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Ordered Test Site Method for Onboard Measurement Results Validation of Medium Resolution Spectroradiometers

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The reduction or elimination of uncertainties is one of the main tasks in the analysis of remote sensing data. For this purpose, the upscaling and downscaling of spectroradiometric data operations are widely used. The downscaling operation is particularly used to validate medium resolution spectroradiometer data. The onboard measurement validation data is a complex task and it includes the solution of such important subtasks as (a) selection of the test site type; (b) determining the site size; (c) determining the sampling order. At the same time, after carrying out selective measurements, the question of scaling up (upscaling or generalization) of the obtained ground data arises, its purpose is to carry out validation of satellite data with low spatial resolution. Solving the problem of remote sensing data validation, terrestrial test sites are often used, their heterogeneity must always be taken into account. This problem is usually solved by applying special weighting coefficients and performing temporary periodic measurements, then using the regularization procedure for the averaged results of iterative calculations. In the absence of temporary changes, the need for regularization is eliminated. In this case, as an alternative, the method of the ordered test section can be proposed, it allows to determine the weight coefficients of the ground validation measurement results, providing a minimum of the newly proposed quadrature cost function. To solve the problem of achieving the proposed cost function minimum, the ordered subsections method as part of a single heterogeneous test section is proposed, the measurements are carried out by a sensor mounted on a low-flying carrier. The optimization problem is formulated to calculate the correction coefficients for the measurement results, where the sum of the squares of difference between the corrected data and the known representative estimate is minimized. The optimization problem is solved using a certain restrictive condition imposed on the sum of the correction factors.

Keywords: optimization; cost function; validation; remote sensing; test sites

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Introduction

One of the most important operations in the analysis and validation of small-scale sounding data is rescaling or downscaling. The operation of reducing small-scale terrain data by analyzing and processing large-scale data (downscaling) is widely used in such areas as climate change [1, 2], forestry [3], precipitation [4], geoscience [5], etc. The process of remote sensing data validation is essentially an operation to assess the uncertainty of the onboard measurement results. The inverse reduction operation, i.e. acquisition of large-scale data by analysis and processing of low-scale data (upscaling) is used in particular for the validation of data from medium-resolution spectroradiometers (MODIS, AQUA) using specialized test sites. The validation process is an important component in the study of raw data from remote sensing of the Earth's natural resources. The validation of onboard measurement data is a complex task and includes the solution of such important subtasks as (a) selection of the test area type; (b) determining the site size; (c) determining the procedure for conducting sampling measurements. At the same time, after carrying out selective measurements, the question arises of scaling up (upscaling or generalization) of the obtained ground-based data, its purpose is to validate satellite data with low spatial resolution [6]. The most important conditions in the implementation of the procedures for such scaling of ground validation data are measurements within a short time interval to prevent the influence of changes in the studied indicator on the validation result, as well as the availability of high-resolution images of the terrain to create a similar map of the studied indicator.

The problem of scaling ground validation data should be solved taking into account such factors as the heterogeneity of the properties of the test sites, as well as temporal changes occurred during the ground measurements. To take into account the degree of homogeneity of the test site, wireless sensor networks are usually used and then weighting factors are applied to determine a single scaled estimate of the measured indicator to be compared with satellite measurement data [7]. To scale the values of ground measurements, the averaging method can be used with a small heterogeneity of the test area [8]. To assess the degree of site heterogeneity, it is useful to use maps with a higher resolution in the presence of empirical functions that relate the radiometric signal to the results of ground-based measurements [9, 10]. The issues of using the wireless network for the validation of satellite data are considered in [11–15]. At the same time, as noted above, taking into account the heterogeneity of the test area is also important carrying out one-time network measurements. To solve this problem, in [7] a two-stage process is proposed, which consists in (a) determining the optimal weighting factors; (b) determination of the scaled value of the measured indicator of terrestrial objects. In particular, work [7] is devoted to the issue of determining the weight coefficients to take into account data from heterogeneous test sites and determining a representative estimate during the validation of the LAI time series in a zone characterized by heterogeneity of properties.

In contrast to [7], in our work we optimize the cost functional at the selected time point by searching for the normalizing function that depends on the value of the argument itself. The article uses some theoretical provisions that are available in [7]. We briefly review the cost function used in [7].

1 Known method of using the cost function in scale of ground test data

According to [7], in the well-known cost function method, the representative value of the measured indicator A_{rep} is calculated on the basis of spectral images obtained from higher resolution spectroradiometers.

The weighted value of the measurement results on heterogeneous measuring subsections in the amount of N pieces is determined by the following formula:

$$\overline{A_{m,t}} = \beta^T \cdot A_{m,t}, \tag{1}$$

where $\overline{A_{m,t}}$ is the measured value A obtained by taking time measurements at N number of points and multiplying the obtained results $A_{m,t}$ by weighting coefficients β_t to take into account the heterogeneity of the corresponding sections.

If we assume that temporal changes in the degree of site heterogeneity are insignificant and the main factor affecting the result of validation is spatial heterogeneity, then the cost function is introduced follows

$$J = \sum_{i=1}^{M} \frac{\left(\overline{A_{rep,i}} - \beta^T A_{m,i}\right)^2}{\sigma^2} + \alpha\beta^T\beta, \tag{2}$$

where σ is the r.m.s. $\overline{A_{rep,i}}$; α is the regularization parameter; i means taking measurements at the moment t_i; M is the number of time points for measurements.

According to [7], the problem of determining such weight coefficients β_i, where $J \to min$ can be solved iteratively, by iteratively estimating the combined indicator $\Theta = (\alpha, \sigma^2)$. Next, we will show that for negligibly small time changes, the problem of determining the optimal weight coefficients β can be resolved at any time point t_i taking into account some additionally introduced integral limiting condition in relation to these coefficients, as well as the newly introduced cost functional, which also contains the newly introduced function of weight coefficients.

2 Ordered test site method for ground measurement data scale and airborne measurement results validation

The suggested method is based on the following assumptions:

1. Since the degree of heterogeneity of a site consisting of sub-sites in the amount of N does not change over time, then the weighting factors introduced do not depend on the index i and are considered as a function of measured quantities A_m, i.e. there is a function
$$\beta_j = f\left(A_{m,j}\right);\ j = \overline{1, N}. \tag{3}$$
2. Since regularization through the introduction of exponents Θ and α not carried out, i.e. $\alpha = 0$, and consider the fixed time moment i, then the formula (2), i.e. the cost function is as follows
$$J = \sum_{j=1}^{N} \frac{\left[\overline{A_{rep}} - f(A_{m,j}) \cdot A_{m,j}\right]^2}{\sigma^2}, \tag{4}$$
where $\overline{A_{rep}}$ is the known representative quantity A_m, for the site, σ_j^2 is the r.m.s. A_{rep}, $j = \overline{1, N}$.
3. We assume that the indicator $A_{m,j}$ is a variable in an ordered way that takes the values
$$A_{mj} = A_{mj-1} + \Delta A_m;\ \Delta A_m = const, \tag{5}$$
wherein $A_{m,j}$ varies within $A_{m.min} \div A_{m.max}$.
4. We assume that the following restrictive condition is given
$$\sum_{j=1}^{N} f(A_{m,j}) = C;\ C = const. \tag{6}$$

In the proposed method of ordered test area, the accepted initial mathematical model of data scaling is in the discrete case in the choice of such weight coefficients $\{\beta_j\}$, $j = \overline{1, N}$; at which the sum (4) reaches a minimum.

Thus, the weight coefficients are chosen depending on the magnitude of the measurement data for the reason that if we assume the same degree of noise in the signals from the test subsections (i.e., with the same amount of additive noise during measurements), then logically the proportion of the test subsection with a high signal-to-noise ratio should be higher than the fraction of the low signal-to-noise ratio test subsection.

In a continuous expression, model (4) can be written in the following form, the procedure for obtaining which is explained below

$$J_H = \int_{A_{m.min}}^{A_{m.max}} \left[\frac{A_{rep} - f(A_m)}{\sigma^2} \right]^2 dA_m, \tag{7}$$

where $f(A_m)$ is the twice-differentiable continuous function. As we can see from the expression (7) J_H is the functional depending on the function $f(A_m)$.

In this case, according to (6), the following notation is possible:

$$\int_{A_{m.min}}^{A_{m.max}} f(A_m) d(A_m) = C_1, \ C = const. \tag{8}$$

An explanatory mechanism for obtaining functional (6). Functional (6) is obtained as follows. The sum (4) is represented as

$$J = \sum_{j=1}^{N} Z_j (A_{rep}, f(A_{m,j}) \cdot A_{m,j}, \sigma)^2. \tag{9}$$

Further, with the data on value Z_j we build a discrete dependency graph Z_j from $A_{m,j}$, which is illustrated in Fig. 1.

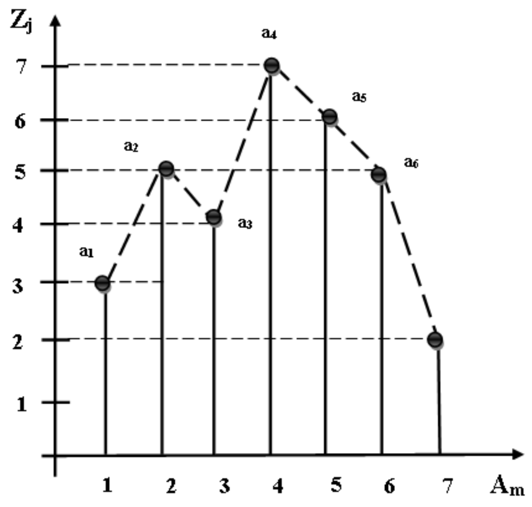

Fig. 1. Conditional graphic illustration of the sum components in expression (4). The dashed line shows the piecewise linear envelope of points a_i, i=(1,7)

If we multiply the left and right sides of (4) by the value of the discrete ΔA_m we get

$$J_0 = J \cdot \Delta A_m = \\ = \sum_{j=1}^{N} Z_j \left(A_{rep}, f(A_{m,j}) \cdot A_{m,j}, \sigma \right)^2 \cdot \Delta A_m \,. \tag{10}$$

At the same time, geometrically, expression (10) determines the area under the dashed curve in Fig. 1.

Now we assume that we have a smooth, twice differentiable function $Z = \varphi(A_m)$, that at the points $A_m = 1, 2, 3, \ldots, 7$ passes through the points $\{a_i\}$; i=1,7; as it is shown in Fig. 1. It is obvious that the function curve $Z = \varphi(A_m)$ as the number of discrete points increases, it coincides in shape with the smooth envelope of these points.

Consequently, upon conditional transition to the continuous value A_m sum (4) turns into functional (7), where the function $\varphi(A_m)$ is the required function.

Condition (8) is also obtained using the course of the reasons which are mentioned above. The basic position in these arguments should be the well-known fact that the sum of the normalization coefficients, i.e. weighting factors are usually set equal to one.

Thus, the problem of the best scaling of ground data is reduced to the search for such an optimal function $f(A_m)$, which, taking into account (8), would lead to the minimum value of the indicator J_H.

3 Optimization problem solution

Taking into account expressions (7) and (8), we compose the objective functional of unconditional variational optimization J_0

$$J_0 = \int_{A_{m.min}}^{A_{m.max}} \frac{\left[\overline{A_{rep}} - f(A_m) \cdot A_m \right]^2}{\sigma^2} dA_m + \\ + \lambda \cdot \left[\int_{A_{m.min}}^{A_{m.max}} dA_m - C \right], \tag{11}$$

where: λ – Lagrange multiplier.

Obviously, functional (11) is a special case of the well-known Euler equation [16], when the derivative of the desired function $f(A_m)$ missing. In this case, the Euler equation is significantly simplified and in this case takes the following form:

$$\frac{d\left\{ \frac{\left[\overline{A_{rep}} - f(A_m) \cdot A_m \right]^2}{\sigma^2} + \lambda \cdot f(A_m) \right\}}{df(A_m)} = 0 \tag{12}$$

From condition (12), we get the follows

$$\frac{-2A_{rep} \cdot A_m + 2\beta(A_m) \cdot A_m^2}{\sigma^2} + \lambda = 0. \tag{13}$$

From expression (13) we find the following

$$f(A_m) = \frac{A_{rep}}{A_m} - \frac{\lambda \cdot \sigma^2}{2A_m^2}. \tag{14}$$

Taking (8) and (14) into account, we can get the following expression for calculating the Lagrange multiplier

$$\lambda = \frac{C - \overline{A_{rep}} \cdot \ln\left(\frac{A_{m.max}}{A_{m.min}}\right)}{\frac{\sigma^2}{2A_{m.max}} - \frac{\sigma^2}{2A_{m.min}}}. \qquad (15)$$

We can see that by solving (14), (15), the objective functional (11) reaches its minimum. We should calculate the second derivative of the integrand in (11) and make sure that it is a positive value.

4 Model investigations using proposed method of ordered test sub-sections

We assume that we have a set of ordered subsections with the characteristic (5). At the same time, based on the analysis of images obtained by spectroradiometers, representative values of the index A measured in these subsections are determined, denoted below A_{rep}. We should calculate the function $f(A)$, further called the weight function of the indicator A, which ensures the minimum of the cost functional (4).

The conditional graphic representation $A_{rep\,j}$ and $f(A)$ is given in Fig. 2.

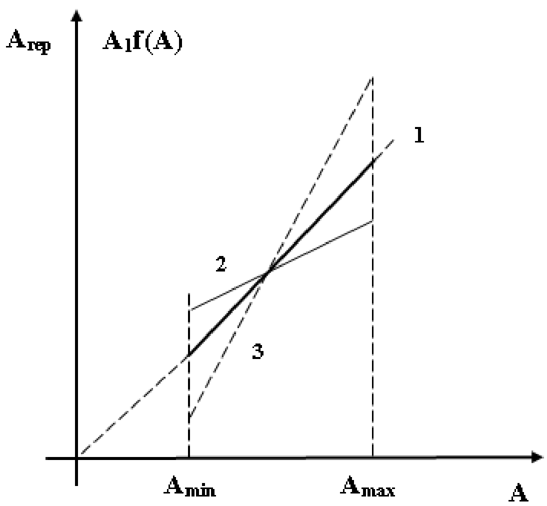

Fig. 2. Graphical illustration of the optimization procedure. Numbers indicate: 1 – the function central line $A = A$; 2 — the function curve $A_{rep} = A_{rep}(A)$; 3 – the function curve $f(A) \cdot A$

In this case, it is assumed that the calculated value A_{rep} can be shown in the form of the function A

$$A_{rep\,j} = A_{rep}(A). \qquad (16)$$

Taking into account (4) and (16), we obtain a discrete cost function; expressing $A_{rep}(A)$ in the form

$$A_{rep}(A) = \varphi(A) \cdot A. \qquad (17)$$

Taking (4) and (17) into account, we write the following expression

$$J = \sum_{f}^{N} \frac{\left[\varphi(A_j) \cdot A_j - f(A_j) \cdot A_j\right]^2}{\sigma^2}. \qquad (18)$$

If we write (18) in continuous form, we get the following cost functional

$$J_H = \int_{A_{min}}^{A_{max}} \frac{\left[\varphi(A) - f(A) \cdot A\right]^2}{\sigma^2} dA. \qquad (19)$$

Our goal is to determine the optimal function $f(A)$ with $J_H \to min$.

If this function $f(A)_{opt}$ exists, then this fact means that there is the considered method for calculating the weight function (i.e., the function $f(A)$) for any $\varphi(A)$ only when $f(A) = f(A)_{opt}$ it provides a minimum J_H, and all other methods of determining $f(A)$ does not provide this minimum value.

Hence, the inequality holds:

$$\int_{A_{min}}^{A_{max}} \left[\frac{\varphi(A) - f(A)_{opt} \cdot A}{\sigma}\right]^2 dA <$$
$$< \int_{A_{min}}^{A_{max}} \left[\frac{\varphi(A) - f(A)_{not\,opt} \cdot A}{\sigma}\right]^2 dA. \qquad (20)$$

We compute $f(A)_{opt}$, reducing the functional on the left in (5) to the minimum value.

According to the previously mentioned regarding the Euler equation, the optimal function $f(A)_{opt}$ must meet the next condition

$$\frac{d\left\{\left[\frac{A_{rep}(A) - f(A)_{opt} \cdot A}{\sigma}\right]^2\right\}}{df(A)_{opt}} = 0. \qquad (21)$$

From expression (21) we find

$$\frac{d\left\{\frac{-2A_{rep}(A)}{\sigma^2} f(A)_{opt} \cdot A + \left[f(A)_{opt} \cdot A\right]^2\right\}}{df(A)_{opt}} = 0. \qquad (22)$$

From condition (7) we get

$$-2A_{rep}(A) + 2A^2 f(A)_{opt} = 0. \qquad (23)$$

From the expression (23) we have

$$f(A)_{opt} = \frac{A_{rep}(A)}{A}. \qquad (24)$$

Consequently, any other choice of function $f(A)$, different from $\frac{A_{rep}(A)}{A}$ does not provide a minimum cost functional.

From (24) and (17) we get

$$f(A)_{opt} = \varphi(A). \qquad (25)$$

Thus, the conducted modeling study showed that the minimum value of the cost functional is obtained only with a single form of the weight coefficient function, i.e. in the form (24).

We give a numerical example to show the correctness of the foregoing.

We assume that the following values of the indicators used in the proposed method of ordered test subsections are given:

$$\begin{aligned} &A_{m.max} = 2e; \quad A_{m.min} = e; \\ &\overline{A_{rep}} = 1.5e; \quad \sigma^2 = 0.01e; \\ &C = \frac{e^2}{2}, \quad \text{where} \quad e = 2.72. \end{aligned} \tag{26}$$

The $f(A_m)$ is calculated according to formula (14):

$$f(A_m) = \frac{1.5e}{A_m} - \frac{\lambda \cdot 0.01e}{2 \cdot A_m^2}. \tag{27}$$

We calculate the value of the Lagrange multiplier

$$\lambda = \frac{\frac{e^2}{2} - 1.5e \cdot (ln2)}{\frac{0.01}{2 \cdot 2} - \frac{0.01}{2}} = -1.83 \cdot 10^3. \tag{28}$$

Taking into account (28) we get:

$$f(A_m) = \frac{1.5e}{A_m} + \frac{1.83 \cdot 5e}{A_m^2}. \tag{29}$$

We calculate the integrand in the main part of the objective functional (11), i.e., in expression (7) taking into account (29)

$$\frac{\left[\overline{A_{m.rep}} - f(A_m) \cdot A_m\right]^2}{\sigma^2} = \frac{\left[1.5e - \left(\frac{1.5e}{A_m} + \frac{1.83 \cdot 5e}{A_m^2}\right) A_m\right]^2}{0.01e}. \tag{30}$$

The value of expression (30) in solving (30) is always lower than any calculated value of this expression for any other solution satisfying condition (8).

Given the specified value $C = \frac{e^2}{2}$, this solution can be written by the expression

$$f(A_m) = e. \tag{31}$$

Calculating the value of the integrand in expression (7) with regard to (31). We obtain

$$\frac{\left[\overline{A_{m.rep}} - f(A_m) \cdot A_m\right]^2}{\sigma^2} = \frac{[1.5e - e \cdot A_m]^2}{0.01e}. \tag{32}$$

We show that the integral of expression (32) is greater than the integral of expression (30). Comparing the numerators.

Therefore, we show that the area under the curve

$$k_1(A_m) = \left(1.5e + \frac{1.83 \cdot 5e}{A_m}\right)$$

greater than the area under the curve

$$k_2(A_m) = A_m e \quad \text{for} \quad A_m = e \div 2e.$$

For $A_m = e$ we have

$$k_1(A_m) = 1.5e + 1.83 \cdot 5 = 4.1 + 9.15 = 13.25,$$

$$k_2(A_m) = e^2 = 7.4.$$

Obviously, for $A_m = e$ we have $k_1(A_m) > k_2(A_m)$. For $A_m = 2e$ we have

$$k_1(A_m) = 3e + \frac{1.83 \cdot 5}{2} = 12.73,$$

$$k_2(A_m) = 2e^2 = 14.8.$$

As we can see from Fig. 1 the area remaining under the curve $k_1(A_m)$ is much larger than the area under the curve $k_2(A_m)$. This fact indirectly proves the optimality of the solution (29), since in this case, the area under the curve (32) is greater than the area under the curve (30). The latter is a necessary condition for the optimality of solution (29).

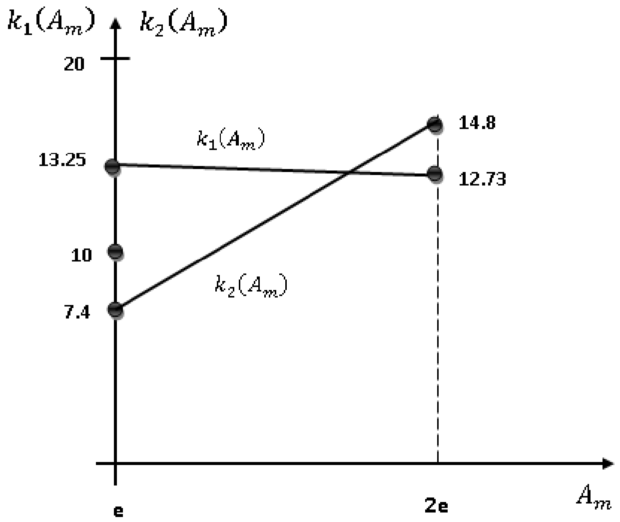

Fig. 3. Linear Curve Approximations $k_1(A_m)$ and $k_2(A_m)$

Conclusion

The task of validating remote sensing data using terrestrial test sites must always be solved taking into account the heterogeneity of the used test sites. This problem is classically solved by using special weighting factors and regularization averaging procedure by iterative calculations. As an alternative, the method of ordered test sections is proposed, which makes it possible to determine the weighting coefficients of the results of ground-based validation measurements, which provide the minimum of the newly proposed quadrature cost functional containing the desired weight function. In this case, the calculated optimal weight function provides a minimum of the goal functional.

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Метод упорядкованої тестової ділянки для валідації результатів бортових вимірювань спектрорадіометрів середнього дозволу

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Одним з головних завдань, що вирішуються під час аналізу даних дистанційного зондування, є зменшення або усунення невизначеностей. З цією метою широко використовуються такі операції, як укрупнення (upscaling) та розукрупнення (downscaling) спектрорадіометричних даних. Операція розукрупнення, зокрема, використовується для валідації даних спектрорадіометрів середнього дозволу. Валідація даних бортових вимірів є комплексним завданням і містить вирішення таких важливих підзадач як (а) вибір типу тестової ділянки; (б) визначення розмірів ділянки; (в) визначення порядку проведення вибіркових вимірів. Разом з тим, після проведення вибіркових вимірювань постає питання про збільшення масштабу (upscaling або генералізація) отриманих наземних даних, метою якого є проведення валідації супутникових даних з низьким просторовим дозволом. При вирішенні задачі валідації даних дистанційного зондування часто використовуються тестові ділянки, гетерогенність яких завжди має бути прийнята до уваги. Ця проблема зазвичай вирішується шляхом застосування спеціальних вагових коефіцієнтів та проведення тимчасових періодичних вимірів, надалі використовуючи процедуру регуляризації осереднених результатів ітераційних обчислень. У разі відсутності тимчасових змін необхідність у регуляризації відпадає. В цьому випадку в якості альтернативи може бути запропонований метод упорядкованої тестової ділянки, що дозволяє визначити вагові коефіцієнти результатів наземних валідаційних вимірювань, що забезпечують мінімум запропонованої нової квадратурної функції витрат. Для вирішення завдання досягнення мінімуму запропонованої функції витрат запропоновано метод упорядкованих підділянок у складі єдиної гетерогенної тестової ділянки, вимірювання в яких здійснюються сенсором, встановленим на носії, що низько летить. Складено оптимізаційне завдання обчислення коригуючих результати вимірювань коефіцієнтів, при яких сума квадратів різниці скоригованих даних та відомої репрезентативної оцінки зводяться до мінімуму. Завдання оптимізації вирішено із застосуванням певної обмежувальної умови, накладеної на суму коригувальних коефіцієнтів.

Ключові слова: оптимізація; функція витрат; валідація; дистанційне зондування; тестові ділянки

Метод упорядоченного тестового участка для валидации результатов бортовых измерений спектрорадиометров среднего разрешения

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Одной из главных задач, решаемых при анализе данных дистанционного зондирования, является уменьшение или устранение неопределенностей. С этой целью широко используются такие операции, как укрупнение (upscaling) и разукрупнение (downscaling) спектрорадиометрических данных. Операция разукрупнения в частности используется для валидации данных спектрорадиометров среднего разрешения. Валидация данных бортовых измерений является комплексной задачей и включает решение таких важных подзадач как (а) выбор типа тестового участка; (б) определение размеров участка; (в) определение порядка проведения выборочных измерений. Вместе с тем, после проведения выборочных измерений встает вопрос об увеличении масштаба (upscaling или генерализация) полученных наземных данных, целью которого является проведение валидации спутниковых данных с низким пространственным разрешением. При решении задачи валидации данных дистанционного зондирования часто используются наземные тестовые участки, гетерогенность которых всегда должна быть принята во внимание. Данная проблема обычно решается путем применения специальных весовых коэффициентов и проведения временных периодических измерений, далее используя процедуру регуляризации осредненных результатов итерационных вычислений. В случае отсутствия временных изменений необходимость в регуляризации отпадает. В этом случае в качестве альтернативы может быть предложен метод упорядоченного тестового участка, позволяющий определить весовые коэффициенты результатов наземных валидационных измерений, обеспечивающих минимум вновь предложенной квадратурной функции издержек. Для решения задачи достижения минимума предложенной функции издержек предложен метод упорядоченных подучастков в составе единого гетерогенного тестового участка, измерения в которых осуществляются сенсором, установленным на низколетящем носителе. Составлена оптимизационная задача вычисления корректирующих результаты измерений коэффициентов, при которых сумма квадратов разницы скорректированных данных и известной репрезентативной оценки сводятся к минимуму. Задача оптимизации решена с применением определенного ограничительного условия, наложенного на сумму корректирующих коэффициентов.

Ключевые слова: оптимизация; функция издержек; валидация; дистанционное зондирование; тестовые участки