Validation of a Web-Based Atmospheric Correction Tool for Single Thermal Band Instruments

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ABSTRACT

An atmospheric correction tool has been developed on a public access web site for the thermal band of the Landsat-5 and Landsat-7 sensors. The Atmospheric Correction Parameter Calculator uses the National Centers for Environmental Prediction (NCEP) modeled atmospheric global profiles interpolated to a particular date, time and location as input. Using MODTRAN radiative transfer code and a suite of integration algorithms, the site-specific atmospheric transmission, and upwelling and downwelling radiances are derived. These calculated parameters can be applied to single band thermal imagery from Landsat-5 Thematic Mapper (TM) or Landsat-7 Enhanced Thematic Mapper Plus (ETM+) to infer an at-surface kinetic temperature for every pixel in the scene.

The derivation of the correction parameters is similar to the methods used by the independent Landsat calibration validation teams at NASA/Jet Propulsion Laboratory and at Rochester Institute of Technology. This paper presents a validation of the Atmospheric Correction Parameter Calculator by comparing the top-of-atmosphere temperatures predicted by the two teams to those predicted by the Calculator. Initial comparisons between the predicted temperatures showed a systematic error of greater then 1.5K in the Calculator results. Modifications to the software have reduced the bias to less then 0.5 ± 0.8K.

Though not expected to perform quite as well globally, the tool provides a single integrated method of calculating atmospheric transmission and upwelling and downwelling radiances that have historically been difficult to derive. Even with the uncertainties in the NCEP model, it is expected that the Calculator should predict atmospheric parameters that allow apparent surface temperatures to be derived within ±2K globally, where the surface emissivity is known and the atmosphere is relatively clear. The Calculator is available at http://atmcorr.gsfc.nasa.gov.

Keywords: Landsat, Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), thermal infrared (TIR), atmospheric correction

1. INTRODUCTION

Since 1984, the systematic collection of Landsat imagery has produced more 60-120m high spatial resolution thermal infrared (TIR) imagery of the Earth's land surfaces than any other satellite system. Yet unlike other Earth observation missions, the Landsat production system does not generate derived physical parameter products, such as sea surface temperature, from the calibrated at-satellite radiance data. The NASA/GSFC Land Cover Satellite Project Science Office has developed a tool to allow the user to generate their own surface temperature products by calculating the effects of the atmosphere for their site.

The Atmospheric Correction Parameter Calculator has been on-line since 2003[1]. Though the ancillary data and methods are well known and used by the Landsat vicarious calibration teams, the automated tool has not been validated up to this point. This paper will discuss the Calculator and the validation of the Calculator over vicarious calibration sites.

1.1 Landsat

The Thematic Mapper (TM) on the Landsat-5 satellite, launched March 1, 1984, and the Enhanced Thematic Mapper Plus (ETM+) on the Landsat-7 satellite, launched April 15, 1999, each have a single 10.5-12.5μm TIR band[2]. Table I

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provides selected features of the thermal bands of the two instruments and the spectral response curves are shown in Figure 1. The calibration of TM thermal data has not been rigorously monitored over its history, though a recent effort has shown data acquired since 1999 may have a bias of –1.0K, though there may be some, as of yet, unresolved dependence on internal instrument temperatures[3]. The ETM+ instrument calibration has been monitored since launch and is calibrated to ±0.6K at 300K[4]. The failure of the Scan Line Corrector (SLC) in 2003 does not appear to have affected the calibration of the thermal band.

Unlike multi-thermal band systems such as AVHRR, ATSR and ASTER, the Landsat instruments, each with a single thermal band, provide no opportunity to inherently correct for atmospheric effects. Ancillary atmospheric data are required to make the correction from Top-of-Atmosphere (TOA) radiance or temperature to surface-leaving radiance or temperature. However, with the long history of calibrated data and the current eight-day repeat cycle between the two instruments, there is strong motivation to use these unique data for absolute temperature studies.

	FWHM (μm)	Spatial Resolution (m)	NEΔT (K at 280K)	Useful Temperature Range (K)
Landsat-5 TM	10.45 - 12.42	120	0.17 - 0.30	min: 230-330 max: 200-340
Landsat-7 ETM+	10.31 - 12.36	60	H: 0.22 L: 0.28	H: 240-320 L: 130-350

TABLE I. Comparison of selected features of the thermal bands of TM and ETM+. Due to the build up of ice on the Landsat-5 dewar window, the Landsat-5 Noise Equivalent Change in Temperature is specified as a range. The Useful Temperature Range is bounded by the sensitivity of the detectors at the minimum NEΔT and the rescaling factors for the geometrically corrected product. Landsat-7 has not exhibited icing, but has two gain states so the same measrures are given separatly for Hihgh (H) nad Low (L) gain settings.

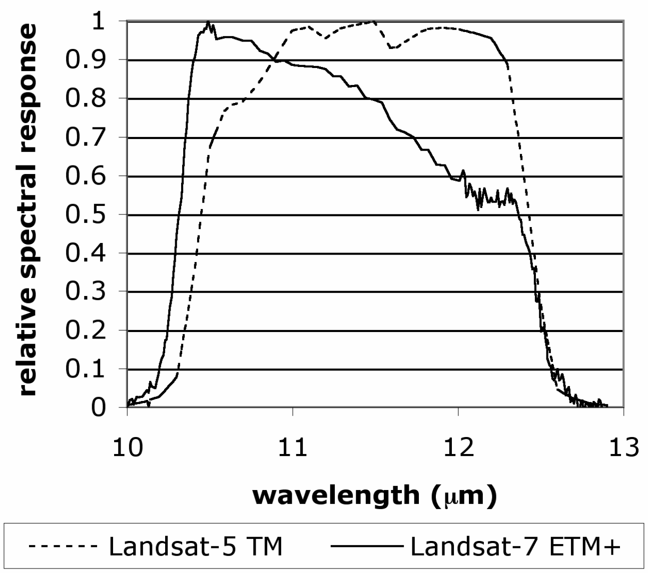


Figure 1. Relative spectral response functions of the Landsat thermal bands.

1.2 Atmospheric Correction

Removing the effects of the atmosphere in the thermal region is the essential step necessary to use the thermal band imagery for absolute temperature studies. The emitted signal leaving a target on the ground is both attenuated and enhanced by the atmosphere. With appropriate knowledge of the atmosphere, a radiative transfer model can be used to estimate the transmission, and upwelling and downwelling radiance. Once these parameters are known, it is possible to convert the space-reaching radiance to a surface-leaving radiance:

$$L_{TOA} = \tau \varepsilon L_T + L_u + \tau(1-\varepsilon)L_d \qquad (1)$$

where τ is the atmospheric transmission; ε is the emissivity of the surface, specific to the target type; L_T is the radiance of a blackbody target of kinetic temperature T; L_u is the upwelling or atmospheric path radiance; L_d is the downwelling or sky radiance; and L_{TOA} is the space-reaching or TOA radiance measured by the instrument. Radiances are in units of $W/m^2 \cdot sr \cdot \mu m$ and the transmission and emissivity are unitless. Radiance to temperature conversions can be made using the Planck equation or the Landsat specific estimate of the Planck curve:

$$T = \frac{k_2}{\ln\left(\frac{k_1}{L_\lambda} + 1\right)} \qquad (2)$$

where T is the temperature in Kelvin; L_λ is spectral radiance in $W/m^2 \cdot sr \cdot \mu m$; and k_1 and k_2 are calibration constants given in Table II.

The radiance measured at the satellite can be converted to a TOA temperature. However, TOA temperature is not a good estimate of surface temperature. Neglecting the atmospheric correction will result in systematic errors in the predicted surface temperature for any given atmosphere. Figure 2 illustrates the errors in surface temperature if no atmospheric correction is made for a series of the vicarious calibration scenes, i.e. if the TOA temperature is used as the surface temperature. For a single day, the temperature will be systematically off, but the error will be different for different days based on the properties of the atmosphere at the overpass time.

2. ATMOSPHERIC CORRECTION PARAMETER CALCULATOR

Traditionally, calculating the atmospheric transmission and upwelling radiance has been difficult and time consuming. The user has to know where to get the atmospheric data, convert it to the proper format for a radiative transfer model and integrate the results over the proper band pass. The Atmospheric Correction Parameter Calculator facilitates this calculation.

2.1 The Web-Based Tool

The Calculator requires a specific date, time and location as input (Figure 3). It outputs the parameters the user will need to convert the satellite radiance to surface radiance. The user has the option to select the TM bandpass, the ETM+ bandpass, or no spectral bandpass, in which case, only the atmospheric profiles are output. Another option allows the user to select how the modeled atmospheric profile is interpolated. If local surface conditions are available, the user can enter them. The local conditions will be used instead of the surface layer predicted by the model, and the lower layers of the atmosphere will be interpolated from 3km above sea level to the surface to remove any discontinuities. A recently added option is the choice between the summer standard atmosphere and the winter standard atmosphere for the upper layers.

The calculated results are emailed to the user and output to the web browser. The emailed file contains not only the integrated transmission and up- and downwelling radiances for the given site, but also all the atmospheric data used to generate the results. In the case where no spectral bandpass is selected, the output is the interpolated atmospheric profiles, for use in a radiative transfer model.

	k_1 [$W/m^2 \cdot sr \cdot \mu m$]	**k_2 [K]**
Landsat-7 ETM+	666.09	1282.71
Landsat-5 TM	607.76	1260.56

TABLE II. THERMAL BAND CALIBRATION CONSTANTS TO CONVERT RADIANCE TO TEMPERATURE

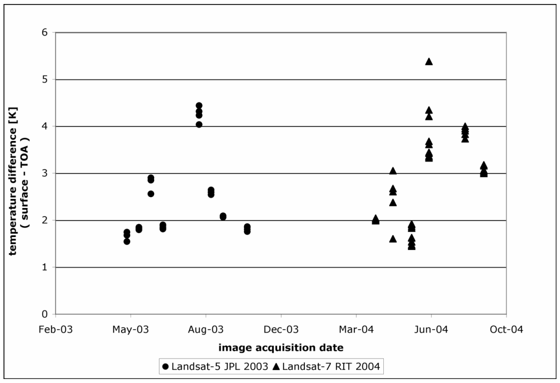
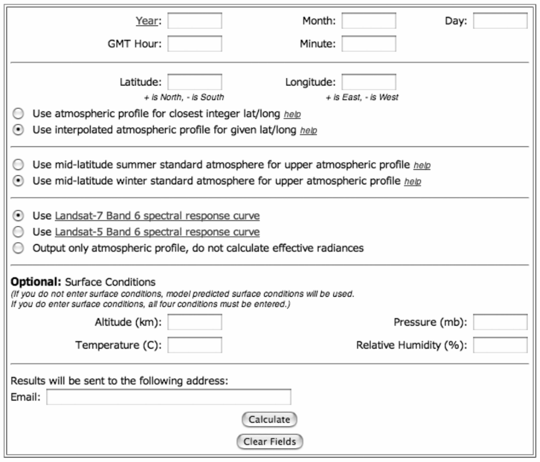


Figure 2. Difference between measured surface temperature and predicted TOA temperature for two years and two sites. If the TOA temperature were used as surface temperature, the temperature estimate would be incorrect by the difference shown here.


Year: ☐ Month: ☐ Day: ☐
GMT Hour: ☐ Minute: ☐

Latitude: ☐ Longitude: ☐
+ is North, - is South + is East, - is West
○ Use atmospheric profile for closest integer lat/long help
● Use interpolated atmospheric profile for given lat/long help

○ Use mid-latitude summer standard atmosphere for upper atmospheric profile help
● Use mid-latitude winter standard atmosphere for upper atmospheric profile help

● Use Landsat-7 Band 6 spectral response curve
○ Use Landsat-5 Band 6 spectral response curve
○ Output only atmospheric profile, do not calculate effective radiances

Optional: Surface Conditions
(If you do not enter surface conditions, model predicted surface conditions will be used. If you do enter surface conditions, all four conditions must be entered.)
Altitude (km): ☐ Pressure (mb): ☐
Temperature (C): ☐ Relative Humidity (%): ☐

Results will be sent to the following address:
Email: ☐

Figure 3. The Atmospheric Correction Parameter Calculator web interface.

The atmospheric profiles are generated by the National Centers for Environmental Prediction (NCEP). They incorporate satellite and surface data to predict a global atmosphere at 28 altitudes. These modeled profiles are sampled on a 1°x1° grid and are generated every six hours, 00:00, 06:00, 12:00, and 18:00 GMT. The Calculator provides two methods of resampling the grid for the specific site input: “Use atmospheric profile for closest integer lat/long” or “Use interpolated atmospheric profile for given lat/long”. The first extracts the grid corner that is closest to the location input for the two time samples bounding the time input and interpolates between the two time samples to the given time (Figure 4a). The second option extracts the profiles for the four grid corners surrounding the location input before and after the time input (Figure 4b). The corner profiles are interpolated for each time, then the resulting time profiles are interpolated resulting in a single profile.

The location and time-specific interpolated profile contains pressure, air temperature and water vapor profiles from the surface to about 30km above sea level. In order to predict space-reaching transmission and upwelling radiance, the radiative transfer code, MODTRAN, requires profiles reaching "space", or 100km above sea level. Either the MODTRAN mid-latitude summer or mid-latitude winter standard atmospheres are extracted from a MODTRAN standard atmosphere and the upper atmospheric layers (~30-100km) pasted onto the site specific interpolated profile. This results in a surface-to-space profile for air temperature, water vapor and pressure.

The completed profile is inserted into a MODTRAN 4.0 input file and processed. The spectral transmission and upwelling radiance are extracted from the MODTRAN output files and integrated over the appropriate instrument's bandpass. The downwelling radiance is generated by running MODTRAN again, placing the sensor 1m above a target with unit reflectance. The surface radiance in the new MODTRAN output file is taken to be the spectral downwelling radiance and is integrated over the instrument bandpass.

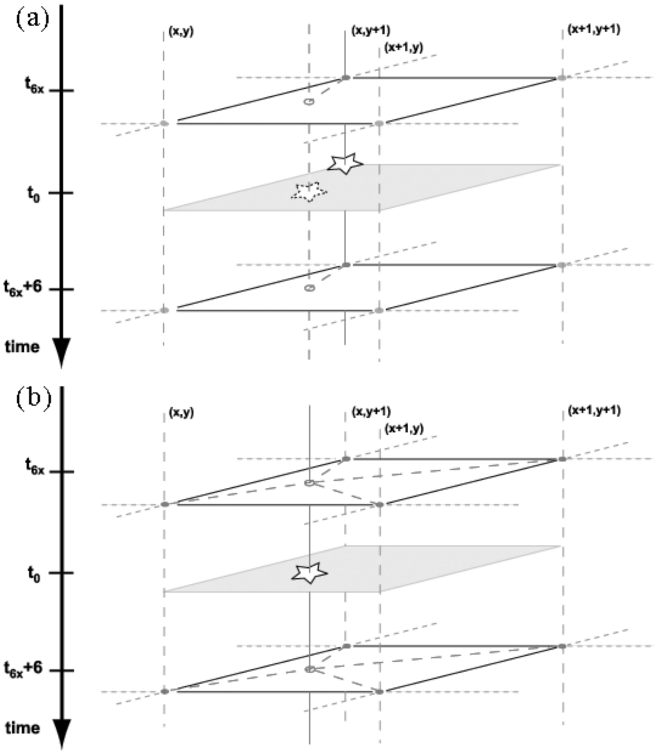


Figure 4. The two interpolation methods. In (a), the profiles are only interpolated in time, In (b), the profiles are interpolated in both space and time.

The resulting integrated transmission, upwelling and downwelling radiance are output to the browser and emailed to the user for use in removing the effects of the atmosphere with Equation (1), where the emissivity is specific to each surface type. The Atmospheric Correction Parameter Calculator is located at http://atmcorr.gsfc.nasa.gov.

2.2 Validation

While techniques the Calculator makes use of have been tested, the Calculator has been in use for several years without validation. The Landsat vicarious calibration teams at NASA/Jet Propulsion Laboratory (JPL) and Rochester Institute of Technology (RIT) have their own versions of an atmospheric correction routine[5,6]. While the Calculator borrows heavily from both the RIT method and the JPL atmospheric data, the results of their algorithms had not previously been compared to those of the web-based Calculator.

JPL has installed an automated buoy system on Lake Tahoe, California. RIT takes ground truth on Lakes Ontario and Erie. Both teams measure the surface temperature or radiance of their target, a large isothermal body of water. Using their atmospheric correction method, they each predict a TOA radiance for their targets. The calibration process involves comparing their predicted TOA radiance to the radiance measured by the Landsat instrument. The two TOA radiances should match, within the error of the process. In the validation of the Atmospheric Correction Parameter Calculator, the Landsat measured radiance is ignored. The TOA predictions of the ground teams are taken as truth.

The dates and locations for two years of vicarious calibration efforts were input into the Calculator. The JPL comparison was made for Landsat-5 2003 data; the RIT comparison for Landsat-7 2004 data. The JPL site is a unique calibration target: the high altitude of Lake Tahoe means the atmosphere is generally clear and the atmospheric path is two kilometers shorter then for surfaces closer to sea level. The lake also is positioned on an integer latitude/longitude

(39/-120) and the Landsat-5 overpass time is at approximately 18:15GMT in 2003, so the Calculator is essentially using a single entry from the NCEP database. The RIT site is closer to what the general user will encounter: it is not on one of the integer latitude/longitude corners (43.26/-77.56) and the Landsat-7 data is acquired at about 15:40GMT in 2004 nearly midway between NCEP time samples.

In the initial validation effort, the data were systematically over corrected, i.e. the TOA temperature was too cold. For JPL, the error was on the order of 1.5K; for RIT, the error was about 2.5K. The large day-to-day variation was corrected for, but a systematic error remained.

An error was found in the calculation of band average transmission. This caused a ~3% error in the estimation of the transmission. The band pass over which the spectral transmission was averaged was too wide; it extended beyond the wavelengths where the instrument was actually sensitive. This was corrected by limiting the average to the wavelengths between the full-width, half maxima of the instrument's spectral response curve. The difference in calculated transmission for the JPL Landsat-5 2003 data was a constant 0.03; for RIT Landsat-7 2004 it was between 0.03 and 0.05. This error appears to have caused most of the error between the TOA temperatures predicted by JPL and RIT and those predicted using the Calculator's parameters. The correction was implemented on June 22, 2005.

There is still a systematic bias between the new Calculator predicted TOA temperatures and those of JPL and RIT, but it is much smaller. Figure 5 and Table III show the difference in TOA predicted temperatures between the JPL or RIT predicted TOA temperature and the Calculator-based TOA predicted temperature (TTOA(AtmCorr)). The average bias is less then -0.5K (Table IV), though after adjusting for the site-specific bias, the RMS for the two sites are different, 0.22K for Lake Tahoe and 0.76K for Lake Ontario. The final three dates from the RIT set all have low transmissions and larger errors. There is some evidence that the NCEP profiles don't work as well when the column water vapor total is above 2.0 cm[7], which may be the problem on the low transmission dates, though this has not been tested in the validation yet. The difference in the RMS error could just be related to the idealized conditions at Lake Tahoe or there could be a difference in the way the two band passes should be treated.

	Image Acquisition Date	**Calculator calculated transmission**	**TOA Temperature Difference (K)**
Landsat-5 JPL 2003	16-May-03	0.94	-0.29
	01-Jun-03	0.91	-0.34
	17-Jun-03	0.88	-0.84
	03-Jul-03	0.94	-0.30
	20-Aug-03	0.75	-0.67
	05-Sep-03	0.89	-0.53
	21-Sep-03	0.94	-0.78
	23-Oct-03	0.94	-0.27
Landsat-7 RIT 2004	11-Apr-04	0.94	-0.44
	04-May-04	0.91	-0.33
	29-May-04	0.92	-0.16
	21-Jun-04	0.78	-1.54
	08-Aug-04	0.74	-0.63
	02-Sep-04	0.67	1.03

TABLE III. CALCULATED DIFFERENCE IN TOA TEMPERATURE (RIT OR JPL-ATMCORR). THE DATES WHEN THE TRANSMISSION IS LESS THEN 0.85 ARE SHADED IN THE TABLE.

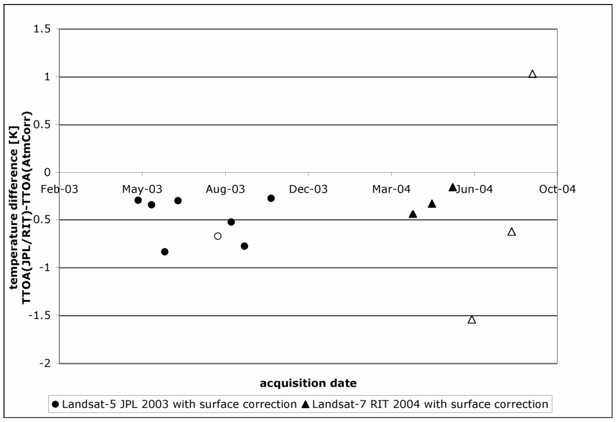


Figure 5. The date-average difference between the JPL or RIT predicted TOA temperature and the Calculator predicted temperature. The dates with transmission less then 0.85 are hollow.

	residual error [K]	**RMS [K]**
Landsat-5 JPL 2003	-0.48	0.22
Landsat-7 RIT 2004	-0.31	0.76

TABLE IV. VALIDATION RESULTS FOR THE TWO SITES

These results presented here were calculated using atmospheres which have been corrected for local surface conditions. Although there was no statistical difference between the TOA temperatures calculated using the model surface conditions and the local surface conditions, it is believed that the local surface conditions should help generate a better prediction. In all of these cases, the model surface was several tenths of kilometers above where the surface actually is, probably due the location of the weather stations. For example, in Rochester, NY, weather is recorded at the airport which is at a higher altitude above sea level then the Lake Ontario shoreline. This lowest portion of the atmosphere is typically the thickest so neglecting even a small amount should affect the prediction of the atmospheric parameters. However, for these dates, although entering the surface conditions did not have obvious benefit, it also did no harm.

Several other minor changes were made during the validation effort:

- The interpolation altitude when surface layers are input was changed from 5km to 3km.
- A sort was added to the atmospheric layers to ensure they were in proper order, lowest to highest altitude. The interpolation of the four corners based on the pressure levels resulted in some cases where the first layer in the profile was not the lowest altitude.

2.3 Limitations

- The Calculator generates parameters for a single point. In some cases, this may be adequate to describe the atmosphere across a whole scene. In others, especially where there is considerable elevation change, more then one run of the Calculator may be necessary to characterize the atmosphere over the scene.
- There is no automatic check for clouds or discontinuities in the interpolated atmosphere. The user should check the profiles contained in the emailed summary file for problems. At present, however, there are no plans to add the ability to modify such a problem atmosphere.
- The user must know the emissivity of the target in order to calculate L_T. A library of spectral emissivities of many target types is available at http://speclib.jpl.nasa.gov.
- NCEP data, in the format currently used, are not available for the entire lifetime of Landsat-7 or Landsat-5. The NCEP holdings include all dates since March 1, 2000.
- The interpolation in time and space is linear. This may not be the most appropriate method for sampling weather fronts or the diurnal heating cycle.

2.4 Future Efforts

- The remaining systematic error needs to be reduced. More validation data, including the RIT Landsat-5 data, can be used to track down the bias. This will also help establish whether the NCEP atmospheres are reliable in wetter conditions.
- The method being used to calculate downwelling radiance should be validated against a full hemisphere ray-trace method.
- The bandpass average transmission should be calculated using the ratio of radiances of targets of different temperatures, rather then band average of the predicted spectral transmission.
- Atmospheric data is available for the entire lifetime of Landsat-5, but it is in a different format. The interface needs to be developed to extract the atmospheric profiles from the file format that is available for those years that are not yet available. With this effort, the tool could be useful for Landsat-4 data as well.

3. CONCLUSIONS

With the abundance of Landsat data now available at low cost and without restrictions on distribution, it is important to make the archive of at-satellite thermal data as usable as possible. The Atmospheric Correction Parameter Calculator provides an automated method to derive atmospheric correction parameters needed for generating surface temperatures. Initial validation efforts revealed a systematic error of greater then 1.5K. Corrections have reduced the bias to less the 0.5 ± 0.8K. Work will continue to remove the remaining bias entirely.

Landsat-5 and Landsat-7 data are available from the USGS National Center for Earth Resources Observation and Science (EROS) at http://earthexplorer.usgs.gov and http://glovis.usgs.gov. The Atmospheric Correction Parameter Calculator is available at http://atmcorr.gsfc.nasa.gov.

ACKNOWLEDGEMENTS

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