ESTIMATION OF HEAVY METAL AND RADIONUCLIDE CONTAMINATION OF SOILS AND VEGETATION WITHIN THE CHERNOBYL DANGER ZONE USING REMOTE SENSING DATA

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KEY WORDS: Remote_Sensing, GIS, Environment, Pollution, Vegetation, Chernobyl

ABSTRACT

The investigations carried out demonstrate the efficiency of airborne spectrometry and multispectral spaceborne remote sensing data in combination with ground truth measurements to assess heavy metal and radionuclide contamination of soils and vegetation polluted after the Chernobyl accident. According to practical experiences plants are sensitive indicators of pollutions which induce changes of their spectral properties. These changes can be assessed by means of remote sensing. The software complex used for processing the remotely sensed data allows to determine polynomial regression dependencies between the remote sensing data and the pollution content in soils and vegetation. These dependencies give indications for polluted vegetation areas affected by toxicants.

KURZFASSUNG

Die vorgestellten Untersuchungen demonstrieren die Effizienz, mit der Flugzeug-spektrometrische und multispektrale Weltraum-Fernerkundungsdaten zusammen mit Bodenmeßdaten zur Bewertung der radioaktiven Kontamination des Bodens und der Vegetation infolge der Tschernobyl-Katastrophe eingesetzt werden. Experimentell wurde nachgewiesen, daß die Veränderung der spektralen Eigenschaften der Vegetation, die mit Hilfe der Erdfernerkundung gemessen werden kann, ein signifikanter Indikator für diese Kontaminationen ist. Zur Auswertung der Fernerkundungsdaten wird ein Software-Paket benutzt, das die Feststellung von polynomialen Abhängigkeiten zwischen den spektralen Signaturen aus Fernerkundungsdaten und dem Kontaminationsgrad von Vegetation und Böden und damit die Abgrenzung belasteter Areale erlaubt.

1. INTRODUCTION

The Chernobyl accident in 1986 has caused extensive contaminations in greater areas of the Ukraine and other European countries. In addition to the long-lived radionuclides (Cs-137, Sr-90 etc.) thrown out into the atmosphere during the accident the rejection composition included Mn, Ni, Co, Ci, V, Mu, Cu, Pb, Zn, Sn, Y, B and other chemical elements. Their distribution patterns after air transfer still need to be estimated. As vegetation responses on pollution remote sensing methods such as airborne spectrometry and multispectral spaceborne imaging are most operational and commercially efficient tools to obtain quickly the distribution patterns of the above mentioned pollutants for large areas. The paper presents the results obtained by a group of scientists from the Center of Aerospace Research of the Earth (Ukraine) and the N. Poushkarov Institute of Soil Science and Yield Programming (Bulgaria). The studies have been carried out for the following purposes:

- to analyze canopy composition and its changes as well as vegetation spectral features under stress conditions induced by heavy metals as a basis to apply remotely sensed data for the identification of such pollutions
- to verifiy the methods to localize heavy metal soil pollution by remote spectrometric sounding of vegetation
- to prove the usefulness of multispectral satellite image facilities for mapping areas contaminated by radionuclides.

2. ESTIMATION OF SOIL AND VEGETATION POLLUTION BY HEAVY METALS FROM AIRBORNE SPECTROMETRY AND GROUND TRUTH DATA

Collins, Goetz, Chang et al. (1983, a-c) detected the „blue shift" for the „red edge" of conifer reflectance spectra due to higher heavy metal content on sulphide deposit areas. The authors investigated this effect on agricultural crops in the industrial region of the Western Donbas (Ukraine), which are exposed to high technogenic load from numerous heavy metal sources (i.e. coal mines, ore-dressing enterprises, plants, thermal power stations, chemical factories, highways etc.). 1350 samples of soil and plants were analyzed for their heavy metal content. Simultaneously from an altitude of 150 m airborne high spectral resolution data were acquired by an airborne spectrometer „Quartz" with the following parameters:

- spectral range 410-770 nm
- spectral resolution 1 nm
- spectrum registration period 0.5 s
- angle of viewing field of 0.05 rad
- radiance range (0.16-52.08) 10^7 W/sr m^2.

The results showed a similar 10 - 20 nm „blue shift" for the „red edge" in the reflectance spectra for wheat, corn, barley, alfalfa, and fodder grass under metal-induced stress conditions (Lyalko, 1992). A correlation was observed between the „blue shift" value and aggregated heavy metal content in the plants. This correlation and spectral ratios (NIR/RED, RED/GREEN) allowed to map the Western Donbas area according to ist heavy metal pollution levels.

These findings were proved by laboratory vegetation experiments with winter wheat, corn, and alfalfa. After the soluble compounds of Be, Zn and Sn had been added in increasing concentrations changes in spectral brightness and shape of wheat spectral function appeared.

The vegetation experiments for corn and alfalfa were performed on substrata of different soil types (i.e. carbonate chernozem, leached chernozem, gray forest soil).

Various amounts of Ni, Cr, Cd were added to the substrata which the plants grew on. During the process of plants growth measurements of the spectral reflectance factor at the 448, 530, 563, 620, 682, 747, 785, 885, 970 and 1025 nm bands as well as of the chlorophylls a and b, the carotenoids, the bulk of green and air-dry amounts of the plants and their roots were performed. The results of the study show a regular decrease of pigment contents (chlorophylls a, b, carotenoids) and green and air-dry weight of the roots under higher heavy metal concentration for chernozem soil (pH 7.5). Under low concentration of heavy metals in the substratum a slight stimulation of the plant growth was observed on acid gray forest soil (pH 5.5), where the migration of heavy metal compounds is higher and induces some increase of the pigments and phytomass amount. Under higher contents of heavy metals in gray forest soil substratum a decrease of pigments content, green amount of plants and their roots could be observed similar to that from the experiment with plants on chernozem soil substrata. The spectrometric data obtained during the vegetation experiments with corn and alfalfa showed that spectral reflectance factor of plants increases in the spectral bands from 680 to 1025 nm. This supports the use of spectrometric and multispectral remote sensing data for localization of heavy metal contaminated areas by measuring spectral features of vegetation cover.

The obtained rules and facilities developed for data processing of airborne spectrometric data have been used to determine the levels of heavy metal pollution in the northern part of the Ukraine in the hazardous zone of the Chernobyl Nuclear Power Plant.

The program package applied was developed to determine the changes in vegetation reflectance spectra as a result of metal-induced stress. The package installed on IBM-compatible PCs consists of programs performing computation of spectral brightness coefficients, spectral smoothing, first and second derivatives of spectral functions as well as the „blue shift" value.

The results of processing remote sensing data were verified by ground truth data obtained on heavy metal polluted sites and by analysis of the pollutants composition from the 30 km Chernobyl zone towards Kiev. The spectral analysis data for 950 samples of soils and plants growing on these soils allows the following conclusions about the pollution level to be made:

- 75% of the soil samples investigated exeed the maximum permissible concentrations (MPC) of Cu (approved in the Ukraine) by more than 10 times, of Zn by more than 2-4 times respectively
- 50% of soil samples exceed the MPC of Ni by more than 2-5 times
- 15% of soil samples exceed MPC of Pb and Mn by more than 2-3 times.

Maximum permissible concentrations of other heavy metals in soils have not yet approved in the Ukraine. Therefore it is not possible to assess the pollution levels for many chemical elements which directly originated in the reactor and indirectly from emissions induced by the melted metal construction of the damaged reactor block.

The MPC's for widespread agricultural crops in the Ukraine have been approved only for Pb, Cu and Zn. The vegetation cover of the test site exceeded the MPC's

- of Pb by more than 2-5 times in 50% of the crop samples
- of Cu and Zn by more than 2-3 times in 8% of the crop samples.

The critical content level of toxicant chemical elements, when crop yield decreases for more than 10% was exceeded in

- 50% of the crop samples for Mn and in
- 15-20% of the crop samples for Ni, Ti, V and Cr.

The results obtained show that the area of the Ukrainian Polissin have been exposed to pollution by a heavy metal complex after the Chernobyl accident. The character of the pollution and the level of toxic impact in combination with the radioactive contamination require studies and assessments. The use of remote sensing methods for the solution of these problems allows to coordinate and intensify long-term and extensive field studies required.

3. ESTIMATION OF RADIONUCLIDE CONTAMINATION ON AREAS USING MULTISPECTRAL SPACE IMAGERY

The use of multispectral remotely sensed data is based on a closed correlation between the environmental conditions and vegetation state. Growth and development of vegetation are connected with metabolism processes and depend on environmental conditions such as light, temperature, moisture, fertility of soil, and of course, on toxicants presence or absence.

The spectral characteristics of plants, as shown in other publications (Vygodskny et al., 1987; Kronberg, 1988; Lyalko et al., 1992 and others) depend on the ability of foliage and needles to reflect, absorb and transmit solar energy.

The plots of spectral reflection for separated species and different vegetation communities have their own features in certian wavelengths both for maximum and for the shape of spectral reflectance curve (Krinov, 1947; Kronberg, 1988). The physiological stress of the plants leads to changes of their spectral characteristics in visible range, because chlorophyl reacts to each change of metabolism and degrades under unfavorable conditions.

The radionuclides released during the Chernobyl disaster are also toxicants though the character of contamination caused by radionuclides is substantial rather than energetic for most parts of the test site.

The radiobiological effects on vegetation for various exposure levels can be assessed more completely only with regard to the critical structure at all stages of its hierarchical organization.

A special „hit" principle and a „target" conception allow to explain the disproportion between the amount of energy absorbed by the biological system with a radioactive contamination and the final biological effect (Grodzinsky, 1991).

This indicates that

- radioactive contamination of an area affects significantly all kinds of vegetation;
- combined action of external and internal exposure induces an injury of the genetic mechanismus of plants; in this case a recovery process is obviously absent against the background of chronic external exposure under influence of incorporated radionuclides;
- radioactivity affects the photosynthetic cells of plants, especially the chlorophyll mutation abundance, which can be revealed in the optical properties of plants.

These changes can be determined by spaceborne remote sensing and can be applied for the assessment of radioactive influence on the environment.

3.1 Methods

In order to study the effects of radionuclides on vegetation of large areas an analysis of the optical properties of wooded and herbaceous vegetation were carried out. Space photographs were used as primary data sources for the investigations. Prior to image processing they had to be scanned.

The software complex for image processing includes ERDAS/IMAGINE and an additional program package implemented by the Centre of Aerospace Research of the Earth Kiew and the uve Remote Sensing Centre Potsdam, which enable:

1. superposition of three one-band images into a single file as a multiband image in order to get a synthetic image for the visual analysis of landscape making the next steps more convenient
2. georeferencing of images and rectification into a map projection
3. inquire digital spectral characteristics at ground truth measurements points for further studies of the environmental objects
4. collection and handling of remote sensing and ground truth data by GIS technology
5. mathematical processing and analysis of measurements.

The determination of spectral characteristics were made on a window template sized, for example 7*7 pixels, for which average and dispersion were computed.

The processing and interpretation of multispectral remote sensing data require the solution of the inverse problem, i.e. the determination of environmental objects state from remote sensing data.

The complication of this problem consists in the unknown functional relations between remote sensing data and the parameters of environmental object state. Using ground truth measurements these parameters can be determined by means of regression analysis.

The authors have treated the problem of defining the functional relations between Cs-137 content in soil and spectral brightness values of the landscape (Lyalko et al., 1996). The mathematical formulation of the problem consists in the description of content as a resultant vector and of digital spectral brightness values as causing vectors. The mathematical model of linear multifactor regression is given by:

$$C(x, y) = \sum_{j=0}^{m} \sum_{i=0}^{m} C_{ij} T_i(x) T_j(y) \qquad (1)$$

where

x, y are the spectral brightness values for two bands;

$T_i(x)$ is the Chebyshev polynomial of i-th power;

C_{ij} are the regression coefficients, usually provided by means of the least-square method.

For correct processing multispectral remote sensing data it is nessesary to compare homogenous kinds of vegetation growing on soils with similar moisture conditions.

In order to estimate the changes of soil moisture a remote sensing determination method for soil moisture (**W**) and ground water (**H**) by means of active nadir soundings in the 0.7 m band were developed and used by ZAKIZ.

The possibility of estimating soil moisture characteristics is based on the dependence between reflected radiation and the dielectric properties of soils determined by the volume content of water and by peculiarities of its vertical distribution. To derive **W** and **H** from the remotely sensed value **E**, the dependencies, which could be received both experimentally and by analytical calculation, were applied using the method of replacing real soil with a system of **n** thin layers with piecewise continous **W** value (Lyalko et al., 1992).

To improve the efficiency of mapping **W**, a new method was offered by joint utilizing microwave airborne nadir sounding and SAR data from the Space Shuttle (L-Band, λ=21cm, parallel polarization, horizontal).

The main idea of this method consists in segmenting the test site into homogenous parts according to the underlying surface. The dependencies between the amplitudes of backscatter signal (σ) expanded into a Fourier series, and **E** were determined within the limits of homogeneous areas using profile data:

$$\sigma^{A}{}_{i} = f(E^{A}{}_{i}) \qquad (2)$$

Therefore the dependencies $\sigma = \sigma(W)$ and $\sigma = \sigma(H)$ could be applied.

Beside gray level intensity each image is characterized by the rules of its spatial distribution, which are determined by texture.

Homogenous landscapes usually have certain features of textures. Hence, the discrimination of these textures in satellite images helps to segment the images to localize exactly boundaries of homogeneous landscapes, upon which the regression functions are modelled.
To define a texture, the Gibbs random field probability model with double interaction of responses (Jain, Gimel'farb, 1995) was used. The model defines a spatial homogeneous texture as realisation of Markov's random field sample which is given by the Gibbs probability distribution.
If the structure is known, the model allows to generate sampling realisations by means of element-by-element stochastic relaxation. The model parameters for each kind of texture can be estimated in accordance to training patterns. First the analytical initial approximation for maximum likelihood potential estimations are calculated for a lot of interaction types. A map of these interactions is generated. This gives the possibility to compare them regarding to its strength and to select the most representative structure of interactions for the given kind of texture.
After this, the initial estimations of potentials for the selected kinds of interactions will be completely determined by stochastic approximation. The texture analysis proposed above was carried out for an area near the Chernobyl Nuclear Power Plant (NPP). Five types of landscapes were discriminated on this site:
1 - pine xerophyto-lichenous
2 - oak-pine hazelous grassy
3 - oak-hornbeam-pine fern-sedgous
4 - alder marshy forest
5 - long-fellow non drained lands.
As a result of the experiment, the discriminated types of landscapes were distinguished according to their texture except for oak-pine hazelous grassy and oak-hornbeam-pine fern-sedgeous forests.
The result of the automatic segmentation of a satellite image subset according to the textures of the landscape types showed pine xerophyte-lichenous and sparse growth of trees to be discriminated most significantly. The other types of landscapes were discriminated something weaker.

The volume of information and the spatial relations of investigated phenomena require the use of GIS technology.
For this purposes the GIS TRIAS has been developed by the uve Remote Sensing Centre Potsdam to match remote sensing data and environmental information (Lyalko, Marek et al., 1995a). TRIAS is a MS-Windows based user friendly and low cost GIS working on IBM-compatible PC's. Similar to other GIS TRIAS allows to model the natural phenomena as point, line or areal objects. These objects can be connected with relational data bases. The definition of object hierarchies, text objects and thematic relations between the objects is possible, too.
The following properties and possibilities of TRIAS have been used to carry out the investigations:
- overlaying of vector and raster data
- interactive vectorization of raster data
- flexible catalogue of object classes which is oriented on cartographic standards and can be extended on thematic characteristics
- free possibilities for combining topographic and thematic map information and various presentation models
- possibilities for generating map output with a great number of presentation tools and a comfortable connection to network plotters under MS-Windows
- connection to retrieving features in a relational data base.

The handling of primary remote sensing and ground truth information allows to compare great numbers of thematic and temporal layers and to derive tendencies with regard to spatial and temporal changes of various natural components.
Finally the use of GIS technology allows to carry out the classification of the test site for further studies on a qualitatively high level.

3.2 Results

The programs developed have been used to analyze the optical vegetation properties within the southern trail of pollution induced by the Chernobyl accident. Primary material for the work were multispectral space images acquired by the KATE - 200 camera with a focal length of 200 mm and a ground resolution of about 30 m on the „Cosmos" satellite, taken at the 10th of July 1980, as well as by the MK - 4 camera with a focal length of 300 mm and a resolution of about 20 m on the „Resource -F-2" satellite, taken at the 27th of July 1989. The three spectral bands were recorded in the green (500 - 600 nm), red (600 - 700 nm), and near-infrared band (700 - 840 nm). Double-negatives of the space photographs enlarged by eight times were used for the investigations.
The brightness values were provided for the various landscape elements by image processing at a quite dense and regular net of observation points. Thus, each point is characterized by its coordinates, brightness in three spectral bands, landscape element feature and radioactive contamination level.
In order to get the radioactive contamination level of the landscape elements, the map of Cs-137 contamination density for soil (scale 1 : 200 000) by V. A. Nagorsky (firm „Pripyat", 1993) and also the map of Cs-137 contamination of coniferous canopy (scale 1 : 200 000) by A. I. Ostravnenko (1990) were used. Currently Cs-137 provide the main radioactive contamination of the Chernobyl region.
Nine homogeneous landscapes were identified within the limits of the test site. The major elements of landscape are pine forest growing on dry soils, grassland, leaf-bearing and mixed forest, and agricenouses on dry and moist soils. The remaining landscape elements play a minor role because of their small area sizes.
Using regression model (1) described above and the programs developed by ZAKIZ, the dependencies for the major landscape elements were determined for the red and near infrared bands of the space photographs. The calculations were carried out for first order polynomials ($m = 1$, m - maximum degree of polynomials).
For coniferous canopies before and after the Chernobyl accident the relations between the spectral properties in the red and near-infrared band are absolutely different which can only be explained due to radioactive contamination.
Even for vegetation growing on soils with low levels of radioactive contamination (less than 2 Ci/km^2) the

relations between the spectral characteristics are different to those with the same vegetation before the accident. The character of this relation is more similar to that for vegetation growing on heavily contaminated areas. This confirms the method proposed to allow the detection of quite low contamination of vegetation by radionuclides. The existence of low level radioactive contaminations influence on vegetation is shown by radiobiologists (Chernobyl disaster), too.

A three-dimensional plot for description of the relation between the spectral characteristics of pine forest in red and near-infrared bands and Cs-137 contamination in coniferous canopy was set up to prove the possibilities of using multispectral space photographs for the assessment of Cs-137 content in vegetation. According to this plot the dependence is unimodal. Vegetation with high Cs-137 content in needles and branches has high brightness values in the two bands, too. This behaviour was expected due to a direct dependence between the content of Cs-137 and other toxicants in soil and in vegetation which was observed in ground observations. In order to predict radioactive soil contamination regression equations were derived. Three-dimensional plots have shown the dependence between the spectral characteristics of the major biocenouses in the test site in the red and near-infrared band on the one hand, and the soil content of Cs-137 on the other hand. All the plots show a quite simple unimodal relation between the analyzed values. According to these plots one can conclude that, the higher the contamination of soils by radionuclides, the higher the spectral brightness of plants in each band. According to the results of several authors, as expected for pine forest, this relation is manifested most clearly that, associated with the strong sensibility of pine forest, as a critical ecosystem for radioactive impact (Figure 1).

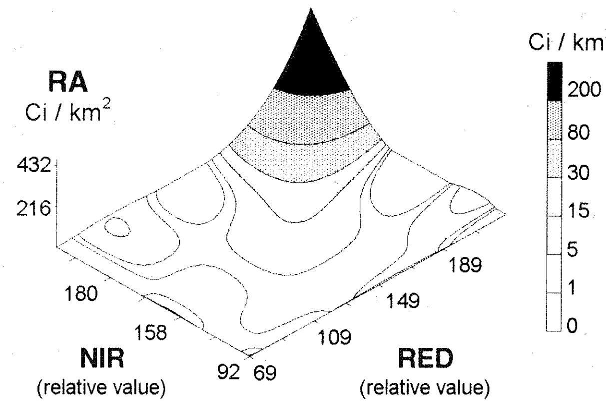
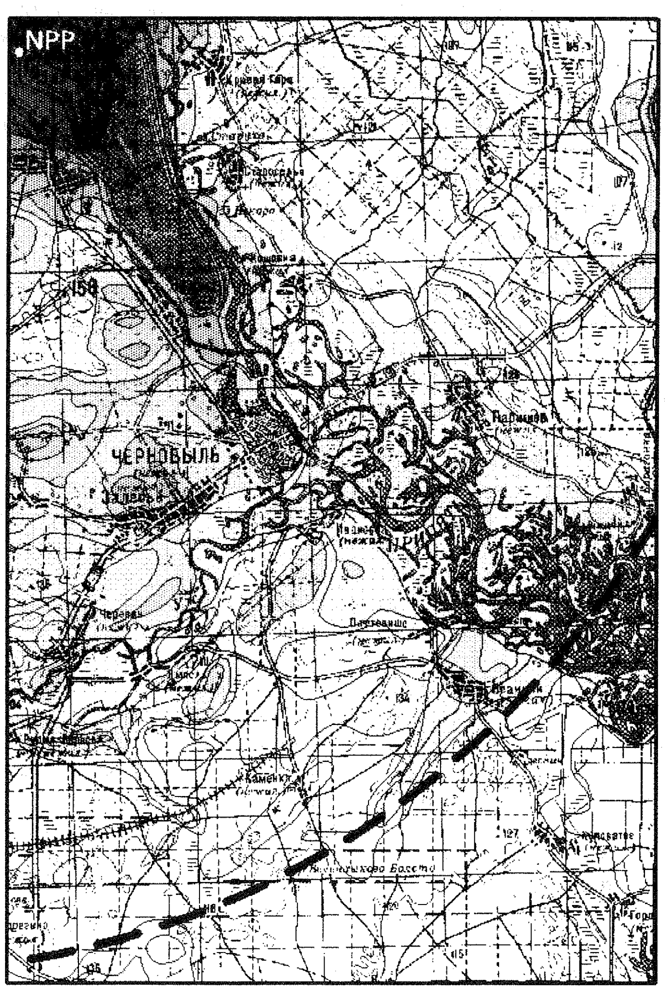


Fig. 1: Relationship between the content of radionuclides RA (Ci / km^2, Cs-137) and spectral brightness in red (RED) and near infrared (NIR) band of a space photograph (multispectral camera MK-4 on satellite „Ressource-F“, July 27, 1989, 13.57) for pine forests on dry soils, Chernobyl test site



Soil contamination by Cs-137 (Ci / km^2)

0 - 5 | > 17 | > 40
> 5 | > 20 | > 80
> 10 | > 30 | > 120
> 15 | > 35

Borderline of the 30 km zone

NPP Chernobyl Nuclear Power Plant

Fig. 2: Prediction scheme of soil contamination by CS-137 derived from red and near infrared band of a space photograph (multispectral camera MK-4 on satellite „Ressource-F“, July 27, 1989, 13.57)

Chernobyl test site

These plots enable to generate the prediction scheme of Cs-137 soil contamination by means of multispectral spaceborne remote sensing data (Figure 2). The scheme includes the south-eastern part of the 30 km dangerous zone and adjacent regions. This scheme shows well that the greatest maximum of contamination with regard to area and intensity is located within the nuclear power plant zone. Besides this, a number of maxima with lower intensity and smaller areas are indicated.

Described previously by other authors, the rules noted of spatial radionuclide distribution in soil observed in the prediction pattern, reflect the real distribution of radionuclides in soil.

Thus, the investigations carried out showed that multispectral spaceborne remote sensing data can be useful for the estimation of radionuclides contamination in soil and vegetation.

The method offered, unlike the physical-chemical analysis, estimates above all the degree of radioactive influence on vegetation and allows therefore to discover large areas of spreaded healthy vegetation and such affected by toxicants. Conventional methods are unable to prove this.

The use of multispectral space images is more efficient under current conditions and allows to check the ecological state of large areas in each time interval as required.

4. CONCLUSIONS

The research of natural conditions using remote sensing and ground truth methods shows the necessity to apply multispectral spaceborne remote sensing data for large scale ecological investigations.

A complex of methods was developed for the determination of correlations between spectral brightness and radionuclides, heavy metals and other toxicants in soils and vegitation.

Based on remote sensing data the use of the dependencies determined allows to create a scheme of the test area contamination by radionuclides.

The method offered could be an effective component of a complex ecological monitoring consisting of the following three main parts:

- remote sensing with ground truth
- data handling by GIS technology
- modelling natural processes for operational prediction and management (Lyalko, Marek et al., 1995b)

The problems of using remote sensing data for creating geosystem models are still insufficiently developed and will require further investigations.

ACKNOWLEDGEMENT

The research project has been sponsored by the German Space Agency (DARA).

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