

For decoding the TLE files, we developed software, shown in Figure 1, that extracts the following orbital elements:

- Epoch: Specifies the time at which the set of orbital elements was taken.
- Orbital inclination: The angle between the orbital and the equatorial plane.
- Right ascension of ascending node: An angle in the range of 0-360° measured at the center of Earth, from the vernal equinox to the ascending node.
- Argument of perigee: The angle between the line of apsides and the line of nodes.
- Eccentricity: In the Keplerian orbit model, the satellite orbit is an ellipse. Eccentricity determines the shape of the ellipse: when e = 0, the ellipse is a circle. When e is very near 1, the ellipse is very long and skinny.
- Mean motion: A number that indicates the complete number of orbits a satellite makes in 1 day.
- Mean anomaly: An angle that increases uniformly with time starting at perigee, used to indicate where a satellite is located along its orbit.

Figure 1. Decoding the TLE file interface.

4. Calculation for positioning antenna

Disposing of the orbital parameters, it is possible now to use the SGP4 propagator, which will provide us with the position and the speed of the satellite in the ECI coordinate system.

The ECI coordinate system, shown in Figure 2, is defined as a Cartesian coordinate system, where the coordinates are defined as the distance from the origin (situated at the center of Earth) along 3 orthogonal axes:

- The z-axis runs along Earth's rotational axis pointing north,
- The x-axis points in the direction of the vernal equinox, and
- The y-axis completes the right-handed orthogonal system.

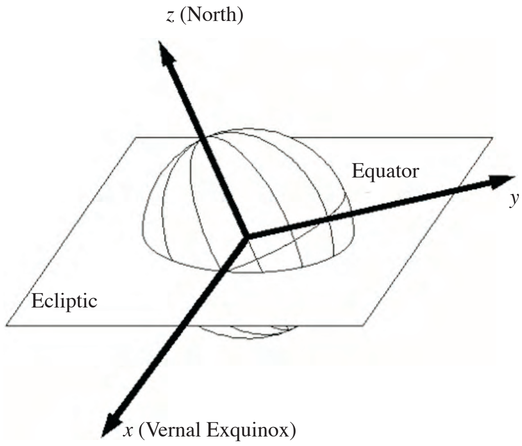

Figure 2. The ECI coordinate system.

If the satellite's position in the ECI system is defined as [x_s,y_s,z_s] and the observer is [x,y,z] then the range vector, defined in the ECI system, is simply: [r_x,r_y,r_z] = [x_s-x, y_s-y, z_s-z].

To generate the look angles (elevation and azimuth of the satellite), we need to convert the vector in the topocentric-horizon system shown in Figure 3. That system, centered on the ground receiving station, has its z-axis pointing toward the zenith, the x-axis pointing south, and the y-axis pointing east

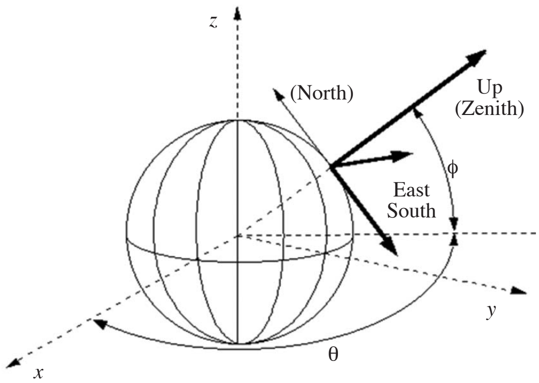

Figure 3. Topocentric coordinate system.

We must proceed to 2 rotations:

- Through the local sidereal time (the θ angle) about the z-axis, and
- Through the observer's latitude (the ϕ angle) about the y-axis.

The coordinates become:

$$r_S = \sin\phi\cos\theta r_x + \sin\phi\sin\theta r_y - \cos\phi r_z, \tag{2}$$

$$r_E = -\sin\theta r_x + \cos\theta r_y, \tag{3}$$

$$r_Z = \cos\phi\cos\theta r_x + \cos\phi\sin\theta r_y + \sin\phi r_z. \tag{4}$$

The range to the satellite is:

$$r = \sqrt{r_S^2 + r_E^2 + r_Z^2}. \tag{5}$$

The elevation is given by:

$$El = sin^{-1}\left(\frac{r_Z}{r}\right). \tag{6}$$

The azimuth is given by:

$$Az_= \tan^{-1}\left(\frac{r_E}{r_S}\right). \tag{7}$$

5. Description of the tracking hardware part

As shown in Figure 4, the tracking can be summarized in 3 steps:

- Getting the antenna position.
- Comparison with the values calculated by the LAAR-TRACK.
- Controlling the azimuth and the elevation of the antenna without human intervention.

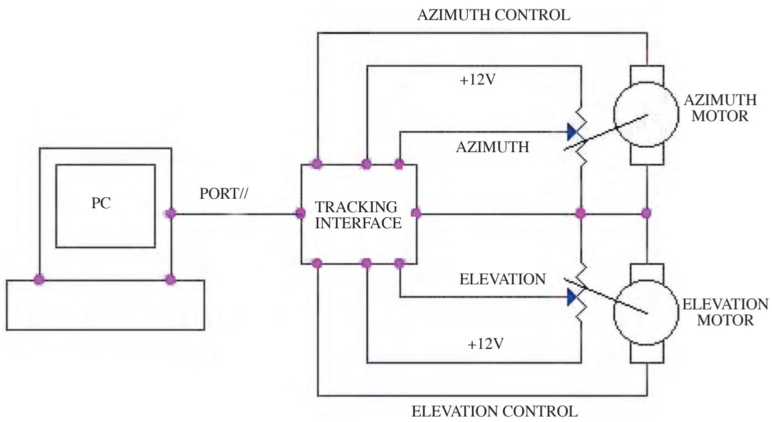

Figure 4. Synoptic diagram of satellite tracking.

We recover the antenna position information via the control panel of the rotor. While comparing the antenna position with the values calculated by the prediction software, the tracking interface directs the rotor so that the values read on the potentiometers correspond to those calculated by the software.

The tracking interface, represented in Figure 5, guarantees communication between the hardware part and the prediction software by ensuring the data flow between the antenna rotor and the computer, which contains the prediction algorithm.

The interface is connected to the PC where the prediction software is installed, through the parallel port.

The antenna elevation is recovered through pin 1 of the rotor:

- When the potential = 0 V $\rightarrow$ elevation = 0°.
- When the potential = 5 V $\rightarrow$ elevation = 180°.

The antenna azimuth is recovered through pin 6 of the rotor:

- When the potential = 0 V $\rightarrow$ azimuth = 0°.
- When the potential = 5 V$\rightarrow$ azimuth = 450°.

These data are compared with the elevation and azimuth values generated by the prediction software using differential amplifiers (LM324, Texas Instruments, Dallas, TX, USA).

Transistors (BC546, Fairchild Semiconductor, San Jose, CA, USA) are used to amplify the control currents of the motors, azimuth (left, right), and elevation (up, down) through pins 2, 3, 4, and 5 of the DIN card located on the back face of the control panel in such way that the difference at the exit of the differential amplifiers is null.

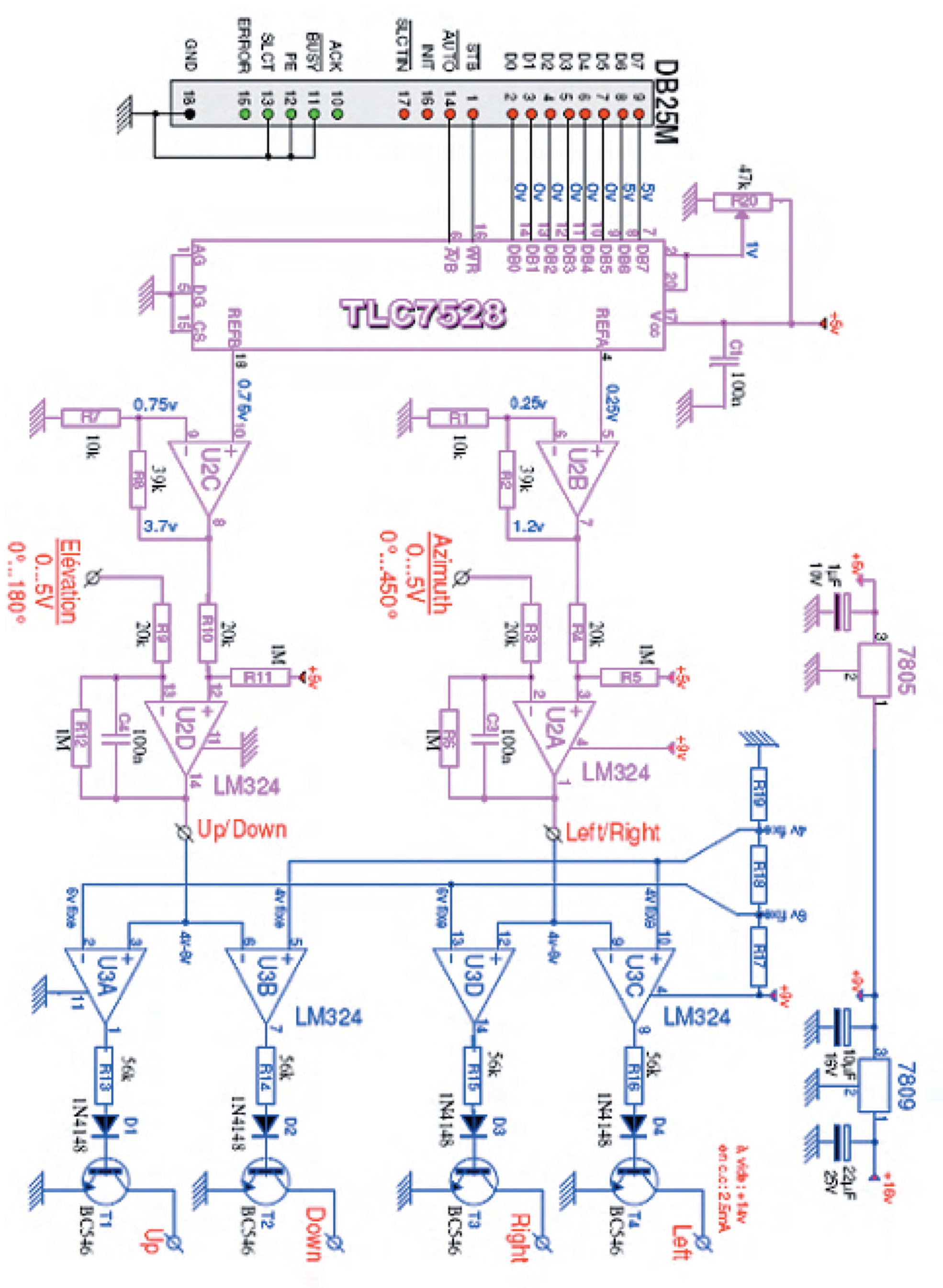

Figure 5. Electronic scheme of the tracking interface.

6. Results of the automation

Since 2005, we have built a database of approximately 2000 images. To reflect the improvement of the automation, a comparison was made between the quality of the automatically and the manually received images.

Figure 6 shows the quality difference between the HRPT images received automatically and manually.

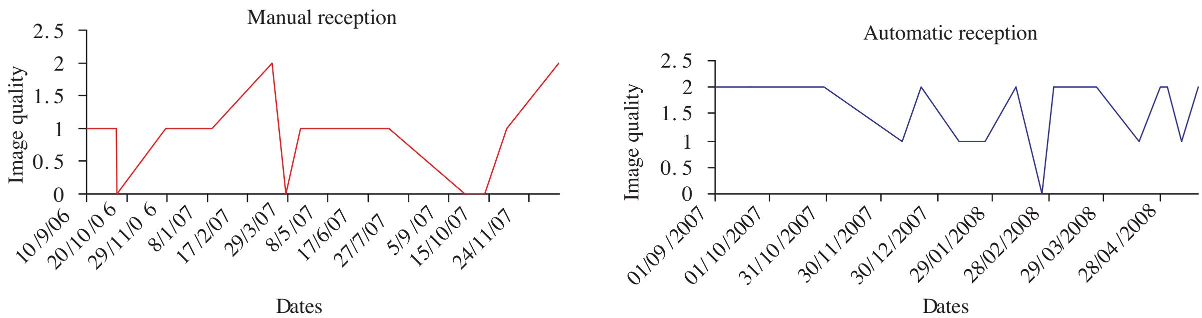

Figure 6. Comparison between the quality of the manual and the automatic reception.

We quantified the quality of some received images (approximately 20) with 3 values:

- Factor = 0: no data received.
- Factor = 1: moderate-quality data.
- Factor = 2: high-quality data.

With manual reception, we always faced cuts in the reception, which cause black horizontal lines in the received images. This was mainly due to the imprecision of the operator maneuvers, slow to find the best position for the antenna.

We can clearly see that since 1 September 2007, with the automatic reception, the NOAA HRPT images were received with high quality. However, in some rare cases (such as on 27 February 2008), there was no received signal, most of the time because of bad weather conditions such as gusty winds, which move the antenna from its position [15].

Figure 7 shows 2 HRPT images. One was received automatically (at left) and the other was received manually (at right). We can clearly see that automatic control of the antenna gives us high-quality received images.

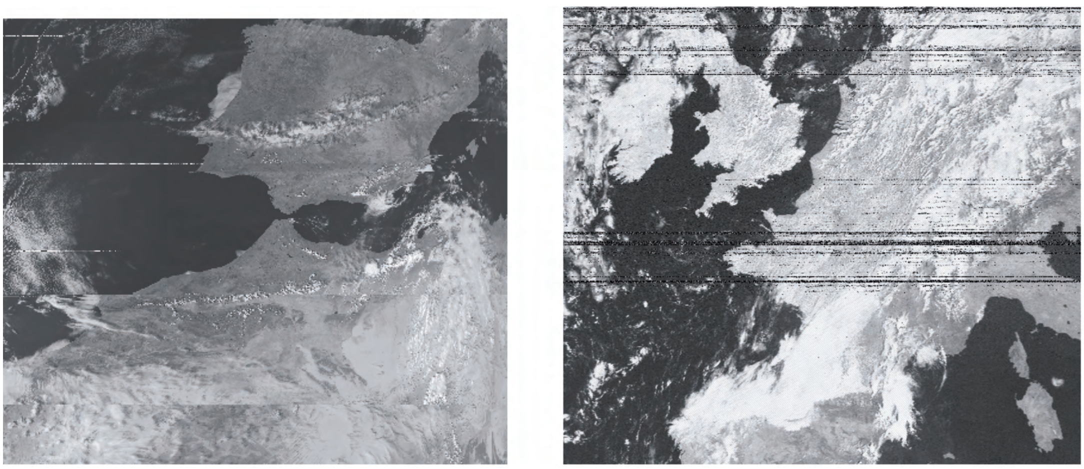

Figure 7. HRPT images received automatically (left) and manually (right).

7. Conclusions

In this paper, we presented a simple, precise, and efficient tracking system for LEO satellites using simple receiving equipment and a computer.

We developed satellite tracking software that calculates the position of polar-orbiting satellites at any time and also calculates where the antennas should be pointed in space to receive the satellite signal. This software is based on the SGP4 model that takes into consideration the disturbing forces constantly affecting the satellite trajectory, such as the gravitational attraction of the Sun, the Moon, and Earth's gravitational field.

The hardware part ensures the automatic control of the antenna rotor (Yeasu G-5500, Yeasu, Cypress, CA, USA). The tracking interface reads the antenna position voltages from the rotor and converts them to a digital word value that is compared with satellite position data information (calculated with the satellite prediction software), and it sends appropriate commands to move the antenna automatically. The advantages of the developed tracking interface are its simplicity and low cost.

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