Satellite imagery of coastlines

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Abstract. An advanced technique for satellite imagery of lengthy coastlines with complex configuration using Earth remote sensing satellites equipped with optical-electronic scanners characterized by ultrahigh spatial resolution has been developed. It has been proposed to image coastal areas directly in the process of satellite retargeting (i.e., with non-zero angular velocities). The paper provides an assessment of comparative efficiency of the technique implemented using automatic satellite attitude program control in the process of retargeting, both in terms of improving the efficiency of satellite imagery, and in terms of coverage in one-orbit period. Approximate methods for lengthy objects with complex configuration using cubic splines are described. When planning such imagery, besides the standard set of parameters (lighting conditions, swath width, onboard equipment constraints, instrument errors, etc.), it is necessary to consider the limits for the angular region and angular velocities of retargeting types of imagery, as well as the features of imagery with significant deviations of the viewing axis from nadir. The results of modeling various types of imagery for a given area using measurement data of cloud amount are presented.

1. Introduction

Currently, satellite imagery of coastlines is an important component in monitoring lake and sea shores, ocean coast, as well as adjacent coastal and marine areas, which is used to solve a wide range of scientific, applied and economic problems [1-5]. It is usually performed with the help of Earth remote sensing satellites equipped with optical-electronic scanners characterized by high spatial resolution, which swath width is much narrower than the area to be imaged [6]. If the coastline is not located in the direction of the satellite motion, then imagery, as a rule, is performed in several non-adjacent orbits with a sufficiently large time interval between them. In this case the scanning direction coincides with the direction of the satellite motion, and imagery of the areas which are located away from the subsatellite track is performed in the roll orientation of the onboard instrument or the satellite itself before the imagery phase.

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.

2. Problem statement

When using optical-electronic scanners characterized with high spatial resolution for satellite imagery of lengthy territories with complex configuration (borders, roads, rivers, coastlines, etc.) located away from the subsatellite track, a problem arises with a narrow (usually from 5 to 20 km) swath width of the scanner, which does not allow to take images of arbitrarily-spaced lengthy territories in one-orbit period. As a rule, in such cases it is necessary to take several images from different orbits (figure 1).
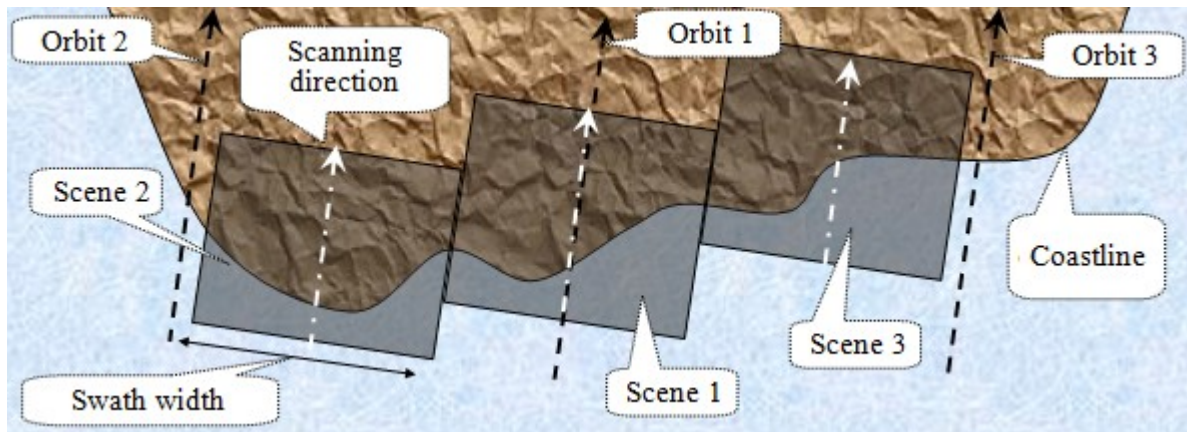

Figure 1. Imaging a long coastline in three orbits

It should be noted that for solar-synchronous orbits, typical for Earth remote sensing satellites with optical-electronic scanners, the same territory can be imaged only once during the orbit. Therefore, even double orbit imagery may take several days if there is no cloud cover and limits for the minimum imagery angles (depending on the swath width of the scanner and the range of the satellite retargeting angles).

It may take even longer time due to cloudiness, which is unacceptable for most tasks.

Current state. Some foreign satellites equipped with high-resolution opto-electronic scanners allow to take images of arbitrarily-spaced straight-line lengthy territories (figure 2).
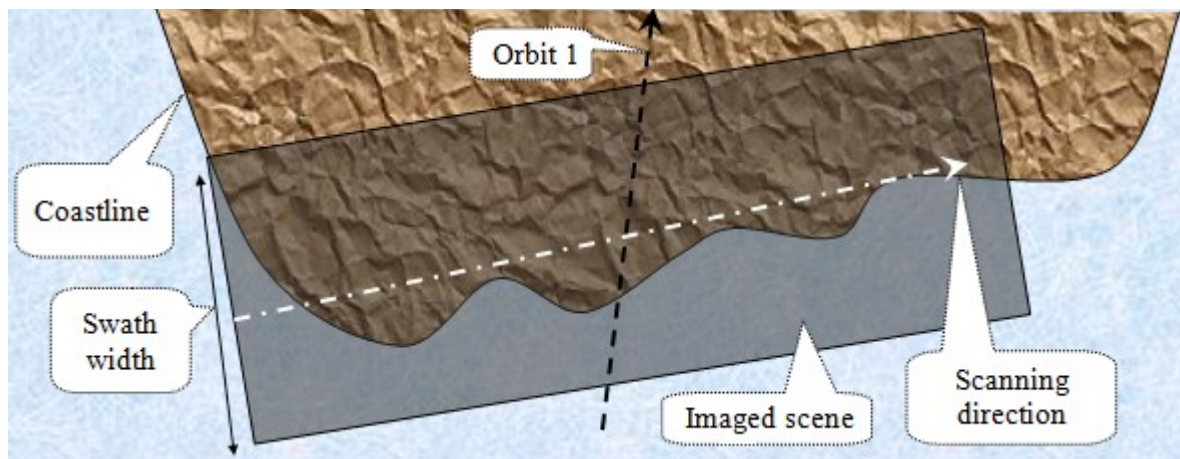

Figure 2. Imaging a long coastline in one-orbit period

To cover a lengthy object with complex configuration, as a rule, it is necessary to take several images from different orbits.

Possible solutions to the problem. An advanced technique implemented using automatic satellite attitude program control in the process of retargeting (i.e., with non-zero angular velocities) may significantly increase the efficiency of satellite imagery of lengthy coastlines with complex

configuration. The most of the existing high-resolution satellites allow to take images in the process of retargeting with an option to select arbitrary scan mode and take images of arbitrarily-spaced lengthy territories in one-orbit period, i.e. much faster.

The characteristics of imagery with retargeting. When planning such imagery, besides the standard set of parameters (lighting conditions, swath width, onboard equipment constraints, instrument errors, etc.), it is necessary to consider the limits for the angular region and angular velocities of retargeting during the imagery phase, as well as the features of imagery with sig-nificant deviations of the viewing axis from nadir.

Aims and objectives of the study. The objectives of the study are to develop a technique for satellite imagery of lengthy coastlines with complex configuration in the process of retargeting (i.e., with non-zero angular velocities) and assess the efficiency of such an imagery using subsequent computer modeling with measurement data of cloud amount for a given area.

The input data. The input data for modeling are composed of:

- the territory to be imaged is the southern coast of Crimea from Sevastopol to Feodosiya (about 160 km in length);

- the type of satellite orbit - solar-synchronous, with about 700 km height;

- the scanner swath width at nadir - 15 km.

3. Research method

The coastline to be imaged is defined on the map by the nodal points x_i with arbitrary latitude and longitude steps (the number of nodal points of the object $n = 6..9$). To approximate the coastline by the function $S(x)$, a natural cubic interpolating spline is used (boundary conditions for the second derivative $S''(x_0) = 0$ and $S''(x_n) = 0$), then smoothed with the least squares method. The function $S(x)$ is interpolated by a polynomial

$$S_i(x) = \omega y_i + \overline{\omega} y_{i-1} + h_i^2 \left[(\omega^3 - \omega)\delta_i + (\overline{\omega}^3 - \overline{\omega})\delta_{i-1} \right]$$

where $h_i = x_{i+1} - x_i$, $\omega = \dfrac{x - x_i}{h_{i+1}}$, $\overline{\omega} = 1 - \omega$.

Spline coefficients for $\delta_0 = 0$, $\delta_n = 0$, $\delta_1 ... \delta_{n-1}$ are defined by a system of linear equations

$$
\begin{pmatrix}
2[h_1 + h_2] & h_2 & 0 & ... & 0 \\
h_2 & 2[h_2 + h_3] & h_3 & ... & 0 \\
0 & h_3 & 2[h_3 + h_4] & ... & 0 \\
... & ... & ... & ... & ... \\
0 & 0 & 0 & h_{n-1} & 2[h_{n-1} + h_n]
\end{pmatrix}
\begin{pmatrix}
\delta_1 \\
\delta_2 \\
\delta_3 \\
... \\
\delta_{n-1}
\end{pmatrix}
=
\begin{pmatrix}
\Delta_2 - \Delta_1 \\
\Delta_3 - \Delta_2 \\
\Delta_4 - \Delta_3 \\
... \\
\Delta_n - \Delta_{n-1}
\end{pmatrix}
\tag{1}
$$

Its matrix is tridiagonal. It has symmetry in the elements, with a strict diagonal predominance.

A given class of systems is effectively solved using sweep method.

Write the following system of equations (1) in the form

$$
\begin{pmatrix}
a_0 & b_0 & 0 & 0 & \cdots & 0 & 0 & 0 \\
c_1 & a_1 & b_1 & 0 & \cdots & 0 & 0 & 0 \\
0 & c_2 & a_2 & b_2 & \cdots & 0 & 0 & 0 \\
... & ... & ... & ... & ... & ... & ... & ... \\
0 & 0 & 0 & \cdots & c_{n-2} & a_{n-2} & b_{n-2} & 0 \\
0 & 0 & 0 & \cdots & 0 & c_{n-1} & a_{n-1} & b_{n-1} \\
0 & 0 & 0 & \cdots & 0 & 0 & c_n & a_n
\end{pmatrix}
\times
\begin{pmatrix}
m_0 \\
m_1 \\
m_2 \\
\vdots \\
m_{n-2} \\
m_{n-1} \\
m_n
\end{pmatrix}
=
\begin{pmatrix}
d_0 \\
d_1 \\
d_2 \\
\vdots \\
d_{n-2} \\
d_{n-1} \\
d_n
\end{pmatrix},
\tag{2}
$$

where: $a_0 = \dfrac{h_1}{3}, \quad b_0 = \dfrac{h_1}{6}, \quad d_0 = -p_0 + \dfrac{y_1 - y_0}{h_1},$

$$i = 1, ..., n-1, \; c_i = \frac{h_i}{6}, \quad a_i = \frac{h_i + h_{i+1}}{3},$$
$$b_i = \frac{h_{i+1}}{6}, \quad d_i = \frac{y_{i+1} - y_i}{h_{i+1}} - \frac{y_i - y_{i-1}}{h_i}$$
$$c_n = \frac{h_n}{6}, \quad a_n = \frac{h_n}{3}, \quad d_n = p_n - \frac{y_n - y_{n-1}}{h_n}.$$

The solution of the tridiagonal system (2) in the form
$$m_i = \lambda_i \, m_{i+1} + \mu_i, \; i = 0, ..., n-1,$$
where λ_i, μ_i – sweep coefficients ($m_n = \mu_n$ if $b_n = 0$).

Recurrent formulas for sweep coefficients run factors λ_i, μ_i
$$\lambda_0 = -\frac{b_0}{a_0}, \quad \mu_0 = \frac{d_0}{a_0}, \quad \lambda_i = \frac{-b_i}{a_i + c_i \lambda_{i-1}}, \quad \mu_i = \frac{d_i - c_i \mu_{i-1}}{a_i + c_i \lambda_{i-1}}, \; i = 1, ..., n.$$

The following types of imagery were modeled:

- multi-orbit imagery with scene orientation along the sub-satellite track direction and zero angular velocities during the imagery phase;
- multi-orbit imagery with an arbitrary scene orientation and non-zero angular velocities during the imagery phase;
- one-orbit imagery of scenes with complex configuration with non-zero angular velocities during the imagery phase.

To obtain measurement data of cloud amount for this area, images taken by NASA's Terra and Aqua satellites (the MODIS instrument) were used.

4. The results of modeling
The results of modeling are shown in figures 3 and 4. In a given 5-day period, the territory to be imaged was completely available for 1 day, partially available for 2 days, unavailable for 2 days.

Figure 3. Computer modeling of imagery with an arbitrary scene orientation
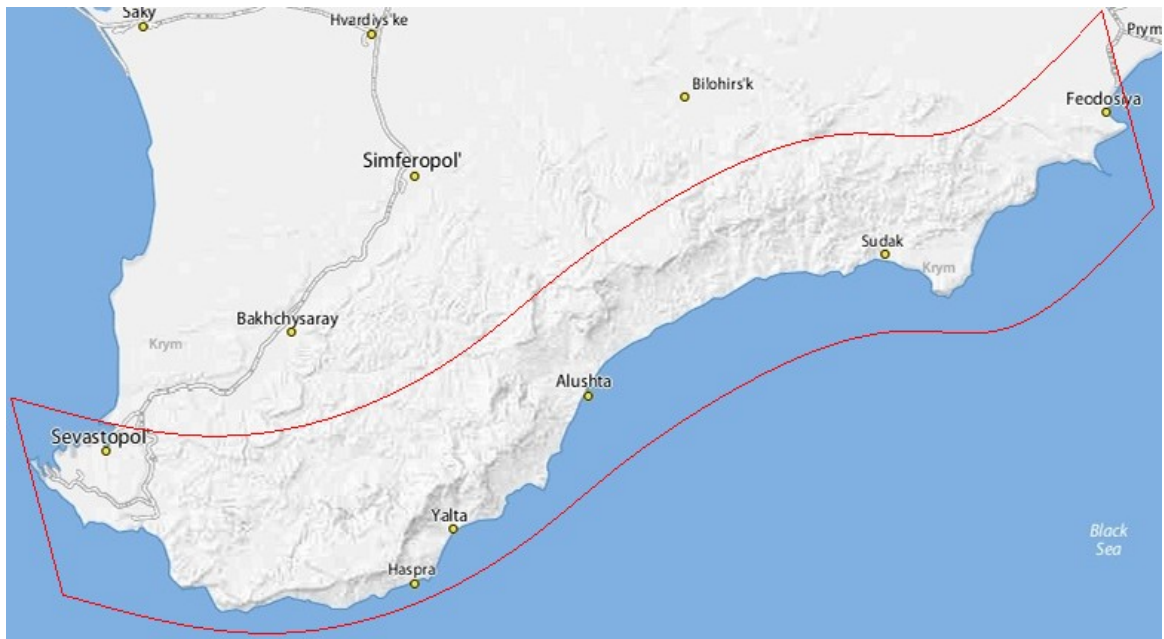(~ 80% of the area of a given territory was imaged in one-orbit period)

Figure 4. Computer modeling of imagery with dynamic retargeting
(100% of the area set is imaged in one-orbit period)

The results of modeling for various types of imagery are shown in table 1.

Table 1. The results of modeling for various types of imagery.

Type	The number of scenes (orbits)	Task duration, days	Coverage
Imagery with scene orientation along the subsatellite track direction	3	5	52%
Imagery with an arbitrary scene orientation	1	1	80%
Imagery of scenes with complex configuration	1	1	98%

5. Conclusion

The results of modeling for various types of imagery allow to make a conclusion that one-orbit imagery of a scene with complex configuration in the process of satellite retargeting during the imagery phase is the most effective type in terms of immediacy and coverage. Weather conditions are more important for other regions and for autumn-winter period. Thus, the comparative efficiency of the technique developed for satellite imagery in the process of retargeting will be even higher.

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