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DELINEATION OF INDUSTRIAL PLUMES ON SATELLITE IMAGES

INTRODUCTION

Rapid increase of air pollution, which can be noticed for last decades is one of many negative results of industrial civilization development.

In order to elaborate the most reliable method for estimation of the air pollution level, at the Polish Remote Sensing Centre (OPOLiS) within the Institute of Geodesy and Cartography some research works have been started, which aimed at utilization remote sensing for this reason, not only as the registration method, but also for preparing characteristics of air pollution sources as well as the state of air quality (Ciołkosz, Bochenek, Bychowski, Nowosielski, 1973; Majcher, Sujkowska, Ciołkosz, Mizerski, Pudykiewicz, 1980).

As the result of present works, it was stated, that remote sensing methods can be applied for:

— investigations of geometric properties of industrial plumes, in particular their shape, range, and the range of industrial dust fall,

— inwestigation of quantitative distribution of pollutant concentration within industrial plumes,

— investigation of influence of pollution on geographical environment deterioration.

Remote sensing methods of air pollution investigations cannot substitute conventional as well as model investigations. They can become, however, the important stage connecting theory of spreading out of pol-

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lutions with measuring and computational practice, through verification of models and their optimal parametrization within particular environmental conditions of certain industrial plants.

DIFFERENTIATION OF IMAGES OF PLUMES PHOTOGRAPHED ON SATELLITE IMAGES IN DEPENDENCE ON ELECTROMAGNETIC WAVELENGTH

The image gathered by any remote sensors is the result of optical relations occurring between an investigated object and electromagnetic radiation illuminating it, which is registered on photographic materials (or on magnetic tapes). Each object located on the way of solar radiation, will be projected on the light sensitive material in the form of image element, characterized by various tones. Tonal differentiation is dependent on properties of photographed objects, such as different values of absorption, reflectance and scaterring factors.

For some atmospheric states (cloudiness, haze, high concentration of industrial smokes and gases), factors of absorption and scatterring become so high, that for particular electromagnetic bands the atmosphere is partially or even fully opaque. On a photograph taken in such conditions the atmospheric state will be visible, instead of the Eearth's surface. This fact is generally applied for investigation meteorological phenomena and for preparation weather forecasts, and lately, also for investigation industrial atmospheric pollution on the basis of satellite images (Ciołkosz, Miszalski, Olędzki, 1978).

Absorption, reflectance and scatterring of solar radiation by aerosol molecules contained in the air, is dependent, first of all, on the chemical constitution of an aerosol, as well as on molecule size and electromagnetic wavelength. This fact results in visibility of particular aerosol trails, their contrast with the background, it means with scatterred ligth of the sky, and in their colours. Such diversified optical effects of plumes are the reason of series of problems, which occur during identification of trails on images.

It turns out from the scatterring theory of Mie and Rayleigh, that intensity of pollution is inversely proportional to registered wavelength, what was also proved during experimental works. It means, in shorter waves of visual radiation the trails are better visible than in longer ones (*Manual of Remote Sensing,* 1975).

It is worth to be noticed, that difference of projection of industrial plumes registered on Landsat images at 4th and 7th bands (the green and infrared radiation) is high; for example the range of the trail can be determined as 45 km for the green spectral band and only as 20 km for the infrared band.

DETERMINATION OF RANGES OF DUST POLLUTION ON SATELLITE IMAGES

Preliminary visual analysis of Landsat MSS images of Poland, multispectral photographs taken from the Salut 6 orbital station, stated high correlation between imaged pollution and the state of the atmosphere. In such situations, when atmospheric stratification is stable, and the flow is approximately stationary, mainly in high pressure areas, the advection is the deciding factor. In such conditions, well shaped pollution trails are visible. The majority of analysed satellite images were taken in these conditions. Poland was usually in the centre or on the border of the high pressure area, temperate Southern-and-Western winds occurred and atmospheric stratification was stable.

An example of such situation can be the image of the Silesian District and Cracow, taken on October 10, 1978 (phot. 1) when the longest ranges of visible trails were noticed. Emitted plumes from industrial plants reached distances of 50, 60, and even 130 kilometres. The satellite image points also the changing width of emitted pollutions. The width of a trail for the case of point emitors is equal from 180 m in the distance of 500 m from the emitors to 2000 m in the distance of 50 km from the emitor. In the case of group emitors, however, the width of trails is equal approximately to 1400 m, even close to the emitor; it is equal to 9 km in the distance of 50 km from the emitor.

The satellite photograph taken on this day shows also the transportation of pollution emitted from the Czechoslovak Ostrava-Karwina Industrial Region to Poland. Smokes from this region reached the distance of 25 km and they influenced on the vicinities of Rybnik, Wodzisław Śląski and Jastrzębie Zdrój.

For situations when inversion effect occurs, for very low speed of flow, domination of microphysical phenomena occurs. The only one transportation mechanism in such cases is turbulence diffusion. On images taken in such conditions only results of photochemical reactions are visible in the form of characteristic shapes.

It turns out from present investigations, that within the inversion areas the highest cumulation of pollutants occurs in lower atmospheric layers. The classical example of such situation is presented on the satellite images of the Silesian District and Cracow taken on June 2, 1978 (phot. 2). Over the whole Upper Silesian District the overlay of polluted air occured, which caused that the image is blurred and hazy. On this image, the area covered with polluted air is equal 35 km in length and approximately 15 km in width; in the Western regions the flow of polluted air towards the Mała Panew and Odra valleys can be observed.

On the basis of analysis of the entire set of satellite images which is at the Institute of Geodesy and Cartography, the air pollution effect within typical low pressure areas and increased speed of air masse flow and strong turbulences has not been stated. The increase of speed of wind causes spreading out pollutions for longer distances, but because of increase of turbulences, pollution concentrations are fast decreased with moving away from the emmitor and they become unvisible.

Specific properties of satellite images acquisition, first of all high altitude and considerably low resolution determine the possibility of their applications and limit it to investigations of phenomena of high intensity and spatial range. In the case of the Landsat images all plants, for which pollution trails are equal at least to 70—80 metres in width, can be included into investigations. They can be the trails from single emmitors, as well as combined trails, from several emmitors, located close to each other. In the case of photographs taken from the Salyut-6 orbital station, the investigations can include also trails equal to 15—20 metres in width (D ą b r o w s k i, M i z e r s k i, 1979).

The basis for trail identification and determination of their range are the difference of optical density of polluted and clear areas. In many cases the borders of trails range were determined directly on diapositives of the Landsat MSS 4 or of the 2rd Salyut band without utilization of specialistic equipment. Very often, however, images were analysed with the densitometer or with the additive colour viewer in order to extract some additional features (colour, shape, optical density value), confirming or negating preliminary conclusions; this procedure was performed when it was impossible to explicitly determine the range or when it was doubtfull, whether an identified element was the trail or not.

Analysis of satellite photographs allows to determine the pollution range both for direct vicinities of plants and for city agglomerations and industrial regions. Investigations carried out from the terrestrial stations do not consider real ranges of pollution, due to their fast dissapearance on the light sky.

Observations of a trail on the usual dark background, carried out on satellite images become the good source of information on real range of pollution. Comparison of ranges of industrial plumes determined on the basis of theoretical data and on the basis of satellite images showed, that in many cases, lengths of trails, visible on images are greater for even tens of kilometres. The greatest range of trails which has been obtained for Poland was equal approximately 130 km, and the clear, continuous image of a trail was approximately 80 kilometres long.

According to theoretical assumptions the range of destructive reaction of that trail on environment should be limitted to the range of approximately 52 km, it means to the distance when the concentration of the pollutants in the trail is 5% of its original value. According to estimation of optical density value of the trail image, which determines the relative concentration level of pollution, the value less than 5% is reached by the trail in the distance over 70 km from the emmitor, it means at least 20 km more. For meteorological conditions occurring during taking the image the range of emmission of all other plants of the Silesian-Cracow agglomeration was also greater than it should be according to theoretical calculations.

Effects of condensation of water vapour on artificial condensation nuclei, which are scatterred molecules of pollutants are also very well visible on satellite photographs. The series of clouds of the Cumulus type occured on extension of plumes and often also over plumes. These clouds occured together with industrial smokes in distances sometimes greater than 100 km.

The images taken from the Landsat are not, in general, prepared for stereoscopic observation. It is possible to obtain 3 dimensional effect, but only in the case of areas covered by photographs taken from two different orbits.

The altitude of taking photographs and the length of the base cause, that height differences equal at least to 500 m can be visible with the use of a stereoscope. The stability of external orientation elements and the knowledge of Sun elevation and its azimuth allows, however, to utilize the shadow of objects for determination of altitudes of these objects (fig. 1).

The shadow of the image of pollution plume is clearly projected on the terrain surface even for low density of this trail. The shadow of the Cumulus type clouds occurring with trajectories of industrial plu-

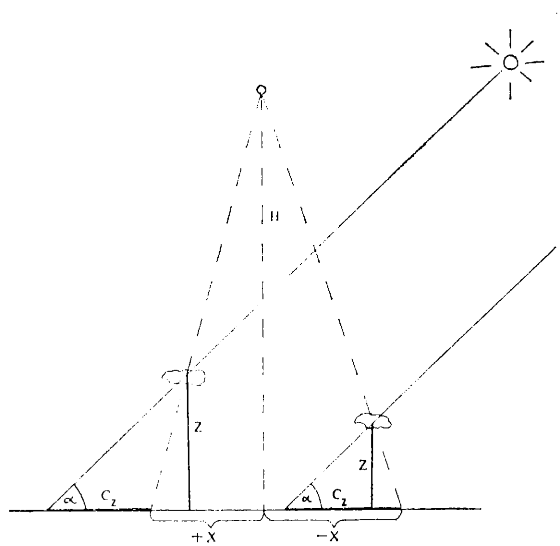


Fig. 1. Relation between plume altitude and length of its shadow

Rys. 1. Zależność między wysokością smugi zanieczyszczeń a długością rzucanego przez nią cienia mes, is also very well visible. Knowledge of mentioned elements allows to determine the altitude of smoke for arbitrary distance from the emmission source. The following equation was applied for computing this altitude:

$$z = \frac{HC_z \operatorname{tg}\alpha}{H-(\pm x \operatorname{tg}\alpha)},$$

where:

z — trail altitude,
H — orbit altitude,
x — distance from the image axis to the trail border,
α — Sun illumination angle,
C_z — length of the shadow on the image reduced according to the formula:

$$C_z = C_p \cos [180^\circ - (As + \sigma)],$$

where:
C_p — length of the shadow measured along the direction of the Sun's azimuth,
As — the Sun's azimuth,
σ — the angle between direction of local meridian and direction of the flight of the satellite.

$$\sigma = \arcsin \frac{\sin\nu}{\cos\varphi},$$

where:
ν — orbital distance of the orbit = 9,1°,
φ — geographical latitude of the centre of the image.

Possibility of analysis of a shadow in the distance of tens of kilometres from the emmission source allowed to calculate the altitude of the trail over the terrain (fig. 2). This value varies for different distances from the emmitor from 110 m to 550 m.

In the case of the Nowa Huta steel mill large groups of the Cumulus clouds accompany emmitted smokes for the distance of 10 km; they cover the image of shadow of the trail. On the basis of the shadow of these clouds their altitude was calculated, which is equal to 750 m (fig. 2).

In contradistinction to the Landsat satellite images the photographs taken from the board of the Salyut-6 orbital station, were taken with stereoscopic overlapping what allows to obtain the 3-dimensional terrain model. Such satellite photographs are characterized by resolution of 15—20 metres, what cause that they can be analysed with optical enlarging systems, for example interpretoscopes. They were taken with the photogrammetric camera, so they can be also processed with photogrammetric devices.

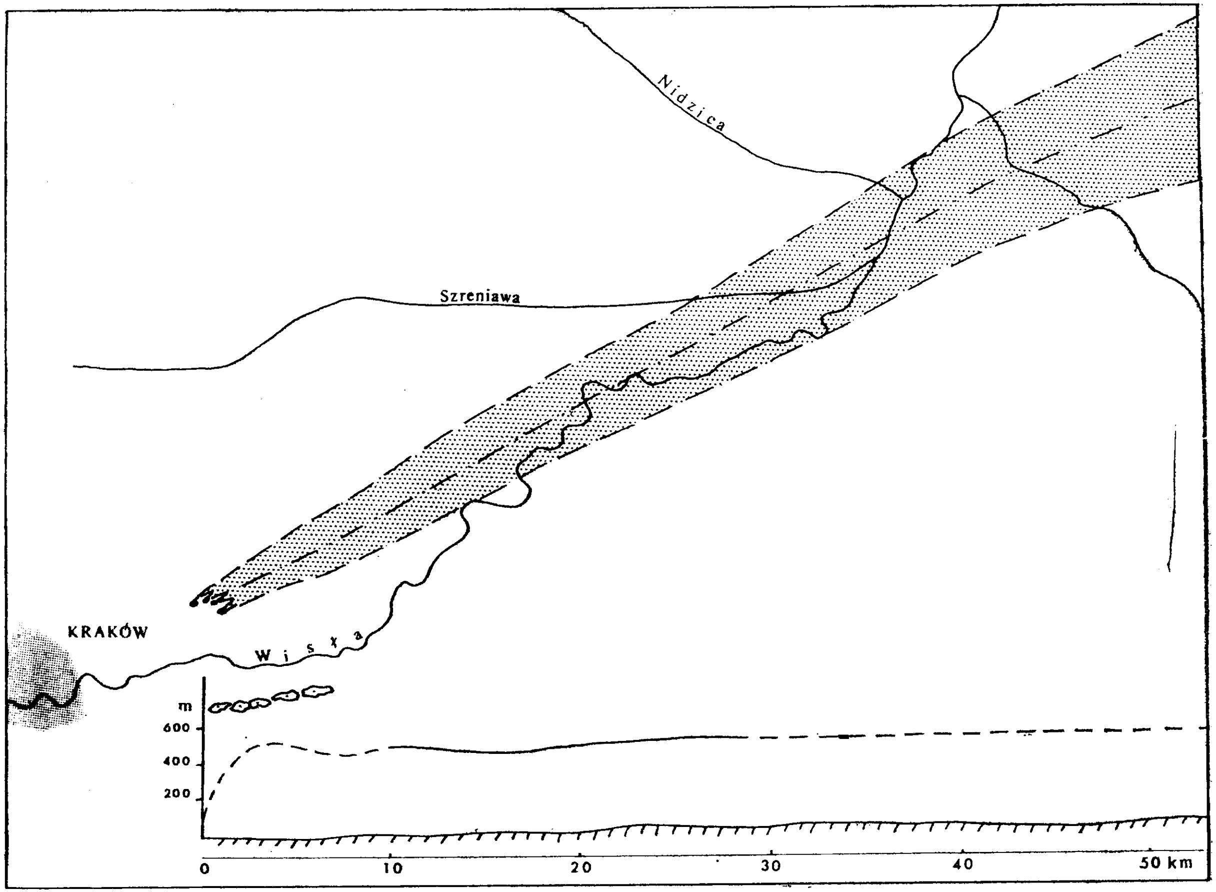


Fig. 2. Spreading out range and altitude of plume emmitted by Nowa Huta Steelwork on October 24, 1978

Rys. 2. Zasięg rozprzestrzeniania oraz wyniesienia smugi dymu emitowanego przez Hutę im. Lenina w dniu 24. 10. 1978 r. o godz. 10^{50}

The photographic camera mounted on the board of the Salyut-6 is a multispectral camera, taking photographs in 6 electromagnetic spectral bands. For analysis of dust emmission, however, only photographs taken in the 3rd band (yellow-orange) were utilized, according to previously mentioned notices. The topic of the stereophotogrammetric elaboration was to determine shape, range and height of plumes, in order to compare real parametres with modelling plumes.

The border between a plume and terrain was so well visible, that the authors suggest, that the error of its identification does not influence the measurements of plume parametres.

The terrain model with recorder momentary location of plumes, which has been the result of continuous process occurring for longer period of time, was reconstructed by means of the Stecometer.

Terrain coordinates of tie points were determined on the basis of a map at the scale of 1 : 200 000.

Spatial, orthogonal transformation of model coordinates into terrain coordinates system was performed by means of the FOTOKOSM programme, which was elaborated at the Institute of Geodesy and Cartography especially for the Salyut-6 satellite photographs processing (M i z e r s k i, 1981).

Results of photogrammetric elaboration of shape, altitude and direction of plumes movements for several chosen emmitors are shown in fig. 3 a, b, c. It is worth to add, that the z coordinate measurement error on satellite images is equal to ± 54 m. These figures show simultaneously axes of plumes, which were determined on the basis of theoretical plume models, applied in meteorology, where the wind fields were described with utilization of geopotential data for the area of 850 mb, information on ground wind, or considering both information supplemented with results of aerological records. For each of these models, characteristic data for different atmospheric layers is utilized, which is acquired with different frequency, thus trajectories obtained this way can have various location.

None of these models consider local topographic conditions, which, as it turns out from analysis of satellite images, can be deciding factors for directions of dislocations of plumes. For example, the trajectory of a plume emmitted by the Turów power plant on August 1, 1978 had the azimuth equal to 315°, which agreed with the azimuth calculated on the basis of information concerning ground winds. On the other hand, according to a model considering aerological register, the plume azimuth should be equal to 355°, and according to the geostrophic wind field – this azimuth should be equal to 25°.

Direction of spreading out of smokes emmited by the same power plant on July 27, 1978 did not agree with directions computed theore-

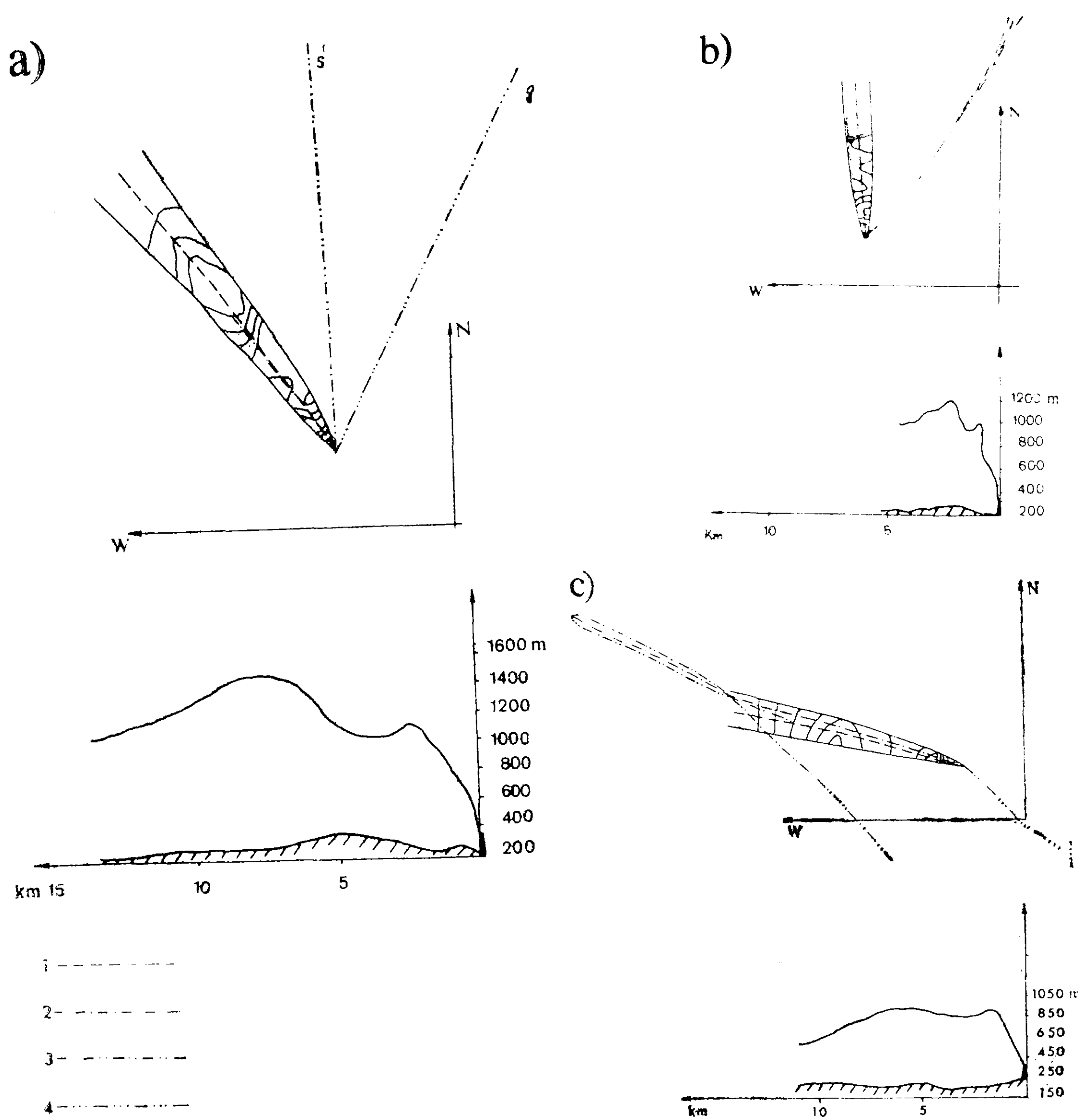


Fig. 3. Comparison of trajectories of plumes determined by photogrammetric method (1) and by method of simulating dispersion processes utilizing the ground wind field (2), aerological record (3) and geostrophic wind field (4), for the emission from the Turów power plant on August 1, 1978 (fig. 3a), on July 27, 1978 (fig. 3b) and for the chemical plants at Oświęcim on August 1, 1978 (fig. 3c). For each analysed case lower diagrams show altitude, shape of the upper laeyr of plume, its range and terrain profile under the plume

Rys. 3. Porównanie trajektorii smug wyznaczonych metodą fotogrametryczną (1) oraz metodą symulacji procesów dyspersji wykorzystującą pole wiatru przyziemnego (2), sondaż aerologiczny (3) i pole wiatru geostroficznego (4) dla emisji z elektrowni Turów w dniu 1. 08. 1978 r. (rys. 3a) oraz w dniu 27. 07. 1978 r. (rys. 3b), a także dla Zakładów Chemicznych w Oświęcimiu w dniu 1. 08. 1978 r. (rys. 3c). W każdym analizowanym przypadku pokazano na dolnych wykresach wyniesienie, kształt górnej powierzchni smugi, zasięg smugi oraz profil terenu.

tically, which in this particular case, cover each other, and they differ from the real direction approximately 35°.

Disagreement of direction of plume spreading out with simulated plumes is a result of omitting local topographic conditions, which caused the flow of air into the Nysa Łużycka valley. Direction of ground wind, however, determined at close meteorological stations was deviated approximately 30° to the Northern-Eastern direction from the directions of wind occurring in the vicinities of the power plant.

A more interesting case was observed during analysis of emmission from the Chemical Plants at Oświęcim. Trajectories of emmission, the real one and one determined on the basis of ground wind almost covered each other. Almost 180° difference was obtained however, for utilization of geostrophic wind field model, and a trajectory determined on the basis of aerological register cover a real trajectory for about 10 kilometers, and then took the opposite direction.

Influence of terrain relief on direction of pollution spreading out can be observed during analysis of satellite images taken on June 26, 1975 over the Sandomierz Basin. The plume emmitted from the chemical plants in Tarnów had the Southern-Eastern direction at first, and, was spreading out for the distance of approximately 25 kilometres, according to the Biała River valley.

Then, this plume turned for 90° in the Southern-Western direction, still according to the mentioned valley. After several kilometres, the plume left the river valley and turned for 90° in the Southern-Eastern direction, in the depression in mountains, reaching the Ropa River valley (fig. 4). Such complicated direction of plume spreading

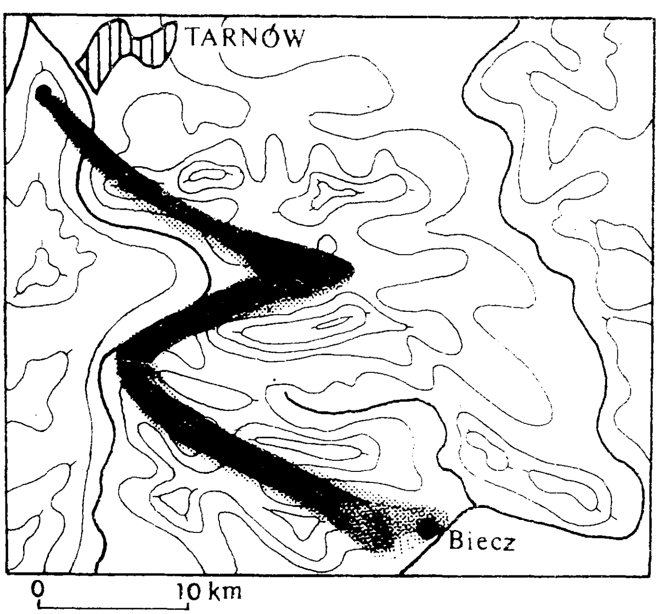
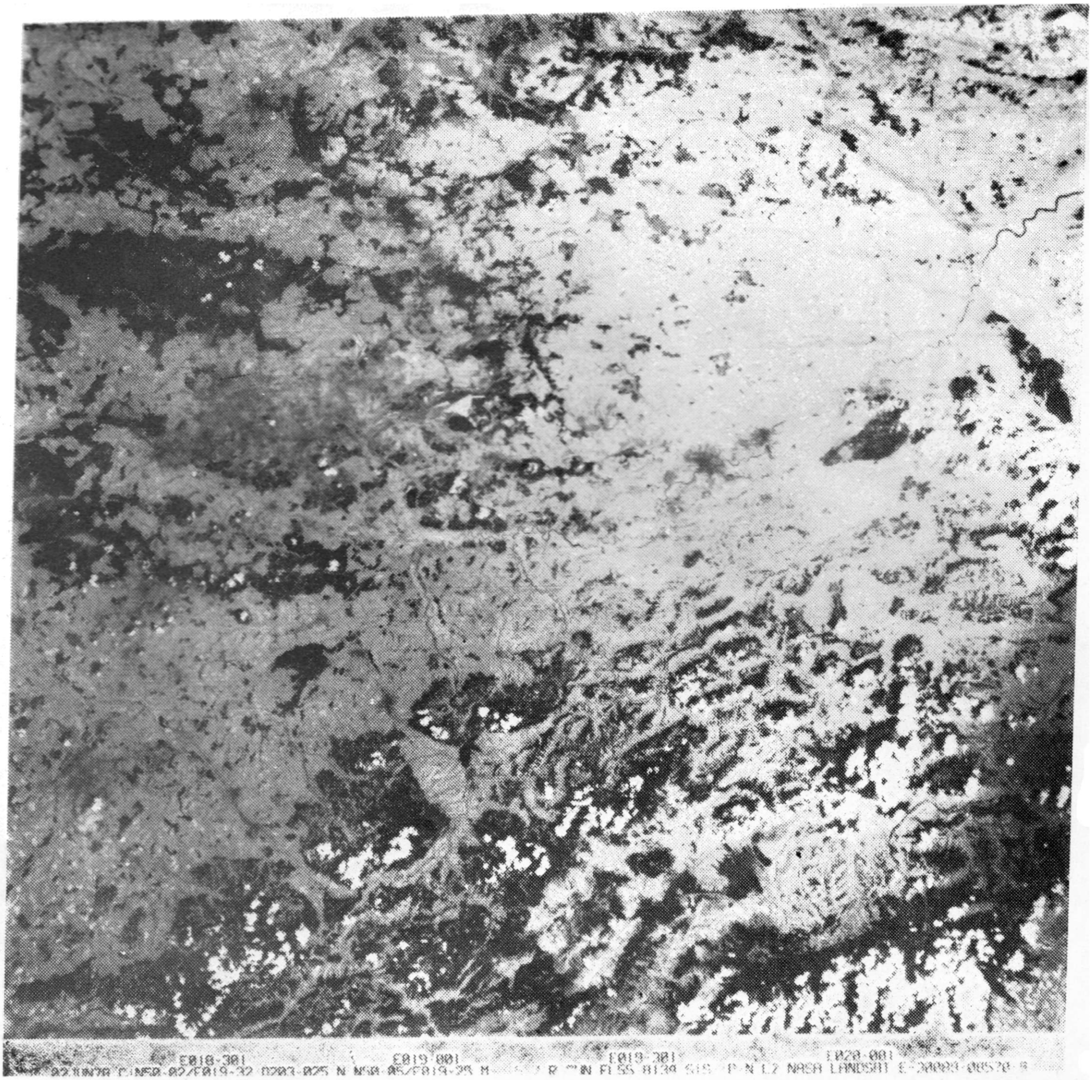


Fig. 4. A sketch of spreading out of the plume emmitted by the chemical plants in Tarnów on June 26, 1975

Rys. 4. Szkic rozprzestrzeniania się smugi emitowanej przez Zakłady Chemiczne w Tarnowie w dniu 26. 06. 1975 r.

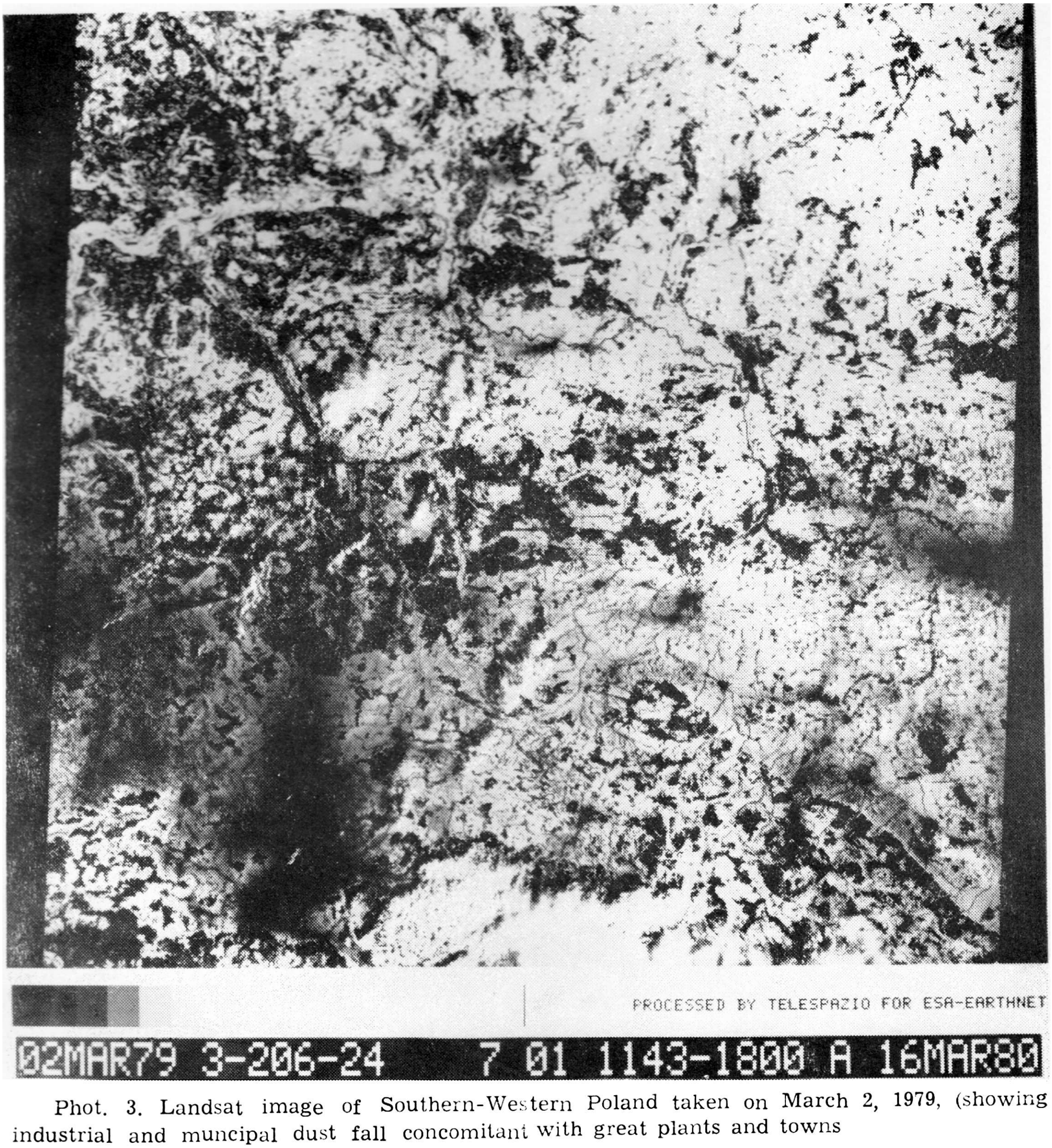
Fot. 1. Zdjęcie satelitarne Górnego Śląska i aglomeracji krakowskiej wykonane 24. 10. 1978 r.

Phot. 1. Landsat image of Upper Silesia and Cracow Agglomeration taken on October 24, 1978



Fot. 2. Zdjęcie satelitarne Górnego Śląska i aglomeracji krakowskiej wykonane 2. 06. 1978 r.

Phot. 2. Landsat image of Upper Silesia and Cracov Agglomeration taken on June 2, 1978



Phot. 3. Landsat image of Southern-Western Poland taken on March 2, 1979, (showing industrial and muncipal dust fall concomitant with great plants and towns

Fot. 3. Zdjęcie Polski południowo-zachodniej wykonane w dniu 2. 03. 1979 r., obrazujące imisję pyłów przemysłowych i komunalnych towarzyszącą wielkim zakładom przemysłowym i miastom out cannot be considered by any of existing models of plumes simulation on the basis of meteorological plumes (see also: D w o r a k, 1980).

The strength of the influence of terrain relief on the direction of smokes spreading out is shown on the satellite photograph taken on November 2, 1973 over the upper Vistula River and the upper Odra River. On the area of Southern Poland, the Southern-Eastern winds occurred this day, directing dust emmission from the Upper Silesian District towards the Opole Plain. Dusts emmitted at the same moment from Ostrava and Karwina were directed to the Upper Odra River valley, by movements of the air flowing through the Moravian Gate. Pollution concentration in the air over this area is so high, that radiation reflected from the terrain surface is fully absorbed. Comparison of image of polluted air over the Upper Silesian District and over the upper Odra River valley shows, that the situation for the Upper Silesian District is considerably better this day. (W a l c z e w s k i, 1976).

Analysis of satellite images of Poland taken from the board of both American, as well as Soviet research satellites allowed to elaborate a map of directions and ranges of plumes emmitted by great industrial plants in Poland. Satellite images, which are at the IGiK disposal were taken in the period between 1973 and 1979. They cover entire Poland, but frequency of their taking over particular areas of our country differs, dependently on meteorological conditions. A map elaborated on the basis of these photographs shows both directions and ranges for different plants with different frequency. In spite of certain disadvantage caused by lack of simultaneous satellite images for the entire country, this map gives an idea on size of areas over which the air is constantly polluted.

It turns out from the analysis of this map, that besides the well known fact of polluting air over the Upper Silesian District, such process is also strong for the vicinities of Cracow (fig. 5). It should be also noticed, that big cement plants located in the central Poland created the area, over which the air is highly polluted. The average distance of dust emmission from the cement plants is equal to 25—30 kilometres for every direction.

It turns out from the analysis of satellite images, that only the Northern-Western Poland and the Northern-Eastern Poland is free from air pollution.

Satellite images allow sometimes to determine a range of industrial and municipal immission. The example can be the Landsat MSS image of the Southern-Western Poland taken on March 2, 1979 (phot. 3). All imaged area was covered by snow. The last snow fall was recorded by local meteorological stations on February 24 and 25, 1979 and thickness of snow cover was equal to 29 cm.

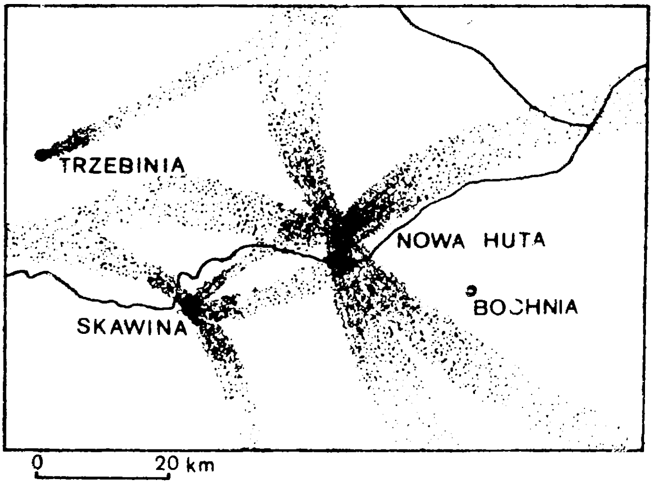


Fig. 5. A portion of the map: ***Range of plumes emmitted by great industrial plants in Poland,*** elaborated at the Institute of Geodesy and Cartography in 1980

Rys. 5. Fragment mapy: *Zasięg smug zanieczyszczeń emitowanych przez większe zakłady przemysłowe w Polsce* opracowanej w Instytucie Geodezji i Kartografii w 1980 r.

The satellite image was taken 6 days later during sunny weather, without haze. Bright terrain surface covered with snow was differently blacked out, depending on quantity of dust fall. On this image a dark area close to the Turów power plant is well visible, which is connected with immission of power plant at Turoszów and immission of German power plants located close to Zgorzelec. The area of reaction of the system of these power plants is equal to about 1 100 square kilometres.

On the basis of results obtained after present investigations it can be stated that satellite images are highly useful for analysis and estimation of state and spreading out of air pollution. Classical methods applied for estimating and forecasting air pollution base on direct point measurements of pollution concentration and on computations performed on the basis of empirical formulae of atmospheric diffusion. It turns out from the works carried out at the Institute of Geodesy and Cartography that analysis of satellite images is an excellent source of auxiliary information for these classical methods.

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ANDRZEJ CIOŁKOSZ, IRENA MAJCHER

WYZNACZANIE ZASIĘGÓW ROZPRZESTRZENIANIA SIĘ DYMÓW PRZEMYSŁOWYCH NA PODSTAWIE ZDJĘĆ SATELITARNYCH

S t r e s z c z e n i e

Szukając nowych metod określania stanu zanieczyszczenia powietrza atmosferycznego przez przemysł, sięgnięto do zdjęć satelitarnych, na podstawie których wyznaczono zasięgi dymów emitowanych przez wielkie zakłady przemysłowe. Zdjęcia satelitarne zostały wykonane przez satelity serii Landsat oraz przez kolejne załogi radzieckiej stacji orbitalnej Salut 6. Najbardziej przydatne do tego rodzaju badań okazały się zdjęcia wykonywane w krótszych zakresach fal, a więc w widmie zielonym rejestrowanym zarówno przez landsatowski skaner, jak i kamerę MKF 6 pracującą na pokładzie Saluta 6.

Zdjęcia satelitarne umożliwiły wyznaczenie przestrzennych parametrów dymów przemysłowych poprzez określenie ich kierunków, jak również rozmiarów w płaszczyźnie pionowej i poziomej. Skala zdjęć satelitarnych predestynuje je do badania emisji pyłowych z wielkich zakładów przemysłowych, takich jak: elektrownie, cementownie, zakłady chemiczne, huty czy fabryki papieru.

Poważne ograniczenia w wykorzystaniu zdjęć satelitarnych do wyznaczania zasięgu zanieczyszczeń stwarzają warunki atmosferyczne. Dymy przemysłowe oddane są najlepiej na zdjęciach wykonanych w warunkach pogody wyżowej, gdy stratyfikacja atmosfery jest stabilna. W sytuacjach typowo niżowych, przy zwiększonej prędkości przepływu mas powietrza i silnych turbulencjach, dymy nie odfotografowują się na zdjęciach, gdyż stężenia zanieczyszczeń gwałtownie maleją w miarę oddalania się od źródła emisji.

Znajomość wysokości i azymutu słońca w momencie wykonywania zdjęcia satelitarnego pozwala obliczyć wysokość wyniesienia smugi dymu, wykorzystując zjawisko cienia rzucanego przez dym na powierzchnię ziemi. W przypadku zdjęć wykonywanych za pomocą kamery MKF 6 wysokość wyniesienia pióropusza dymu określa się za pomocą metod fotogrametrycznych.

Trajektorie dymów przemysłowych wyznaczone na podstawie zdjęć satelitarnych zostały porównane z modelami trajektorii obliczonymi na podstawie procesów symulacji dyspersji. Wzięto pod uwagę trzy modele: uwzględniający wiatr geostroficzny, wiatr przyziemny oraz obie te informacje uzupełnione wynikami sondażu aerologicznego. Najlepszą zgodność między trajektoriami wyznaczonymi na podstawie zdjęć satelitarnych i obliczonymi z modeli otrzymano dla modelu

uwzględniającego wiatr przyziemny. Żaden z modeli nie uwzględnia lokalnych warunków topograficznych, które — sądząc z analizy zdjęć satelitarnych — mogą w wielu przypadkach decydować o kierunku przemieszczania się smug zanieczyszczeń.

Analiza zdjęć satelitarnych całego obszaru Polski umożliwiła opracowanie mapy obrazującej zasięgi dymów emitowanych przez duże zakłady przemysłowe. Na podstawie tej mapy można wyznaczyć regiony o różnym stopniu zanieczyszczenia powietrza atmosferycznego.

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LA DÉLIMITATION DES AIRES D'EXPANSION DES FUMÉES INDUSTRIELLES À PARTIR DE PHOTOGRAPHIES COSMIQUES

Résumé

Recherchant de nouvelles méthodes de détermination de l'état de la pollution de l'air atmosphérique par l'industrie, on a fait appel aux photographies cosmiques à partir desquelles on a délimité les aires d'expansion des fumées émises par les grands établissements industriels. Les photographies cosmiques ont été prises par des satellites de la série Landsat ainsi que par les équipes successives de la station orbitale soviétique Saliout 6. Ce sont les photographies réalisées dans les gammes des ondes très courtes qui se sont avérées les plus utiles à ce genre de recherches, et donc dans le spectre vert qui est enregistré tant par les scaners des landsats que par la caméra MKF 6, installée à bord de Saliout 6.

Les photographies cosmiques ont permis d'établir les paramètres spatiaux des fumées industrielles par la détermination de leurs orientations ainsi que de leurs étendues tant sur le plan vertical que sur le plan horizontal. La gamme des photographies cosmiques les prédestine à l'étude des émissions de poussières provenant de grands établissements industriels à l'étude des émissions de poussières provenant de grands établissements industriels tels que les centrales électriques, les cimenteries, les usines chimiques, les hauts-fourneaux ou usines de papier.

Les conditions atmosphériques limitent dans une grande mesure la possibilité d'utiliser les photographies cosmiques pour délimiter les aires d'expansion des pollutions. Les fumées industrielles ressortent le mieux sur les photographies lorsque celles-ci sont prises dans de conditions d'anticyclone et que la stratification de l'atmosphère est stable. Dans les situations typiques de basse pression, avec une vitesse accrue de la circulation des masses d'air et de fortes turbulences, les fumées ne se laissent pas photographier car la densité des pollutions diminue promptement au fur et à mesure de leur éloignement de la source d'émission.

La connaissance de la hauteur et de l'azimut du soleil au moment de la prise de la photographie cosmique permet de calculer la hauteur de l'élèvement de la traînée de fumée, par l'utilisation du phénomène de l'ombre de cette fumée à la surface du sol. Dans le cas des photographies prises à l'aide de la caméra MKF 6, la hauteur de l'élévation du panache de fumée se définit à l'aide des méthodes photogrammétriques.

Les trajectoires des fumées industrielles établies à partir des photographies cosmiques ont été comparées aux modèles de trajectoires calculés d'après les

processus de simulation de la dispersion. Nous avons pris trois modèles en considération: celui qui tient compte du vent géostrophique, celui qui tient compte du vent superficiel ainsi que celui qui tient compte de ces deux informations complétées par les résultats d'un sondage aérologique. Nous avons obtenu la concordance la meilleure entre les trajectoires établies à partir des photographies cosmiques et celles qui étaient calculées d'après les modèles pour le modèle qui tenait compte du vent superficiel. Aucun des modèles ne prend en considération les conditions topographiques locales qui — si l'on en juge d'après l'analyse des photographies cosmiques — peuvent dans bien des cas être décisives en ce qui concerne l'orientation du déplacement des traînées de pollutions.

L'analyse des photographies cosmiques de tout le territoire de la Pologne a permis d'élaborer une carte illustrant les aires d'extension des fumées émises par les grands établissements industriels. A partir de cette carte, on peut délimiter les régions de divers degrés de pollution de l'air atmosphérique.

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