Solution of problems of atmospheric correction of satellite IR measurements accounting for optical-meteorological state of the atmosphere

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Received August 3, 2007

A method of atmospheric correction of EOS/MODIS satellite measurements is presented. The method is based on the IMAPP program package and the program of modeling the transfer heat radiation. A concise description of the program complex structure and its basic blocks are described. The application of the method to retrieval the underlying surface temperature in the presence of semi-transparent clouds and smoke are given as an example.

Introduction

Efficient solution of fast control for the environment state from space is possible only on the base of application of high-accurate algorithms of thematic processing and atmospheric correction of space measurements. This is particularly important in temperature sensing of the environment under complex observational conditions including the detection of weak-intensity fires at early stage of their development.[1,2] Regretfully, the presently available methods do not solve this problem.

Analysis of literature on the issue allows setting off three basic types of algorithms used in the atmospheric correction of the space IR measurements of the underlying surface temperature (LST):

- the spectral method of LST measurements (Split-window LST algorithm or SW algorithm);
- the angular method of measurement of the underlying surface temperature (Dual-angle LST algorithm or DA algorithm);
- application of radiation models (Radiative transfer approaches or RT method).

Application of the SW-algorithm[3] is based on linear relations between LST and satellite measurements in two spectral channels close to 11 and 12 μm. The relations can also include values of the underlying surface emissivity $\varepsilon(\lambda)$ for these channels. Parameters of these relations are calculated from modeling data or data of combined analysis of LST satellite and ground measurements.

As an example, we can consider the standard MODIS algorithm for LST remote measurement[4]:

$$T_0 = C + \alpha(T_{11} + T_{12})/2 + \beta(T_{11} - T_{12})/2;$$

$$\alpha = A_1 + A_2(1 - \varepsilon)/\varepsilon + A_3(\Delta\varepsilon/\varepsilon^2);$$

$$\beta = B_1 + B_2(1 - \varepsilon)/\varepsilon + B_3(\Delta\varepsilon/\varepsilon^2);$$

$$\varepsilon = (\varepsilon_{11} + \varepsilon_{12})/2,\ \Delta\varepsilon = (\varepsilon_{11} - \varepsilon_{12})/2,$$

where coefficients A_i and B_i (i = 1, 3) depend on the satellite zenith angle and integral moisture content of the atmosphere.

In practice, this approach is an efficient way of the global monitoring of LST at a limited amount of input data. However, note that algorithms of such type give good results only for a bounded range of standard situations in the cloudless atmosphere, moderate content of water vapor and background aerosol. In this connection, the report by the Head of MODIS LST Group, doctor Zhengming Wan (Institute for Computational Earth System Science, UCSB, USA) “MODIS LST and Emissivity Algorithms and Products” at the MODIS Collection 5 Workshop in January, 2007, should be noted. In this report, among other prospective directions of further development of the LST retrieval algorithms, the solution of the problem of fast accounting of the influence of aerosol and semi-transparent cloudiness was underlined.

The angular method also uses linear relations between LST and space measurements near 11 μm at two angles of vision of the device axis. The method can be used for devices of ATSR type.[5,6] The method has its advantages, but on the whole, its application is bounded.

In the framework of the RT-method, the distorting atmospheric characteristics are accounted for via special programs like LOWTRAN7, MODTRAN, ATCOR, and others, based on *a priori* optical-meteorological information about the atmospheric state in the moment of satellite observations. Then, using the equation of the heat radiation transfer, the sought values of LST are retrieved. As examples of such approach, the atmospheric correction of the MSU-SK, NOAA/AVHRR, Landsat, ASTER[7–13] radiometer data can be cited.

In respect to versatility and explicit accounting for all distorting factors in the retrieval problems, as

0235-6880/08/02 125-07 $02.00

well as from the theoretical point of view, this approach is believed most sensible and correct, although its application in practice needs in a large amount of *a priory* information of the required quality.

In addition, the requirements to the accuracy of optical atmospheric models and the rate of computations are rather high as well. However, the combined approach, i.e., the use of fast SW algorithm in case of standard situations and RT method in more complicated cases (the presence of aerosol, semi-transparent cirrus clouds) can widen the possibilities of LST space-sensing methods .

At the Institute of Atmospheric Optics SB RAS, a particular attention historically is paid just to realization of the RT method.[7–9] Thus, in 2005 the first version of the software for atmospheric correction of LST aerospace measurements,[14] including widely used space systems EOS/MODIS and NOAA/AVHRR was designed.

When using the RT method for LTS retrieving from satellite measurements, the primary condition is the availability of online *a priory* information on meteorological and optical parameters of the atmosphere at the moment of space-borne observations. Therefore, the presence in the program complex of the block of *a priori* information is necessary. In this work, realization of such a block for the EOS/MODIS satellite system is described. In the following works, a similar software for NOAA/AVHRR will be presented, in which the retrieval of the atmospheric meteoparameters is performed on the base of NOAA/ATOVS measurements.

Structure of the program complex

Note firstly that two types of the basic software for thematic processing of information from EOS/MODIS system are known to the present time.

The first type includes DRL licensing programs (Direct Readout Lab, GSFC/NASA), where basic algorithms are grouped in PGE (Product Generation Executive), which include the program texts and necessary data for their assembling, setting, and exploiting. In Russia, this software is successively used for many years at the Center of Space Monitoring of the Altay State University.[15]

The second type is presented by the well-known program package IMAPP (International MODIS/AIRS Processing Package). The design, maintenance, and distribution of the Package are conducted under GNU General Public License at the Space Science and Engineering Center (SSEC), being a division of the University of Wisconsin–Madison (ftp://ftp.ssec.wisc.edu/pub/IMAPP/MODIS/).

To solve our problem, we chose the IMAPP v. 2.0 package and adapted it to the operation medium Windows. General scheme (Fig. 1) of the designed software for thematic processing of the EOS/MODIS data includes three stages.

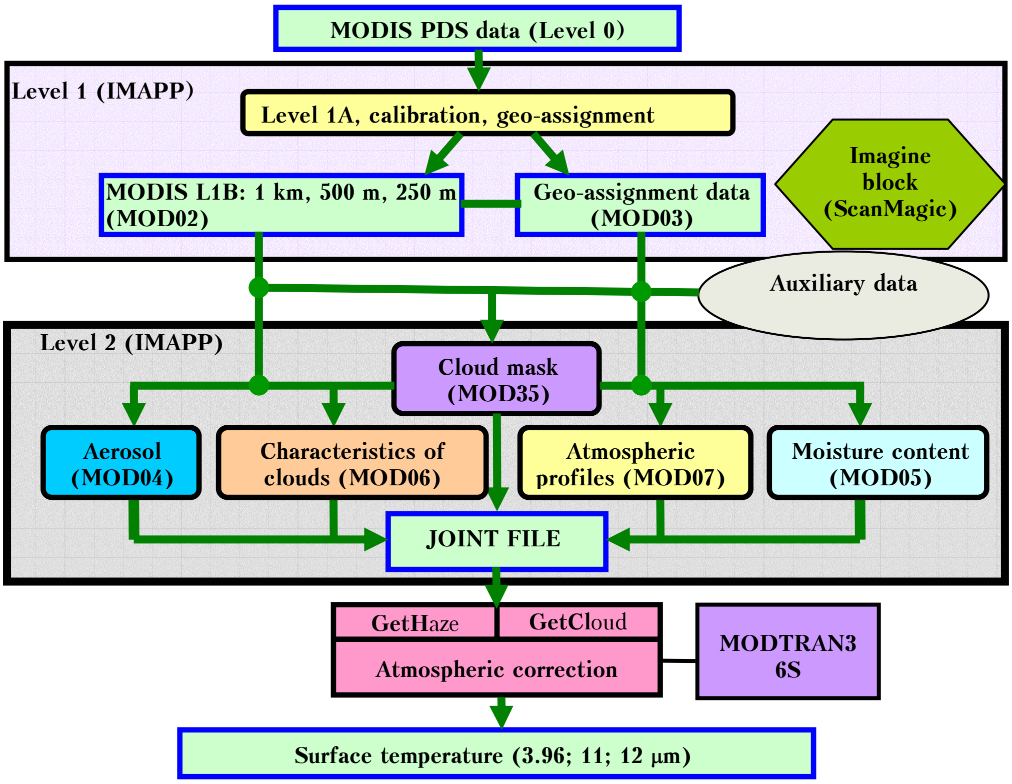


Fig. 1. Schematic view of the atmospheric correction of remote measurements of the underlying surface characteristic variations with the use of the EOS/MODIS satellite system.

1. At the initial stage (levels 0 and 1), the satellite file EOS/MODIS is unpacked with the help of IMAPP program from PDS format to a set of HDF-EOS formats; the geographic assignment of data and calibration of the space measurements are performed.

2. At the second stage (level 2) the *a priori* information from MODIS on parameters of the atmospheric state is prepared for processing. This information includes:

– cloud mask (MOD35);

– optical characteristics of aerosol (MOD04);

– integral moisture content of the atmosphere (MOD05);

– characteristics of clouds (MOD06);

– vertical profiles of the geopotential, temperature, and humidity of air, ozone content (MOD07).

3. Based on the *a priori* information, formed at the stage 2, with the use of the program block "Atmospheric correction" (described in detail in Ref. 14), characteristics of distorting effects of the atmosphere are calculated and the space measurements of LST and its spectral reflectance are corrected. At present, this is made by the well-known programs MODTRAN, 6S. The application of the 6S allows possibilities of the basic algorithms for retrieval of aerosol and cloud characteristics to be widened by their adaptation to regional monitoring conditions through GetHaze/GetCloud programs.

To set values of the emissivity $\varepsilon(\lambda)$ in the IR channels at $\lambda = 3.96$, 11, and 12 μm of EOS/MODIS device, data of MODIS UCSB Emissivity Library (http://www.icess.ucsb.edu/modis/EMIS/html/em.html) or the database Global Infrared Land Surface Emissivity Database (http://cimss.ssec.wisc.edu/iremis/) are used.

The interface of the program block operating at the key stage 2 is presented in Fig. 2.

An example of the method application

To preliminary test the program complex performance, the temperature of some area of 60 × 60 km of the Luginetsk oil-gas condensate field (58.15° N, 78.89° E) was sensed under different atmospheric conditions. Figure 3 shows space patterns of the area with spatial resolution of 250 m, resulted from the composition of three spectral channels of the visible range of EOS/MODIS space system for June 2 and 5, 2004. Torches of the oil-gas condensate field are located in the image center.

At the image A, where the atmosphere is free of clouds and the aerosol has the background content, two basic types of surface are clearly seen: areas covered with vegetation (dark) and open areas (light). Analysis of a series of the cloud-free images allows us to conclude that the spatial distribution of the underlying surface temperature follows the image outlines and is sufficiently stable, as well as that the temperature of light areas is by 2–3° higher than that of dark ones. A different situation is seen at the image B: the smoke of the forest fires, as well as dense and semi-transparent cloudiness noticeably distort spatial outlines of the underlying surface.

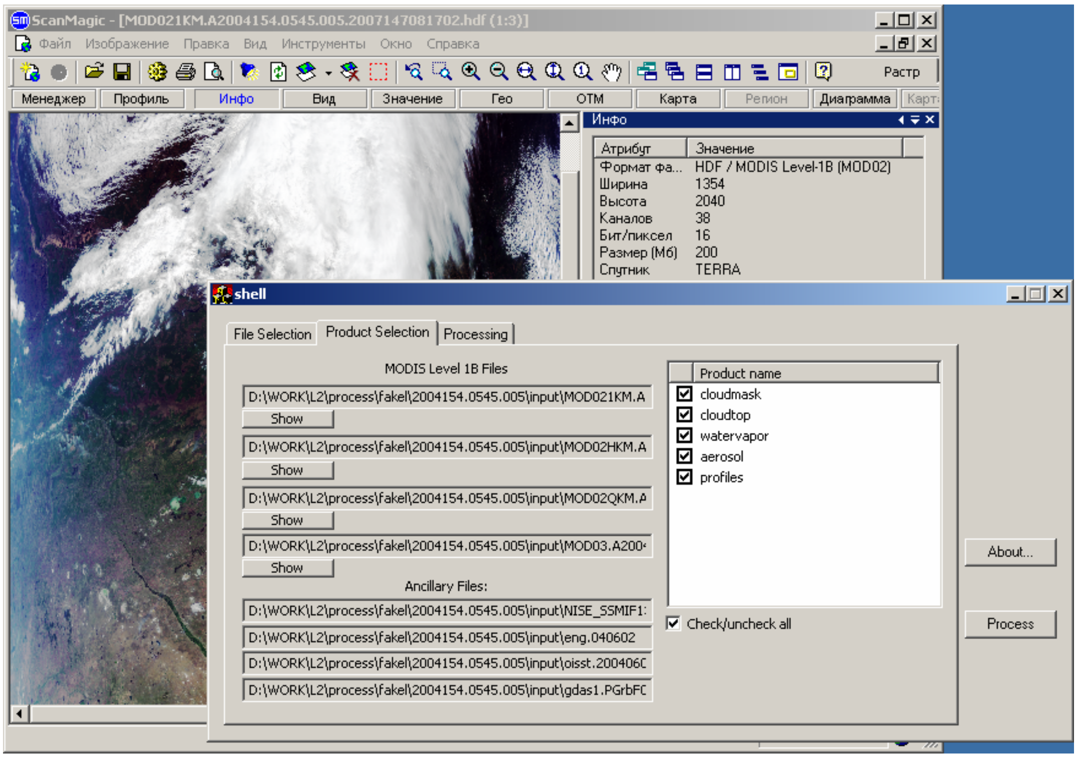
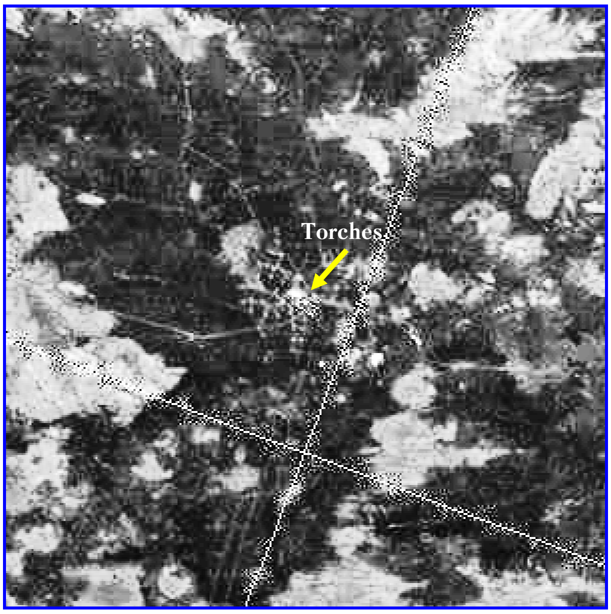


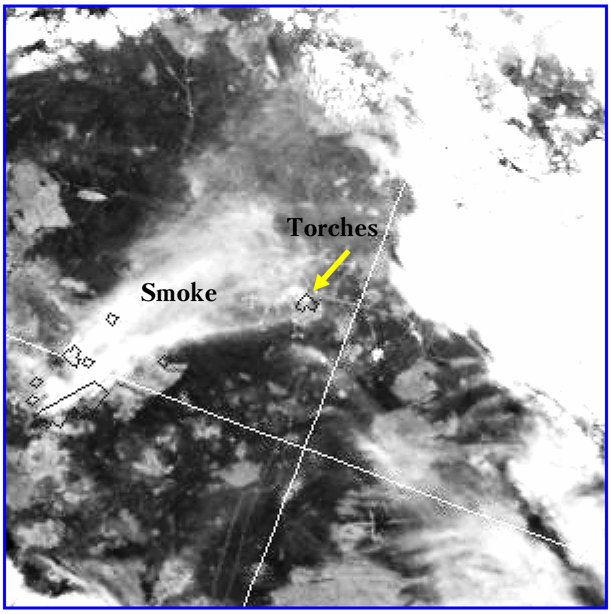
Fig. 2. Interface of the program of atmospheric parameters determination from EOS/MODIS measurements.

June 2, 2004; 12:38 LT



A. Clear atmosphere

June 5, 2004; 13:15 LT



B. Smoke, cloudiness

Fig. 3. MODIS space images of the Luginetsk oil-gas condensate field; geographical projection – Albers Conical Equal Area.

Space images in Fig. 3 are supplemented by data from Fig. 4, which are constructed by MODIS photographs in Cartesian coordinates.

For the case A, open areas are outlined; the characteristic values of albedo measurements at λ = 466 nm (ρ_{466}) and the brightness temperature at λ = 11 μm (T_{11}) are marked. Bright torches (λ = 466 nm) and the sand quarry (to the right) are well seen in the image center. The differences of brightness temperatures in the channels λ = 11 and 12 μm characterize the scale of spatial dissimilarity of the atmosphere distorting properties in the IR spectral range.

Analysis of the values $T_{11} - T_{12}$ for the case A allows a conclusion that distorting properties of the atmosphere in this case can be considered quasihomogeneous (one range of values 0.5–1.3°, r.m.s. = 0.11°). Oppositely, in the case B, the values of $T_{11} - T_{12}$ fall in the range 0.4–7.1° and r.m.s. = 0.71° due to the smoke and cloudiness.

Naturally, the results of operation of the basic SW algorithm[4] are of interest (a standard product is called MOD11_L2) in the both cases under consideration. These data, obtained from the site Land Processes Distributed Active Archive Center (LP DAAC, http:// edcdaac.usgs.gov / datapool / datapool.asp), are presented in Fig. 5.

In case of the cloudless atmosphere, the standard algorithm MOD11 retrieves the LST everywhere, excluding only a few pixels, because the cloud mask due to bright pixels (erroneously, to our opinion) fixes the presence of partial cloudiness. In this case, LST spatial structure is almost similar to the spatial structure of brightness temperatures.

In the case B, spatial structures of ρ_{466}, T_{11}, and LST are noticeably distorted by the smoke and cloudiness. The number of white pixels, where MOD11 data are absent, significantly increased.

The retained structures T_{11} are outlined in the image. Note that the results of LST retrieval in this case, aside from misses, contain explicitly underestimated LST values, falling into the limits of cloud outlines.

Now we have to fill white misses in LST in order to retrieve the temperature structure similarly to the case of the cloudless atmosphere through the atmospheric correction of data at the areas, where the thermal radiation passes mostly through the smoke and aerosol.

The designed program complex was used for this purpose. As the *a priori* information, we used the IMAPP-retrieved data from MODIS measurements. Using the MODTRAN program,[14] the distorting characteristics of the atmosphere were calculated for the channel λ = 11 μm (the bottom in Fig. 5), measurements of the brightness temperatures T_{11} were corrected, and new spatial distribution B′ of LST was found.

After the correction, a part of the temperature structure of the area, centered at the point (Y = 25, X = 52), was retrieved. Note an important fact that the difference between the retrieved LST values for B and B′ in the vicinity of this point does not exceed 1°. Besides, the surface temperature near torches ($Y = X$ = 30) was also retrieved.

Consider one more result of the program complex application, i.e., the retrieval of the thermal radiation temperature of torches T_F from measurements

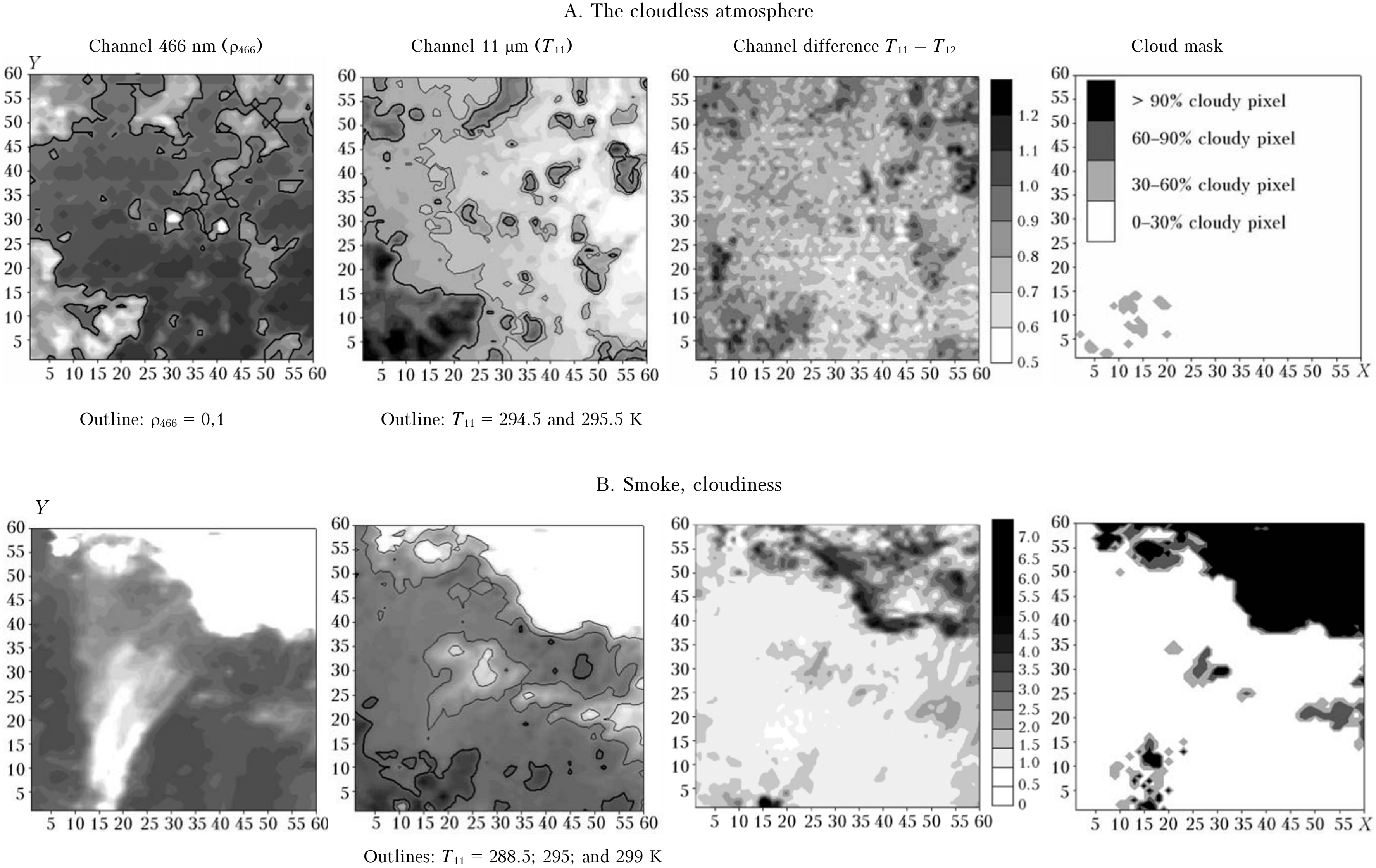


Fig. 4. MODIS space data: albedo values in the channel λ = 466 nm, brightness temperatures in the channel λ = 11 μm, difference of brightness temperatures in the channels λ = 11 and 12 μm, cloud mask.

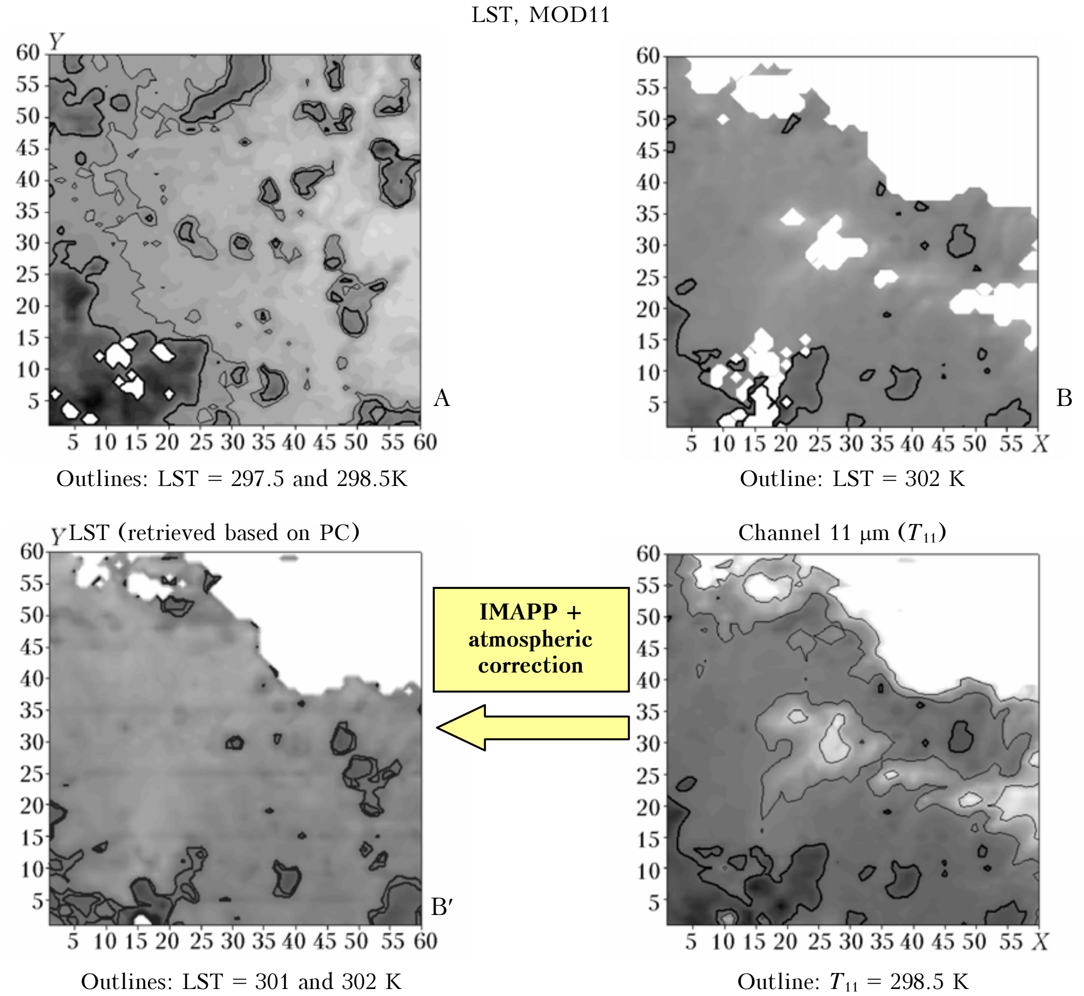


Fig. 5. Results of the LST retrieval by the MOD11 standard algorithm (two top images) and based on the designed program complex.

of brightness temperatures T_4 in the channel $\lambda = 3.96$ μm, accounting for (based on IMAPP data) the optical-meteorological state of the atmosphere[2]:

$$B(T_\lambda) = I_{\text{hot}} + I_{\text{bg}},$$

$$B_{\text{hot}} = S(\theta)\varepsilon_\lambda^F B(T_F) P\lambda;\ I_{\text{bg}} = I_{\text{srf}} + I_{\text{atm}} + I_{\text{rfl}} + I_{\text{sct}},$$

$$B_{\text{hot}} = (B(T_\lambda) - I_{\text{bg}})/P_\lambda,$$

where $B(T_\lambda)$ is the Planck function; T_λ is the brightness temperature of the thermal radiation; I_{hot} is the intensity of torch emission attenuated by the atmosphere; I_{bg} is the background radiation intensity; I_{srf} is the contribution of the surface thermal radiation attenuated by the atmosphere; I_{atm} is the contribution of thermal radiation of the atmosphere; I_{rfl} is the contribution of the incident flows of thermal and solar radiation, reflected from the surface; $P_\lambda = \exp\{-\tau_\lambda\}$ is the atmospheric transmittance; τ_λ is the optical thickness of the atmosphere; $S(\theta)$ is the ratio of the torch area to pixel size.

Table illustrates the results of the problem solution provided the flame diameter is 8 m.

Case	LST, K	P_λ, τ_λ	T_{11}, K	T_4, K	T_F, K
A	300.0	0.822 (0.196)	297.4	334.0	2430
B	302.0*	0.344 (1.067)	293.8	321.0	2450

* LST = $T_{11,\text{cor}}$ – the temperature is retrieved after atmospheric correction of measurements in the channel $\lambda = 11$ μm with the help of the designed program complex (see Fig. 5, case B′).

Thus, retrieving results for torch flame temperature are very close despite different atmospheric conditions during space observations. It should be noted that excluding this operation (atmospheric correction) results in significantly different values for A and B cases: 2180 and 1410 K, i.e., the overestimation for the case B exceeds 1000 K.

Conclusion

The pilot software, described in this paper and intended for fast atmospheric correction of space MODIS IR measurements widens possibilities of the available methods of temperature sensing of the underlying surface due to accounting for distorting effects of aerosol and semi-transparent cloudiness.

Acknowledgements

The authors thank Doctor V.V. Belov for his interest to this work and its support, as well as I.V. Engel for information on the Luginetsk oil-gas condensate field and torches.

References

1. S.V. Afonin and V.V. Belov, Vychisl. Tekn. **8**, Special Issue, 35–36 (2003).
2. S.V. Afonin, Atmos. Oceanic Opt. **18**, No. 4, 299–301 (2005).
3. C. Coll and V. Caselles, J. Geophys. Res. D **102**, No. 14, 16,697–16,713 (1997).
4. Z. Wan, *MODIS Land-Surface Temperature Algorithm Theoretical Background Document (LST ATBD)* (1999), Version 3.3, http://modis.gsfc.nasa.gov/data/atbd/atbd_mod11.pdf
5. J.A. Sobrino, Z.L. Li, M.P. Stoll, and F. Becker, Int. J. Remote. Sens. **17**, No. 11, 2089–2114 (1996).
6. F. Prata, *Land Surface Temperature Measurement from Space: AATSR Algorithm Theoretical Basis Document* (2002), http://earth.esa.int/pub/ESADOC/LST-ATBD.pdf
7. S.V. Afonin, "*Design and application of the atmospheric radiation model for detection of the ocean temperature from space sensing data*," Cand. Phys.-Math. Sci. Dissert., Tomsk, 1987, 192 pp.
8. V.E. Zuev, A.S. Selivanov, V.V. Fomin, A.S. Panfilov, A.V. Romanov, S.V. Afonin, and B.I. Khamarin, Atmos. Oceanic Opt. **1**, No. 11, 76–80 (1988).
9. S.V. Afonin, A.S. Panfilov, A.V. Romanov, A.S. Selivanov, V.V. Fomin, and B.I. Khamarin, SPU Planeta **42**, 33–37 (1993).
10. A.B. Uspenskii and G.I. Shcherbina, Issled. Zemli iz Kosm., No. 5, 102–112 (1996).
11. K. Thome, F. Palluconi, T. Takashima, and K. Masuda, IEEE Trans. Geosci. and Remote Sens. **36**, No. 4, 1199–1211 (1998).
12. F. Palluconi, G. Hoover, R. Alley, M. Jentoft-Nilsen, and T. Thompson, *Algorithm Theoretical Background Document* (1999), Version 3.0, http://eospso.gsfc.nasa.gov/eos_homepage/for_scientists/atbd/viewInstrument.php?instrument=24
13. J.A. Sobrino, J.C. Jiménez-Muñoz, and L. Paolini, Remote Sens. of Environ. **90**, 434–440 (2004).
14. S.V. Afonin, V.V. Belov, and D.V. Solomatov, Atmos. Oceanic Opt. **19**, No. 1, 62–68 (2006).
15. A.A. Lagutin, Yu.A. Nikulin, A.P. Zhukov, A.A. Lagutin, A.N. Reznikov, V.V. Sinitsin, and I.A. Shmakov, Vychisl. Tekn. **12**, No. 2, 67–89 (2007).