

Fast satellite imagery of lengthy territories with complex configuration

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Abstract. When solving a number of remote sensing problems, there arose a need for fast satellite imagery of arbitrarily-spaced lengthy territories with complex configuration (borders, roads, rivers, coastlines, etc.). The distinctive features of Earth remote sensing satellites equipped with optical-electronic scanners providing sub-meter spatial resolution are a narrow swath width, which does not allow to take images of arbitrarily-spaced lengthy territories in one-orbit period, and a small pixel size of CCD photocells (i.e., low sensitivity), which does not allow to take images of low-contrast objects, as well as take pictures from neighbouring orbits at low angles of the Sun. An effective technique for controlling the high-resolution remote sensing spacecraft orientation in the process of retargeting (i.e., with non-zero angular velocities) is proposed, which allows to choose the best scan mode and take images of arbitrarily-spaced lengthy territories with complex configuration in one-orbit period, i.e. much faster. Moreover, non-zero angular velocities allow to increase the exposure time and take pictures of low contrast, low light or camouflaged objects. The main characteristics and disadvantages of Earth remote sensing satellites equipped with optical-electronic scanners providing sub-meter spatial resolution are shown in the article. The features of planning high-resolution satellite imagery and remote sensing data processing require consideration of a larger number of additional influencing factors than when using traditional imagery with optical-electronic scanners characterized by sub-meter spatial resolution. The main stages of modeling and planning ultra-fast satellite imaging of lengthy territories, as well as the basic design formulas are considered in the article. To approximate a lengthy object defined by the nodal points on the map, smoothing with a cubic interpolating spline is used. For short forecast periods and low earth circular orbits, sufficient accuracy is achieved with the propagator SGP4, which allows to work with the initial conditions in TLE files generated by NORAD.

1. Introduction

In recent years, remote sensing data play an increasingly important role in various spheres of human activity [1-5]. In particular, satellite imagery, which, compared to ground-based methods of measurement, have indisputable advantages, including:

- objectivity and reliability (satellite images allow to eliminate errors resulting from human factors, as well as deliberate distortion or concealment of important information);
- visibility and self-descriptiveness (it is possible to observe any, even the most remote places on Earth covering thousands of kilometers);

- relevance and efficiency (it is possible to deliver images without delay when user terminals receive information immediately);
- high revisit rate (up to several images a day);
- multidisciplinary (the same image can be applied to a wide range of tasks in the interests of various government agencies and private companies);
- multispectral imagery using optoelectronic scanners (synchronous imagery in several spectral bands in the visible and IR portions of the spectrum);
- multipolarization imagery using synthetic aperture radars (imagery for transmission and reception in C- and X-bands are acquired under different polarizations);
- safety (no adverse health outcomes compared to ground-based methods);
- high economic efficiency (significantly lower costs compared to ground-based methods);
- maximum availability and confidentiality (simplicity of obtaining data and minimizing the risk of information leakage).

2. Problem statement

When solving a number of remote sensing problems, there arose a need for fast satellite imagery of lengthy territories with complex configuration (borders, roads, rivers, coastlines, etc.). For this purpose ultrahigh resolution remote sensing satellites are commonly used (table 1).

Table 1. Satellites with ultra-high resolution multispectral scanners.

Satellite	Year of Launch	Country-operator	Resolution			Swath width, km	Georeferencing Accuracy, m
			PAN/MS, m	Radiometric, bit	Number of bands		
Kompsat-2	2006	Korea	1,0/4,0	10	4	15	NIA*
GeoEye-1	2008	USA	0,4/1,6	11	4	15	2...3
WorldView-2	2009	USA	0,46/1,84	11	8	16	5
Pleiades-1A	2011	France	0,5/2	12	4	20	4,5
Kompsat-3	2012	Korea	0,5/2	14	4	17	13
Pleiades-1B	2012	France	0,5/2	12	4	20	4,5
DubaiSat-2	2013	UAE	1,0/4,0	10	4	12	NIA
SkySat-1	2013	USA	0,8/2,0	11	4	8	NIA
KazEOSat-1	2014	Kazakhstan	1,0/4,0	12	4	10...60	NIA
Gaofen-2	2014	China	0,8/3,24	10	4	45	50
ASNARO-1	2014	Japan	0,5/2,0	11	6	10	10
WorldView-3	2014	USA	0,3/1,2	11/14	8	13	3,5
SkySat-2	2014	USA	0,8/2,0	11	4	8	NIA
Deimos-2	2015	Canada	1,0/4,0	10	4	12	NIA
Jilin-1A	2015	China	0,8/3,2	NIA	4	48	NIA
Kompsat-3A	2015	Korea	0,4/1,6	14	4	12	13
Cartosat-2C	2016	India	0,65/2,0	10	4	10	100
PeruSat-1	2016	Peru	0,7/2,0	12	4	10	NIA
SkySat-3...7	2016	USA	0,8/2,0	11	4	8	NIA
Gokturk-1A	2016	Turkey	0,7/2,8	12	4	20	10
SuperView-1A/B	2016	China	0,5/2	11	4	12	20
WorldView-4	2016	CHIA	0,3/1,2	11	4	13	3
Cartosat-2D/2E	2017	India	0,65/2,0	10	4	10	100
SkySat-8...13	2017	USA	0,8/2,0	11	4	8	NIA
Cartosat-2F	2018	India	0,65/2,0	10	4	10	100
SuperView-1C/D	2018	China	0,5/2	11	4	12	20

* NIA- no information available

The distinctive features of Earth remote sensing satellites with optical-electronic scanners providing sub-meter spatial resolution are:

1) a narrow swath width, which does not allow to make images of arbitrarily-spaced lengthy territories in one-orbit period;

2) a small pixel size of CCD photocells (i.e., low sensitivity), which does not allow to make images of low-contrast objects, as well as take pictures from neighboring orbits at low angles of the Sun.

To cover a lengthy object with an arbitrary configuration, it is necessary to take several images from different orbits, which takes from 3 days to 3 weeks. It may take even longer time due to cloudiness, which is unacceptable for most tasks. In the existing high resolution remote sensing systems used abroad, these problems are partially solved (some satellites allow to take images of arbitrarily-spaced straight-line lengthy territories, as well as to take long exposure images). When such imagery is performed in the process of retargeting (i.e., with non-zero angular velocities), it is possible to choose the best scan mode and take images of arbitrarily-spaced lengthy territories in one-orbit period, i.e., much faster. Moreover, non-zero angular velocities allow to increase the exposure time (that is, to take images of low contrast or low light objects).

The main stages of planning such imagery are [6]:

- approximation of a lengthy object defined by separate nodal points on a digital map (linear, quadratic, spline, etc.);
- determination of the optimal coverage of a lengthy object, taking into account the swath width of the imaging instrument and the required scanning direction;
- calculation of the orbital motion in order to choose the orbit for imagery and the time for switching on the imaging instrument, taking into account the Delay coefficient (when implementing the "Time Delay and Integration" mode);
- calculation of the satellite attitude angles required for imaging a given lengthy object, taking into account the installation angles of the imaging instrument;
- estimation of the satellite angular velocities during the imagery and analysis of the imagery feasibility, taking into account the existing limitations on the values of pointing angles and satellite angular velocities;
- modeling of satellite imagery process, taking into account additional factors (terrain relief displacement, atmospheric refraction etc.);
- Estimating the impact of systematic and random errors on the accuracy of obtaining an object coordinates from an image (errors in the installation of the imaging instrument, errors in determining the satellite elevation and azimuth, etc.).

3. Approximation of a lengthy object

To approximate a lengthy object defined by the nodal points on the map, smoothing with a cubic interpolating spline is used (the minimum number of nodal points of the object is 6).

4. Calculation of the orbital motion

The task of determining a spacecraft's motion at each moment of time comes to sixth-order numerical procedure for solving differential equations with a given initial value at a given time. The solution of a system of differential equations can be performed using various numerical procedures that ensure sufficient stability of solutions (for example, using the fourth order Runge-Kutta method). For short forecast periods and low earth circular orbits, sufficient accuracy is achieved with the propagator SGP4, which allows to work with the initial conditions in TLE files generated by NORAD.

5. Determination of satellite orientation using two reference points

The input data are composed of:

- coordinates of the reference points in geographic coordinate system corresponding to start and end points of the line which contains the node of the object;
 - satellite coordinates in geographic coordinate system;
 - geographic longitude, geocentric latitude and azimuth of the satellite.
 - pointing vectors of reference points in the instrument coordinate system;
- Yaw, pitch and roll orientation angles identify a reference frame that moves with the satellite.

6. Obtaining an object coordinates from an image

The input data are composed of the semi-axes of the Earth's ellipsoid a and b ; satellite coordinates in geographic coordinate system x_{cn}, y_{cn}, z_{cn} ; coordinates V_x, V_y, V_z of the pointing vector in geographic coordinate system V_{gcs} .

The latitude and the longitude of the point φ and λ create an output data set.

To find the coordinates x, y, z of the point in geographic coordinate system, a system of parametric equations of a straight line and an ellipsoid is used.

$$\begin{cases} x - x_{sat} = V_x \cdot t, \\ y - y_{sat} = V_y \cdot t, \\ z - z_{sat} = V_z \cdot t, \\ \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{b^2} = 1. \end{cases}$$

A quadratic equation is used to solve the system of equations.

$$Kx^2 + Lx + M = 0,$$

where
$$K = \frac{b^2 + b^2 \cdot A_y + a^2 \cdot A_z}{a^2 b^2}, \quad L = \frac{b^2 \cdot B_y + a^2 \cdot B_z}{a^2 b^2}, \quad M = \frac{C_y}{a^2} + \frac{C_z}{b^2} - 1,$$

$$A_y = \left(\frac{V_y}{V_x}\right)^2, \quad B_y = 2 \cdot (y_{sat} \cdot \frac{V_y}{V_x} - x_{sat} \cdot \left(\frac{V_y}{V_x}\right)^2), \quad C_y = (y_{sat})^2 - 2y_{sat} \cdot \frac{V_y}{V_x} \cdot x_{sat} + \left(\frac{V_y}{V_x}\right)^2 (x_{sat})^2,$$

$$A_z = \left(\frac{V_z}{V_x}\right)^2, \quad B_z = 2 \cdot (z_{sat} \cdot \frac{V_z}{V_x} - x_{sat} \cdot \left(\frac{V_z}{V_x}\right)^2),$$

$$C_z = (z_{sat})^2 - 2z_{sat} \cdot \frac{V_z}{V_x} \cdot x_{sat} + \left(\frac{V_z}{V_x}\right)^2 (x_{sat})^2$$

The coordinates of the point are calculated using the formulas

$$x_{1,2} = \frac{-L \pm \sqrt{L^2 - 4KM}}{2K}, \quad y = y_{sat} + \frac{V_y}{V_x} \cdot (x - x_{sat}), \quad z = z_{sat} + \frac{V_z}{V_x} \cdot (x - x_{sat}).$$

To choose between two solutions, the minimum distance from the satellite to the point is taken as a deciding factor.

The geodetic coordinates of the point - the latitude φ and longitude λ are calculated with the x, y, z coordinates of the point in geographic coordinate system using the formulas:

$$\varphi = \arctg \frac{z}{p(1 - e^2)}, \quad \lambda = \text{sign}(y) \arctg |y/x|, \quad \text{where } p = \sqrt{x^2 + y^2}, \quad e^2 = \frac{a^2 - b^2}{a^2}$$

7. Conclusion

An effective technique for controlling the high-resolution remote sensing spacecraft orientation in the process of retargeting (i.e., with non-zero angular velocities) is proposed, which allows to choose the best scan mode and take images of arbitrarily-spaced lengthy territories in one-orbit period, i.e.

much faster. Moreover, non-zero angular velocities allow to increase the exposure time and take pictures of low contrast or low light objects (so-called “Time Delay and Integration” mode). The features of planning high-resolution satellite imagery and remote sensing data processing require consideration of a large number of additional influencing factors that were not taken into account when designing earlier remote sensing satellites. In particular, it is necessary to analyze the impact of simplifications and errors in the existing models of satellite imagery on the efficiency of solutions to target problems in terms of immediacy, coverage and reliability of data obtained.

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