Application of atmospheric radiance/scattering models in the problem of fire detection from space

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Abstract – Analysis of the results of detecting fires in the Tomsk region of Western Siberia from space allows us to note the following. Complex situations often arise in satellite observations under conditions of aerosol or semitransparent cloudiness when standard algorithms do not allow one to detect automatically small-sized fires from space. In such situations, the problem can be solved successfully by using atmospheric correction of satellite measurements for the distorting effect of the atmosphere based on atmospheric radiance/scattering models. In this case, *a priori* information on optical and meteorological parameters of the atmosphere and on the geometry of observations is used. In the present study, some results of numerical simulation and atmospheric correction for the distorting effect of the atmosphere in the problem of fire detection are given.

Keywords: fire detection, satellite measurments, atmospheric correction.

1. INTRODUCTION

In remote sensing of the underlying surface from space, the actual problem of real-time detection of fires in forests and industrial objects is solved. In this case, it is important to detect a seat of fire in early stages (when its area is less than 5–10 ha) when its extinguishing does not require great efforts. In this case, reliable algorithms of automatic detecting of small-sized high-temperature objects (SHTO) with area less than 0.1% of the pixel size are required. The importance of correction of satellite IR measurements for the distorting effect of the atmosphere with the use of information on the atmospheric conditions (meteorological and aerosol parameters of the atmosphere) and on the geometry of observations at the time of satellite measurements is obvious for obtaining maximum accuracy.

An analysis of algorithms of detecting fires seats from space published in the literature allowed us to conclude the following. In most fire detection algorithms used in practice, the decision rule $P\{x\} > dP$ is used, where dP is the threshold value of the function $P\{x\}$, and its parameters $\{x\}$ are satellite measurements of albedos and brightness temperatures (or their functions). The threshold values dP are strictly fixed or can be determined based on statistical analysis of $\{x\}$ in the vicinity of the potential fire seat. However, the actual parameters of the atmosphere at the time of satellite measurements are in fact disregarded in algorithms used in practice.

The researchers from the Institute of Atmospheric Optics (IAO) SB RAS (Tomsk, Russia) have been involved in work on the study of the distorting effect of the atmosphere on the results of remote sensing of the underlying surface from space (see, for example Afonin, 1997, 2003; Belov, 1997, 1999, 2002). In this paper, results of numerical simulation considering the distorting effect of the scattered solar radiance in the problem of fire detection are given. By the practical example of the atmospheric correction of satellite measurements the successful detection of small-sized petroleum gas flares from a NOAA satellite under conditions of broken cloudiness is shown.

2. FORMULATION OF THE PROBLEM OF FIRE DETECTION FROM SPACE

We now write down the main formulas used to calculate the upwelling thermal radiance in the “surface + atmosphere + SHTO” system. Let a high-temperature object characterized by area S_H and temperature T_H ($T_H > 600$ K) be in the region of the underlying surface with area S_{FOV} ($S_H << S_{FOV}$) corresponding to the Field Of View (FOV) of the remote sensor and with the background underlying surface temperature T_S. The integrated upwelling thermal radiance at the top of the atmosphere I_λ can be written as follows:

$$I_\lambda = B_\lambda (T_\lambda) = I_{HOT} + I_{BG} \quad (1)$$

$$I_{HOT} = B_{HOT} P_\lambda,\ B_{HOT} = R(\theta)\, B_\lambda (T_H),\ R(\theta) = S_H / S_{FOV}(\theta)$$

$$P_\lambda = \exp\{-\tau_\lambda / cos(\theta)\}$$

$$I_{BG} = I_{SRF} + I_{ATM} + I_{RFL} + I_{SCT}$$

where $B_\lambda (T)$ = Planck’s function
- T_λ = observed brightness temperature
- I_{HOT} and I_{BG} = SHOT and background radiance
- P_λ = atmospheric transmittance
- τ_λ = optical thickness of the atmosphere
- θ = view angle
- I_{SRF} = transmitted surface radiance
- I_{ATM} = atmospheric radiance
- I_{RFL} = ground reflected (thermal and solar) radiance
- I_{SCT} = path scattered (thermal and solar) radiance.

From the viewpoint of correct consideration of optical-geometrical conditions of observations, the problem of detection of a small-sized high-temperature object from space must be solved by the reconstruction of the radiance B_{HOT}:

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$$B_{HOT} = (I_\lambda - I_{BG}) / P_\lambda \quad (2)$$

where I_λ is the observed thermal radiance and the values I_{BG} and P_λ are calculated from *a priori* optical-meteorological data. In this case, the decision rule for detecting a seat of forest fire from space $B_{HOT} > dB$ will be independent of the optical-geometrical conditions of observations.

From the viewpoint of complexity of computational algorithms, the volume of the required *a priori* information, and difficulties in assigning actual *a priori* information with required accuracy, the calculation of I_{RFL} and I_{SCT} is the most labor-consuming problem. It is based on knowledge of:

- Geometrical conditions of observations (the view angle θ, solar zenith angle Z, and relative azimuth angle of measurements φ)
- Meteorological parameters of the atmosphere
- Optical characteristics of the atmospheric aerosol.

In this regard, we consider some results of numerical simulation of the I_{SCT} value.

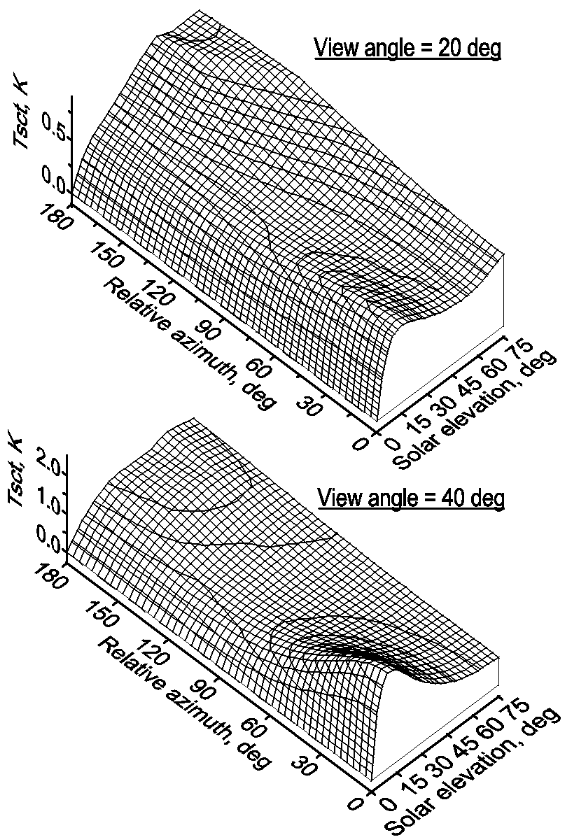

Figure 1. Dependence of the scattered radiance T_{SCT} on geometry of satellite observations; rural boundary-layer aerosol, *Vis* = 5 km.

To study the peculiarities of the behavior of the scattered solar radiance in the channel with λ = 3.75 μm, the I_{SCT} value was simulated numerically using the LOWTRAN-7 computer codes (Kneizys, 1988) for the cloudless atmosphere and the following conditions of satellite observations:

- Meteorological parameters for the atmospheric model for the midlatitudes in summer
- Rural and urban boundary-layer aerosol models (meteorological visibility range *Vis* = 50–2 km)
- Geometry of observations: θ = 0–55°, H_S = 90° – Z = 75–0° (solar elevation angle), and φ = 0–180°.

As we see in Fig. 1, the results of modeling demonstrated a complex dependence of the I_{SCT} value on the conditions of satellite observations. For convenience, the I_{SCT} value in the figure is expressed as increment T_{SCT} to the brightness temperature T_λ corresponding to the situation with $H_S < 0°$.

First it should be noted that the azimuth dependence of T_{SCT} value becomes more pronounced with increasing scanning angle and decreasing *Vis* value (increasing of the atmospheric turbidity). For solar elevation angle H_S of the order of 10° and azimuth angles $\varphi < 50°$, an abnormal formation of a local maximum of the T_{SCT} value is observed. The amplitude of this maximum depends on the value of θ and on the optical characteristics of the boundary-layer aerosol.

An analysis of the NOAA satellite data on the relationship between the geometrical parameters H_S and φ for the Tomsk region demonstrated the occurrence of such region of their values in which the abnormal growth of T_{SCT} takes place. This must be taken into account in correction of satellite measurements for the distorting effect of the atmosphere.

In this paper, we study how the quality of the *a priori* meteorological information (AMI) affects the accuracy of reconstructing the object radiance from space data in the spectral region of 3.5-4 μm. The atmospheric transmittance and characteristics of the upward radiation in the NOAA/AVHRR IR channels were calculated for the conditions of Tomsk with allowance for the actual geometry of satellite observations and meteorological parameters of the atmosphere specified in accordance with the IAO SB RAS data for the period of May–September 1998-2000.

Satellite measurements were simulated by calculations with the use of meteorological data closest in time to satellite observations. A high-temperature object with the temperature of 800–1200 K and area of 10–1000 m^2 was simulated in the radiometer field of view. Different types of AMI and sources of information about the background surface temperature T_S were used for atmospheric correction of the simulated “satellite measurements”.

As a result, the dependence was found between the characteristics of AMI and the accuracy of radiance reconstruction for a high-temperature object. For an object with the area smaller than 100-200 m^2, the results demonstrate the marked effect of the quality of AMI on the results of reconstruction. Depending on the type of AMI, the RMS values of radiance reconstruction may vary several times, but remains at least half as small as without atmospheric correction.

3. RESULTS OF CORRECTION OF SATELLITE DATA FOR THE DISTORTING EFFECT OF THE ATMOSPHERE

The approach to the correction of the data of monitoring of small-sized high-temperature objects for the distorting effect of the atmosphere examined in Section 1 was used in practice for processing of the NOAA/AVHRR satellite data. Fig. 2 shows an image fragment (the channel with $\lambda = 3.75$ μm) recorded in the morning (at 07:56, Tomsk Local Time) on May 21, 2001 from the NOAA-14 satellite.

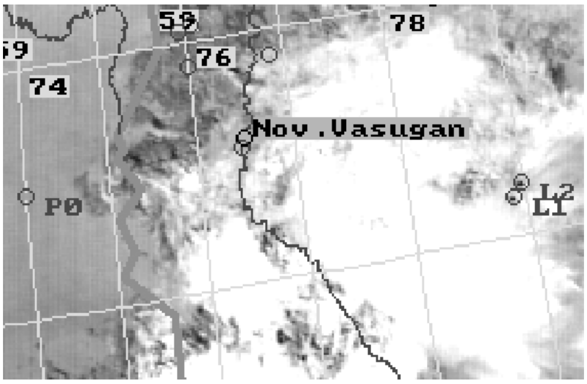

Figure 2. NOAA/AVHRR image ($\lambda = 3.75$ μm); Tomsk region, *L1* and *L2* are the petroleum gas flares.

Two stationary high-temperature objects (petroleum gas flares) are clearly seen in the image at points *L1* and *L2*. These objects were observed from space under rather complex optical conditions, since inhomogeneous broken cloudiness was observed in the vicinity of points *L1* and *L2*. Moreover, a higher optical density of cloudiness was exactly around point *L1*.

Point *P0* characterized by cloudless conditions of satellite measurements is also shown in the image. The data obtained in its vicinity allowed us to estimate the atmospheric meteorological parameters (the vertical temperature and humidity profiles) and the background surface temperature T_S.

Table 1. Statistical characteristics of satellite measurements at points *L1*, *L2*, and *P0*

Points	A_1, %	A_2, %	T_3, K	T_4, K	T_5, K
L1	8.38	8.80	293.0	259.3	256.9
	8.59 1.35	8.79 1.20	273.7 4.51	260.1 3.27	258.2 3.16
L2	5.77	6.40	322.6	268.4	266.2
	5.78 1.06	6.09 1.11	276.9 8.03	266.8 2.61	264.8 2.50
P0	3.02	3.84	281.3	280.0	279.0
	2.98 0.11	3.73 0.09	280.2 0.46	279.9 0.15	278.9 0.14

The characteristics of five-channel measurements at points *L1*, *L2* and *P0* (albedos A_1, A_2 and brightness temperatures T_3, T_4, and T_5) are tabulated in Table 1. The second row for each point shows the average value of the parameter (for the window of 9×9 pixels), and the third row shows its standard deviation.

From Table 1 it follows that object *L2* will be successfully detected by most satellite algorithms because of high value of the brightness temperature $T_3 = 322$ K. At the same time, object *L1* cannot be detected automatically because of low value of the brightness temperature $T_3 = 293$ K.

Thematic processing of the satellite image fragment shown in Fig. 2 was carried out as follows.

1. To assign the parameters of the atmospheric meteorological state, the temperature and humidity profiles nearest to point *P0* extracted from the data of the TOVS/NOAA atmospheric sounder were used.
2. The background surface temperature T_S at point *P0* was estimated by the single-channel method (using the channel with 11 μm) from the TOVS/NOAA satellite weather data and by the split-window method (Price, 1984) from IR measurements in channels with 11 and 12 μm. As a result, we obtained $T_S \approx 283$ K.
3. The optical atmospheric parameters were reconstructed from the AVHRR data for models of the atmospheric aerosol and cloudiness (Kneizys, 1988).
4. The characteristics I_{BG} and P_λ required for reconstruction of the B_{HOT} value at points *L1* and *L2* were then estimated. They are tabulated in Table 2.

Table 2. Results of reconstruction of the SHTO thermal radiance; values of I_λ, I_{BG}, and B_{HOT} are expressed in mW/(m^2·sr·cm^{-1}).

Points	I_λ	P_λ	I_{BG}	B_{HOT}
L1	0.503	0.055	0.260	4.459
L2	1.650	0.251	0.297	5.390

The reconstructed values B_{HOT} were equivalent to the radiation temperature exceeding 355 K (82°C). This allows us to confirm the presence of high-temperature objects not only at point *L2* but also at point *L1*.

4. CONCLUSIONS

Thus, despite the complicated optical-geometrical conditions of observations, the problem of automatic detection of small-sized high-temperature objects (SHTO) can be solved using the procedure of correction for the distorting effect of the atmosphere if one succeeded in:

1. Evaluating the actual input information (optical-meteorological parameters of the atmosphere and the background surface temperature) from ground-based and satellite data obtained at time of satellite measurements.
2. Estimating the quantities included in Eqs. (1) by numerical modeling from *a priori* optical- meteorological and geometrical data.
3. Determining the radiance of SHTO from Eq. (2).

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