Sequential Modelling of Remote Earth Sensing Process

(IJCSNT) International Journal of
Communication Systems and Network
Technologies
ISSN Number: 2053-6283
Volume 13, Issue No. 1, 21–28

https://journals.mirlabs.in/index.php/ijcsnt
DOI-10.18486/ijcsnt/13.1.172
IJCSNT

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Abstract

This paper proposes a method of modelling of remote Earth sensing (RES) process, based on modelling of electromagnetic beam passing through various layers located in between Earth surface and registering sensor, like a number of filters. Such approach allows performing a flexible investigation of RES process, along with providing an ability for scientists to work on models of different layers in parallel in terms of the protocol, defined for inter-filter data flow exchange.

Keywords

Remote Earth Sensing (RES), Sequential Modelling, Electromagnetic Wave Propagation, Micro-satellites, Linear Image Sensors, Filter-based Modelling, Satellite Imaging, Beam Refraction, Earth Observation

Received: 01 January 2024; **Revised:** 10 April 2024; **Accepted:** 20 April 2024;
Published: 30 April 2024;

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Introduction

These days, it is hard to imagine our life without wide range of data, received from or via satellites, working on various orbits around the Earth[?]. One of the key sources of data, used in many different aspect of human life is remote Earth sensing (RES). This term includes monitoring and observation of planet surface in a wide electromagnetic specter[2]. Gathered information used in different ways, including weather monitoring and forecasting, control of natural resources usage, monitoring and preventing of wildfires and many other applications.

Along with technology evolution, science and industries have more and more requirements for volume and quality of RES data[3]. Such requests leads to evolution of communication, sensing and other satellite capabilities. However, an issue with space area is very high price of all kinds of development, production and testing both: separate components and whole systems. That is why very important role given to the various modelling technics and technologies, allowing decreasing of satellite development price.

From the RES perspective, the most profitable class of satellites is micro satellites[4]. This class of devices has operational weight up to 100 kilograms, what allows placing on it reasonable complicated sensing equipment with required amount of support equipment including power, cooling, transmission and other sub-systems. On one hand, usage of micro-satellites is much cheaper than other classes, but because of weight limitations, such satellites have set of restrictions[5]. From the RES point of view, key restriction is that such satellites in most cases are equipped with linear sensors, instead of matrix, because they have significantly less weight and power consumption. Since linear sensor has much less photoactive elements, they much more dependent on the level of signal which reached surface of the sensor. This leads to the usage of special techniques of sensing which allow increasing of exposure time for the sensor over the area where sensing is currently performed[6].

One of the practices widely used to solve problem with exposure time for linear sensor based on varying a tangage angle of the satellite during sensing cycle. Figure 1 depicts schema of this method[7].

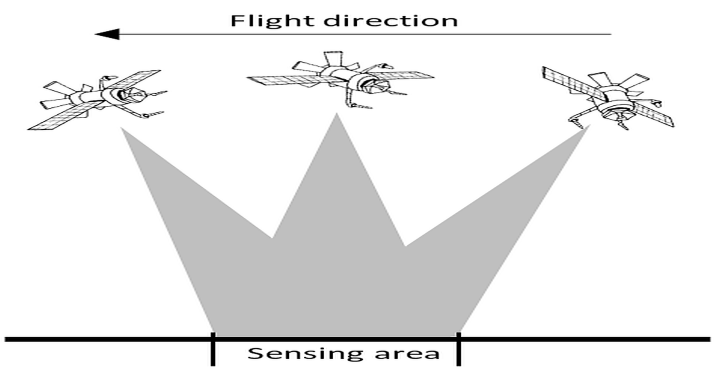

Figure 1. Basic idea of increasing sensor esposure time by varying tangage angle of the satallite

Key idea of this method, is to start sensing over target area before it will be reached by the satellite and complete sensing when satellite already pass the target are. Such technique allow significantly slow down the speed ot the target area image projection on the surfcace of the sensor, what leads to the increased esposure time of the target area where sensing is performed. Jointly with high precision of tangage angle control and satellite stabilisation mechanisms, described algorithm allows to create high-quality pictures in wide electormagnetic range. However, this approach has also significant disadvantage, which is called “blind” spots. When sensing is done over one target area, to start the new cycle it is required to change tangage angle in the way that will point sensor to the next sensing target and the area which will run under the satellite at this moment will be competely lost. Figure 2 shows the mechanism of “blind” spots appearing[8,9].

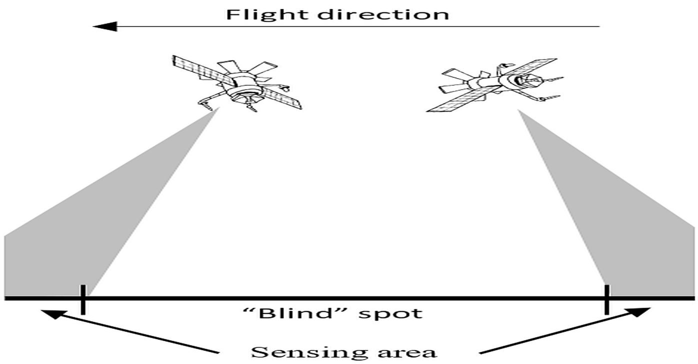

Figure 2. “Blind” spots caused by usage of method of varying tangage angle during RES

The key motivation of this paper and underneath research to is to investigate deeply RES process in various electromagnetic specter ranges and to find solutions to reduce size of “blind” spots when performing RES from the micro-satellites equipped with linear sensors[10].

Sequential modelling of RES process

There is a variety of methodic and approaches for modelling RES process from different perspectives. Some of them focused on the modeling of track of satellite with analysis of its flight angles; others focused on modelling of different sub-systems like modelling of different kinds of sensors or image construction algorithms. The idea of sequential modelling of RES process based on building a model, explaining how particular target area reflects on the surface of the sensor located on board of the micro-satellite[11].

Information about sensing target brought to the sensor by a certain amount of electromagnetic waves, which issued or reflected by target sensing area, in a wide specter of wavelengths.

So, to figure out what is affecting resulting image, we need to model full path of the sub-set of electromagnetic waves going from the Earth surface to the sensor. By splitting this path to the segments, which parameters may bring reasonable influence for the current modelling goals, we can build a chain of filters, which superposition will give us an answer, what kind of surface reflection in a given part of spectrum will be detected by the sensor installed on-board of the satellite.

To build such chain of filters, first interface between them should be defined. In the simplest possible case, we can take a two dimensional model. Figure 3 contains an example of simplest modelling filter.

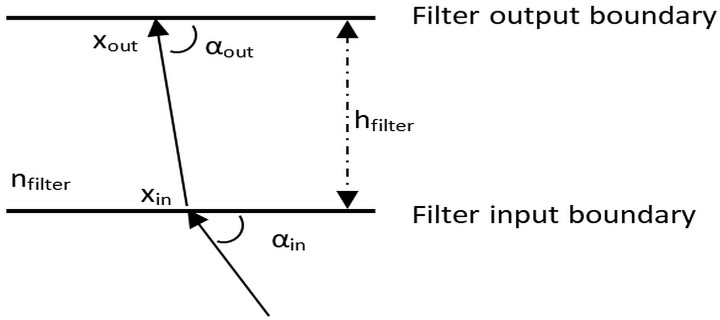

Figure 3. Simple filter structure

Independently on how simple filer modeled is, all the parametrs and variable are attached to three groups: positional, filter own properties and energetic. In the given case, in positional group will be parameters which are directly related to the physical displacement of the beam going from the surface towards sensor via specific filter. In the given example these parameters are:

x_{in} – position where beam entered a filter

α_{in} – filter entering angle

x_{out} – position where beam left a filter

α_{out} – filter leaving angle

To define beam properties on filter exit, we need to know at least some basic filter own properties. As such properties we can count following:

h_{filter} – height of the given filter

n_{filter} – filter refraction coefficient

In third bucket of parameters, we can place energetic parameters and variables. In simplest case, such parameters can be omitted, for example if it is required to build a simple model to trace beams track through the given number of filters in some specific conditions. However, when we need to look at the possible picture that can be produced by a sensor, we need to know at least energy losses on the beam path. In this case, we can add a filter property like

e_{filter} – this coefficient represents energy loses for the beam when it is passing though the filter. This parameter can be not only a scalar variable, but also be a function, for example if it varies for different wavelength ($e_{filter}(\lambda)$) or depends on filter hight ($e_{filter}(h)$).

Considering these variable and properties, we can represent simple two-dimensional filter with following equation:

$$f_{filter}\begin{pmatrix} x_{in} \\ \alpha_{in} \\ h_{filter} \\ n_{filter} \end{pmatrix} \xrightarrow{yields} \begin{pmatrix} x_{out} \\ \alpha_{out} \end{pmatrix} \tag{1}$$

Now, we can represent stack of three filters like a superposition of the functions, where results of one evaluation treated as an input for the send filter simulation:

$$f_{3filter}\left(f_{2filter}\left(f_{1filter}\begin{pmatrix}x_{in}\\ \alpha_{in}\\ h_{1filter}\\ n_{1filter}\end{pmatrix},\begin{pmatrix}h_{2filter}\\ n_{2filter}\end{pmatrix}\right),\begin{pmatrix}h_{3filter}\\ n_{3filter}\end{pmatrix}\right)=\begin{pmatrix}x_{out}\\ \alpha_{out}\end{pmatrix} \tag{2}$$

Complicated filters and filters with variable geometry

Shown filter example is very simple and such filters are valuable mostly to show basic principles of the proposed modelling approach or for testing modelling software, that it passes all the parameters properly between model components.

To work with real use cases, filters appears more complicated. First complication is a filter geometry. Optics, installed in front of the sensor on board of satellite provides a view angle which in two-dimensional mode results into the trapezoidal shape of the filter where lower bound is longer than upper bound. This means that not all the beams, which are entering filter at the bottom, will provide an output beam on the top of the filter. From physics point of view, these lost beams will represent beams, which were not captured by the optics and were not routed to the sensor surface.

Another complicated case faced during preparation of a model that takes into account method of varying of tangage angle to increase exposure time of the sensing target. Filters of this model not only have trapezoidal shape, but also angles of trapezes changes in time, since model includes computation of satellite track. Figure 4 shows two described cases.

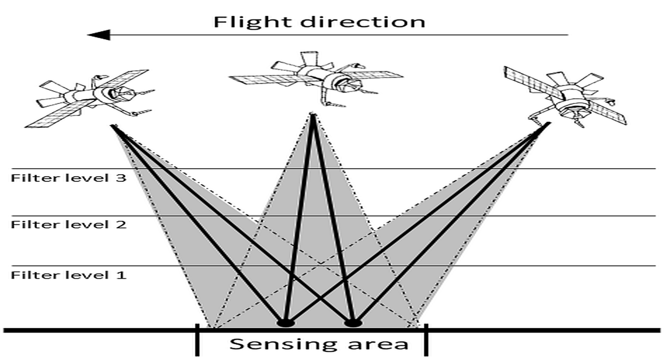

Figure 4. Variable shpae of the filters caused by changing of tangage angle during sensing

Finally, the last big aspect which increases model compexity is switchind from flat two-dimensional model to three-dimensional model. In this case we will have alreay two input and two output coordinates (x and y instead of x only for 2D), and also we introduce extra input and output angle.

Example of modelling a simple two-dimensional filter

To show in a bit more details how modelling of single filter works, look at the simple two-dimensional filter in more details. According to the example requirements, we need to estimate quality of the image, which model will built. It means that we will be interested in wavelengths within visible range. The filter we are modeling will the closest to the surface we are sensing. To keep modelling simpler we will also assume, that only wavelength representing red, green and blue colors make sense for the target image composition. Figure 5 shows schema of the described case.

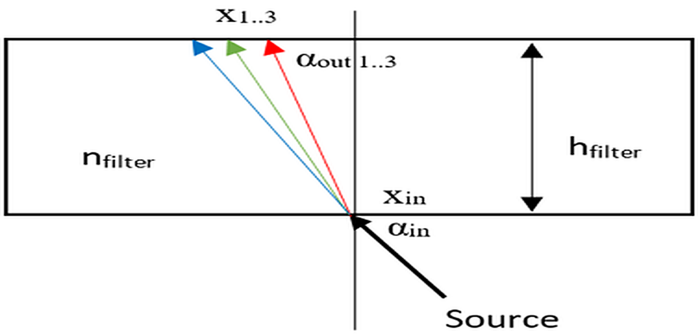

Figure 5. Example of 2D-filter

Since we are interested not only in delivery of the whole beam in a visible range of wavelengths, but each color-reflecting wavelength separately, we will take into account that refraction coefficient depending on the wavelengths and will use equation of Augustin-Louis Cauchy helping to link wavelength with material refraction coefficient:

$$n = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4} \tag{3}$$

Where λ is a wavelength in vacuum and a,b and c are constants defined for each envirnment empirecally.

For red, green and blue components we will get n_1, n_2 and n_3 for three color components we are interested in.

When reflection coefficient for each component is defined, we can easyly define a reflection angle for them using following standard equation for beam refraction:

$$\alpha_{refraction\,1..3} = \arcsin\left(\frac{n_{source} \cdot \sin(\alpha_{in})}{n_{1..3}}\right) \tag{4}$$

Now, when we have a refraction angle and hight of the filter we can easily define output x coordinate for each color component from sine definition. As a result with (1), (3) and (4) we got following:

$$\begin{pmatrix} x_{in} \\ \alpha_{in} \\ h_{filter} \\ n_{source} \end{pmatrix} \xrightarrow{yields} \begin{Bmatrix} n_1 = a + \dfrac{b}{\lambda_1^2} + \dfrac{c}{\lambda_1^4} \\ n_2 = a + \dfrac{b}{\lambda_2^2} + \dfrac{c}{\lambda_2^4} \\ n_3 = a + \dfrac{b}{\lambda_3^2} + \dfrac{c}{\lambda_3^4} \end{Bmatrix} \xrightarrow{yields} \begin{Bmatrix} \alpha_1 = \arcsin\left(\dfrac{n_{source} \cdot \sin(\alpha_{in})}{n_1}\right) \\ \alpha_2 = \arcsin\left(\dfrac{n_{source} \cdot \sin(\alpha_{in})}{n_2}\right) \\ \alpha_3 = \arcsin\left(\dfrac{n_{source} \cdot \sin(\alpha_{in})}{n_3}\right) \end{Bmatrix} \tag{5}$$

$$\xrightarrow{yields} \begin{Bmatrix} x_1 = \tan(\alpha_1) \cdot h_{filter} \\ x_2 = \tan(\alpha_2) \cdot h_{filter} \\ x_3 = \tan(\alpha_3) \cdot h_{filter} \end{Bmatrix} \xrightarrow{yields} \begin{pmatrix} x_1 \\ n_1 \\ \alpha_1 \end{pmatrix} \begin{pmatrix} x_2 \\ n_2 \\ \alpha_2 \end{pmatrix} \begin{pmatrix} x_3 \\ n_3 \\ \alpha_3 \end{pmatrix}$$

Conclusion

This article describes an approach for modelling of remote Earth sensing process from space. The key idea of the proposed model structure is moduled architecture, which allows construction of various models with different complexity and detalization levels, required by each particular usage. For example, in some cases it may not be required to have a detailed model of atmosphere, a single filter with 10,000 kilometers height can represent it, and in the same time, optical system installed on the micro-satellite can be represented by a chain of filters to have a precise model that allows fine-tuning of optics parameters. For another usage another model required, which cannot rely on a simple single-filter atmosphere model, so a chain of filters representing troposphere, stratosphere, mesosphere and ionosphere can replace it.

Another benefit of such modelling approach is that proposed mode defines an interface, which is simple and in the same time flexible, so scientists and engineers who are working in the area can contribute and extend the model filters library with new kinds of filters what will lead to increasing of combinations of resulting models that can be built

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