due July 6, 04

Spectral Cloud-filtering of AIRS Data: Non-Polar Ocean[1]

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ABSTRACT

The Atmospheric Infrared Sounder (AIRS) is a grating array spectrometer which covers the thermal infrared spectral range between 640 and 1700 cm^{-1}. In order to retain the maximum radiometric accuracy of the AIRS data, the effects of cloud contamination have to be minimized. We discuss cloud filtering which uses the high spectral resolution of AIRS to identify about 100,000 of 500,000 non-polar ocean spectra per day as relatively "cloud-free". Based on the comparison of surface channels with the NCEP provided global real time sst (rtg.sst), AIRS surface sensitive channels have a cold bias ranging from 0.5K during the day to 0.8K during the night. Day and night spatial coherence tests show that the cold bias is due to cloud contamination. During the day the cloud contamination is due to a 2-3% broken cloud cover at the 1-2 km altitude, characteristic of low stratus clouds. The cloud-contamination effects surface sensitive channels only. Cloud contamination can be reduced to 0.2K by combining the spectral filter with a spatial coherence threshold, but the yield drops to 16,000 spectra per day. AIRS was launched in May 2002 on the Earth Observing System (EOS) Aqua satellite. Since September 2002 it has returned 4 million spectra of the globe each day.

Key Words: Infrared, temperature retrieval, remote sensing, ozone, carbon dioxide, cloud filter

1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) is a grating spectrometer on the EOS Aqua satellite, which was launched in May 2002 (Aumann et al 2003). AIRS covers the 650-2700 cm^{-1} region of the spectrum using 2378 channels with $\lambda/\Delta\lambda$=1200 spectral resolution. Since September 2002 AIRS has produced 4 million spectra of the globe each day. The absolute radiometric accuracy based on pre-launch testing of AIRS is 0.2K (Pagano et al. 2003). Like all infrared sounders, AIRS is sensitive to the presence of clouds. In order to retain the maximum radiometric accuracy of the AIRS spectra, the effects of clouds have to be eliminated. In principle this can be done by cloud-clearing or cloud-filtering. In cloud-clearing the effects of clouds are theoretically eliminated using the combined information from AIRS infrared channels and Advanced Microwave Sounding Unit (AMSU) channels (Susskind et al. 2003). In cloud-filtering the effects of clouds are detected by a cloud-screening algorithm and those spectra which are cloud-contaminated above some threshold are rejected.

Cloud screening has historically been done by a spatial coherence test and radiometric tests which includes some knowledge of the surface temperature from climatology or the forecast. The spatial coherence test is based on the assumption that temperature gradients between adjacent footprints are much smaller than gradients introduces by difference in cloud-cover between adjacent footprints (Coakley, J.A. and F.P. Bretherton 1982). This works well for high (cold) clouds over ocean. Broken low stratus clouds, with cloud tops 6-15K colder than the surface temperatures, are much more difficult to detect. If cloud-contamination is to be eliminated to a level below the instrument radiometric accuracy of 0.2K, the spatial coherence threshold has to be set very low. The ultimate limit to the threshold is the noise level of the channel used in the coherence test. In the following we discuss a cloud filter which makes use of the high spectral information content of AIRS. Results are compare for the filter alone (single spectrum) and in combination with a spatial coherence filter (spatially adjacent spectra) using day and night observations of the non-polar oceans between +/-50 degree latitude.

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[1] SPIE 49th Annual Meeting on Optical Science and Technology 2-6 August 2004, Denver Colorado Paper number 5548-42 (16 June 04 draft)

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2. APPROACH

AIRS measures the upwelling radiance between 650 cm^{-1} and 2700 cm^{-1} in 2378 spectral channels in 13.5km (footprints (at nadir). AIRS also includes four visible/near IR channels for diagnostic purposes: vis1 (0.4-0.44 microns), vis2 (AVHRR1), vis3 (AVHRR2) and vis4 (0.4-1.0 micron), which measure the reflected light in 4 (8x9) arrays centered on the AIRS IR footprint. A typical tropical ocean spectrum is shown in Figure1. Eight of the 2378 spectral channels (gray dots in Figure 1) are used for spectral cloud filtering.

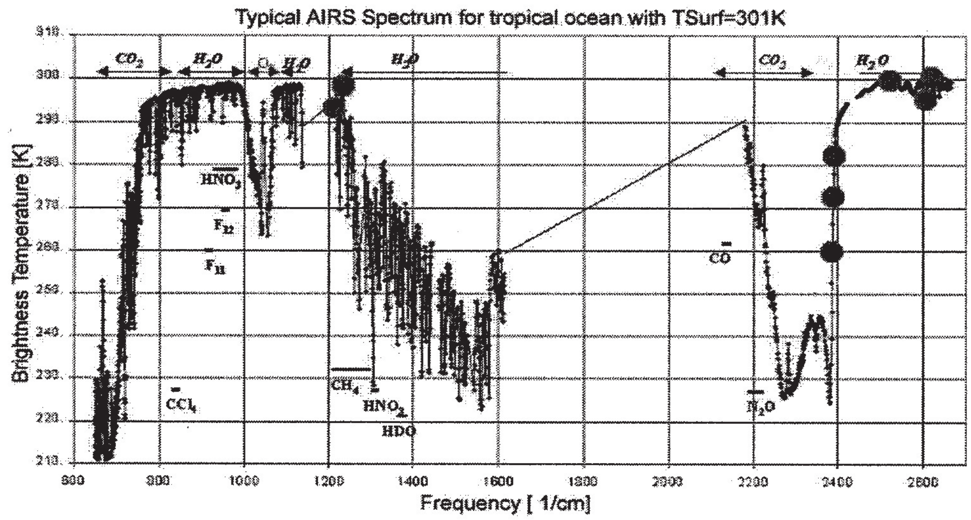

Figure 1. The spectral cloud filter uses 8 of the 2378 AIRS channels

Table 1. summarizes information about these eight channels. The approximate frequency is encoded in the name of the brightness temperature measured by the channel. The noise equivalent delta temperature (NEDT) is with respect to the typical brightness temperature observed for tropical ocean. Micro-windows are channels where the transmission to the surface is almost unobstructed by water or CO2 lines. The best micro-window is at 2616 cm^{-1}, where the atmospheric attenuation is only 0.3K.

Table 1. name	PGE number	Frequency cm^{-1}	TB typical brightness temperature tropical ocean	NEDT at brightness temperature TB	TSurf - brightness temperature
bt2616	2333	2616.38	298.9K	0.07K	0.3K
bt2607	2325	2607.89	295.1K	0.07K	4.2K
bt2508	2204	2508.11	297.8K	0.06K	1.4K
bt2392	2113	2392.07	281.0K	0.05K	18.6K
bt2390	2111	2390.11	271.7K	0.06K	27.9K
bt2388	2109	2399.15	259.2K	0.09K	40.5K
bt1231	1291	1231.33	296.4K	0.06K	2.4K
bt1228	1285	1228.23	294.4K	0.07K	4.7K

The spectral tests combine the use of micro-windows, the leverage of the Planck function and the co2 R-branch channels between 2385 and 2407 cm^{-1}. The tests take advantage of the high spectral resolution of AIRS and the very high sensitivity (small NEDT) of the selected channels.

Key to the cloud filter is the knowledge of the apparent skin surface temperature measured in the presence of clouds, sst2616. We derive sst2616c6 from the best of the infrared window channel at 2616 cm-1, corrected for water vapor using bt2607. The atmospheric transmission correction , and emissivity corrections are based on first principles (Aumann, Chahine and Barron 2003). The 2616 cm-1 channel is sensitive to solar reflected light and can only be used at night. During the day we use the 1231 cm-1 window channel, corrected for water vapor using the 1227 cm-1 channel, sst1231r3. (The "c6" and "r5" codes refer to version numbers). The sst1231r5 was derived by tuning the output to the sst2616c6 solution for a large set of cloud-free footprints at night, using regression. Given sst2616c6 and/or sst1231r5, we can define the cloud filter figure of merit: d2616=sst2616c6-rtg.sst ay night, and d1231=sst1231r5-rtg.sst during the day, where rtg.sst is the real time global sst generated on an operational basis in support of data assimilation by NOAA NCEP (Thiebaux et al. 2002). The rtg.sst is technically a short term forecast, which integrates data from the drifting buoy network in the GCM. Based on the daily quality control results published by NCEP, rtg.sst tracks the buoy network with a global bias of less than 0.1K and a rms of 0.45K

There are three spectral tests:

1) The d2392 test is the most powerful of the spectral tests: The gradient measured by the mid-tropospheric co2 R-branch channels bt2388, bt2390 and bt2392 can be extrapolated to the surface to estimate the surface air temperature, TSurf.air. This estimate is insensitive to clouds below 600mb. Except under the most unusual conditions, TSurf.air (over ocean) is within two degrees of the surface skin temperature. Define d2392=TSurf.air-sst, where sst equals sst2616 or sst1231. Under cloud-free conditions the distribution of d2392 has zero mean with 0.5K rms. In the presence of clouds the calculated value of the sst is much colder than TSurf.air. This will be illustrated in Figure 1. Spectra with d2392>-2 pass this test.

2) The q2 test: For certain types of low clouds the temperature contrast between the surface and the cloud tops is so small that it is not detected by the d2392 test. This is typical for a broken cover of low stratus and strong surface inversions. The quantity q2=bt2616-bt2607 is proportional to the moisture in the lower troposphere. Under tropical conditions q2 is of the order of 4K. In the presence of low inversions and low stratus clouds q2 becomes very small and is often several degrees negative. Spectra with q2>0.1K pass this test.

3) The d12 test makes use of non-linearity of the Planck function. It compares the observed (bt2616-bt1231) to the predicted after correcting for water vapor using (bt1231-bt1227), i.e. d12=(bt2616-bt1231)(observed-predicted). Under cloud-free conditions at night the statistical distribution of d12 has a mean of zero with an rms of 0.2K. Due to the non-linearity of the Planck function bt1231 becomes colder in the presence of clouds faster than bt2616, i.e. d12 shifts from zero to positive values. In order to handle the sun reflected light there is a night version and a day version of the test. For the night versions spectra with abs(d12)<0.5K pass the test. The day version corrects the d12 threshold for solar reflected light, which is estimated from the slant path corrected difference between bt2616 and bt2508, g5n. During day time d12<g5n passes the test. Typically gn5 is between 1.2K and 3 K.

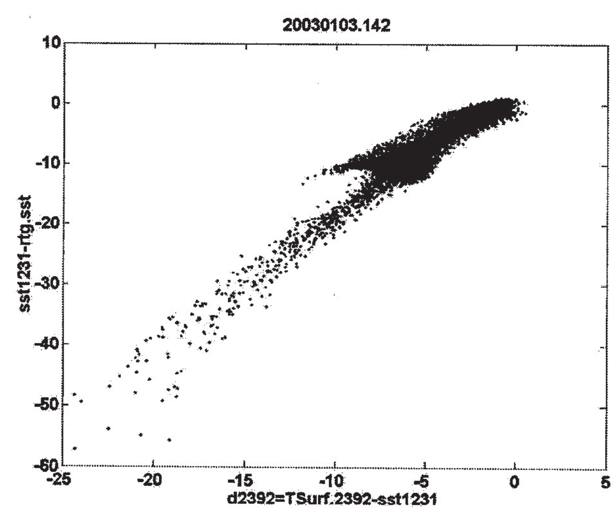

Figure 2. The correlation between sst1231-rtg.sst and d2392 can be used to identify cloud contaminated footprints.

3. RESULTS

We first illustrate the spectral cloud filtering using data from a single day time granule. An AIRS data granule corresponds to the data gathered in 6 minutes and corresponds to 12150 spectra in an area of about 2400 x 2400 km. We selected granule 142 from 3 January 2003, located on the equator near zero longitude in the middle of the tropical Atlantic ocean. This granule is from an ascending orbit, i.e. day time. Figure 2. shows d1231 as function of d2392 for all 12150 spectra in the granule. Of the 12150 spectra in the granule, 4681 spectra, pass the spectral clear tests, d2392>-2, and are "d2392 clear". The median of these points is -0.59K with standard deviation, std68, 0.68K.

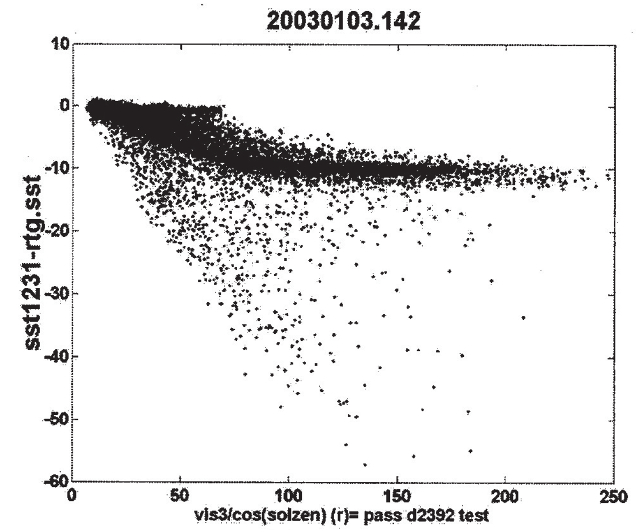

Figure 3. d1231 versus vis3c for all points in granule 142 shows the correlation between cold bias and cloud contamination.

Granule 142 is a day time granule. This allows us to use AIRS vis3 to diagnose where the cold bias relative to the rtg.sst is coming from. In order to correct approximately for the Sun zenith angle, solzen, we define vis3c=vis3m/cos(solzen), where vis3m is the mean signal measured by the 72 pixels which cover the AIRS footprint. Figure 3. shows d1231 vers. vis3c for all points in the granule. Under tropical conditions vis3c values range from vis3c=4 watt/m2 micron sr to vis3c=250. The lowest values of vis3c = 4 correspond to calm (dark) ocean cloud-free, while the brightest values near 250 correspond to full overcast. Figure 3. shows a strong correlation between increasing vis3c and increasing d1231. The points which pass the d2392 test are shown in gray. The d2392>-2 threshold eliminates all obvious cloud contamination (d1231<-2K) encountered in this granule. It can be seen that a significant number of spectra with sst1231 within 2K of the rtg.sst pass the d2392 test, but have vis3c as large as 50. Since 250 corresponds to full overcast, vis3c=50 corresponds to 20% overcast with cloud very close to the surface.

b) One day results: In order to evaluate the cloud filter on a global scale, we use day (ascending) and night (descending) ocean data from 30 November 2003. The choice of days is somewhat arbitrary and has no bearing on the conclusions. Ascending and descending orbits (day and night time) have different area coverage, so there is no one-on-one correspondence between footprints which passed the clear test during the day and those which passed at night. Table 2. summarizes results for the night data. Of all night ocean spectra within +/- 50 degree latitude, 25% pass the spectral test. The figure of merit for both d2616 and d1231 agree within 0.1K. Both show a cold bias relative to the rtg.sst[2] of 0.8K. Entries for sst1231r3-rtgsst in Table 2, column three, show that cold bias in sst2616c6 and sst1231r5 agrees within 0.1K.

Table 2. Night clear spectra	d2616= sst2616c6-rtgsst*	d1231= sst1231r3-rtgsst*	number	percent
all data			566347	100%
spectral filter only	-0.81+/-0.84K	-0.87+/-1.10K	140824	24.9%
spectral and sc2616<1K	-0.44+/-0.57K	-0.38+/-0.65K	31472	5.5%
spectral and sc2616<0.5K	-0.29+/-0.51K	-0.18+/-0.57K	9606	1.7%
rtgsst* =rtgsst-0.35K to correct for night/skin bias				

While the identification of spectra as "cloud-free" with a cold bias of 0.8K in surface sensitive channels may be adequate for some purposes, it is out-of-line with the 0.2K absolute calibration accuracy of AIRS. In row three and four of Table 2. we illustrates the effect of adding a spatial coherence test to the spectral

[2] The rtg.sst is a day night average of the bulk temperature, while sst2616 and sst1231 refers to the skin temperature. This causes the rtg.sst at night to be on average 0.35K warmer than the skin temperature, while it reads essentially the skin temperature during the day. The numbers shown in Tables 1. and 2. have been corrected by this amount.

test. The spatial coherence test parameter sc2616 measures the difference between the maximum and the minimum bt2616 in a 3x3 footprint pattern centered on the footprint under evaluation. For spectra identified as cloud-free by the spectral tests alone, sc2616 can be as large as 50K.
From Table 2. it can be seen that the cold bias decreases from 0.8K to 0.4K to 0.2K as sc2616 decreases from 1K to 0.5K. at the same time the yield of "cloud free" spectra decreases from 25% to 5% to 2%. The value of sc2616 is theoretically limited by the detector noise to 0.1, but produces essentially zero yield.

Table 3. Comparison of day and night data	day orbits	night orbits
Total non-polar ocean spectra	588367	566347
(d2392>-2) (d12<3) (g5n<3 day filter	113668	
(d2392>-2) (|d12|<0.5) (g5n<3) night filter		140824
percent of total	19.3%	24.9%
(sst1231-rtg.sst) +/- stdev	-0.51 +/- 0.88K	-0.87+/-0.89K**
vis3c [watt/m2 micron sr]	11.3	
(d2392 >-2) (d12<3) g5n sc2616<0.5K day	7876	
(d2392 >-2) (d12<0.5) g5n sc2616<0.5K day		9606
percent of total	1.3%	1.7%
bias(sst1231-rtg.sst) +/- stdev	-0.17 +/-0.58K	-0.18+/-0.57K**
vis3c [watt/m2 micron sr]	8.0	
** corrected for the 0.35K day/night and skin bias of the rtg.sst.		

Table 3. summarizes day and night results for spectra filtering without and with spatial coherence filtering. When the spatial coherence test is added the cold bias decreases from 0.51K to 0.17K, while at the same time the yield decreases from 11% to 1.3%. Table 3. shows that the average vis3c signal decreases from 11.3 to 8.0 while going from spectral filtering alone to the spectra and spatial filtering.

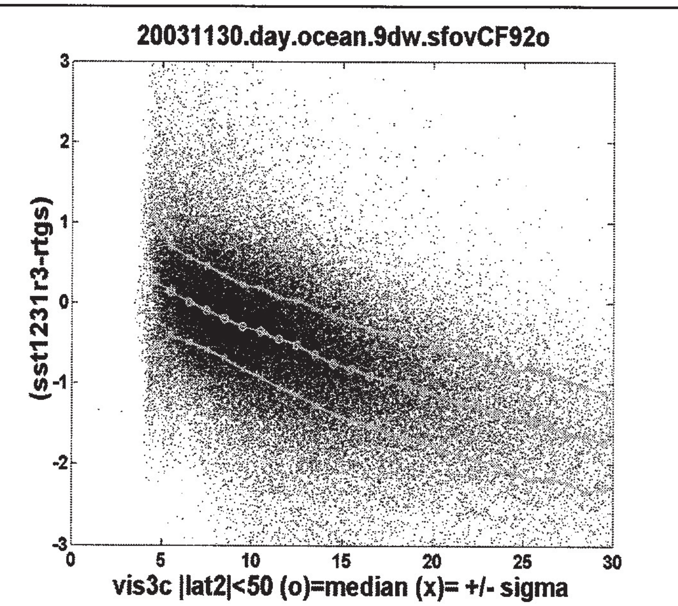

Figure 4 shows d1231 for the day data as function of vis3c for the 113668 spectra which passed the spectral test.

In Figure 3. we saw the correlation between vis3c and d1231 for all data in a granule.
Figure 4. shows the correlation between vis3c and the cold bias for the 113668 spectra which passed the spectral cloud filter for ocean data from the ascending orbits.

Superimposed on the scatter plot is the median and +/- 1 sigma population in equal width slices of vis3c. There is a linear correlation between vis3c and the cold bias in sst1231r5-rtg.sst. The number of points available in one day with vis3c=5 is statistically significant and corresponds to d1231=0.05K. For the darkest value for cloud-free ocean, vis3c=4, d1231 is approximately +0.2K, but is statistically weak, as seen by the divergence of the +/- 1 sigma boundaries in the scatter diagram.

The mean vis3c is directly related to the fractional cloud cover in the AIRS footprint. Given that full overcast corresponds to vis3c=250, dark ocean corresponds to vis3c=4, and the median(vis3s)=11.3, the estimated fractional cloud cover for the spectral filtered case is (11.3-4)/250=0.029. For the combined spectral and spatial filtering, median(vis3)=8.0, corresponding to a fractional cloud of 0.016. If the vis3 clouds are optically thick in the IR, then the 0.17K cold bias corresponds to a cloud top temperature which is 17K colder than the surface. This cloud top temperature points to thin scattered stratus clouds at 1-2 km above the surface.

4. DISCUSSION

1) Using data from one day, between 19% and 25% of the spectra are passed as clear by the spectral tests alone. For spectral filtered data the yield is good, but the bias of 0.5K and 0.8K day/night for the surface sensitive channels is considerably larger than the AIRS absolute radiometric accuracy of 0.2K. The cold bias and the yield were larger at night than during the day, suggesting that the spectral filter alone has more difficulty identifying night clouds than day clouds. Since the cloud contamination comes from a very low cloud layer, AIRS channels which peak significantly above these clouds suffer much less degradation.

2) In order to decrease cloud contamination below 0.5K, spectral filtering has to be augmented by some form of a spatial coherence test. The lowest usable coherence threshold for AIRS, 0.5K, set by the desire to have no less than about 1% yield, not by the measurement noise of the AIRS channel used for the spatial coherence test. With the 0.5K threshold day and night data have comparable cold bias of about 0.2K and a comparable low yield of only 1-2%. For the analysis of trends and global maps on monthly time scales this yield is acceptable, since it still produces over 200,000 points per month for day and night global analysis.

3) As a spatial coherence requirement is added to the spectral test, the bias of the AIRS calculated sst relative to the rtg.sst <u>and</u> the standard deviation decrease, from about 1K to 0.5K: The more certain we are that the data are cloud free, the better the AIRS derived sst agrees with the rtgsst for both the bias and the standard deviation. Since sst2616c6 was derived totally from first principles, this is a tribute to the AIRS radiometric calibration, the radiative transfer used in the derivation of the atmospheric correction and to the skill in the rtg.sst product.

4) As vis3c approaches the dark ocean limit during the day, the bias of the AIRS derived sst relative to to the rtg.sst is within 0.2K of zero. This is consistent with the claimed absolute radiometric accuracy based on pre-launch testing (Pagano et al. 2003), any likely bias between the rtg.sst and the true temperature during the day selected for the test, and the statistical correction from bulk to skin temperature and day/night bias. Work is in progress using "cloud-free" data from one month, i.e. 30 times more data, to evaluate the bias as the spatial coherence approaches zero and vis3c approaches 4.

5) We estimated a 2.9% cloud cover with cloud tops 17K colder than the surface, i.e. about 2 km altitude, for the spectra passed as "cloud-free" from the data . For granule 142 from 3 January 2003 we would get 9% cloud cover with the cloud tops 7K colder than the surface. There is a large variability in the correlation between d1231 and vis3c related to local cloud conditions. Full overcast at the surface (ground fog) would have the cloud top temperature equal the surface temperature, resulting in a very large vis3c signal and virtually no cold bias in the thermal infrared. The clean correlation between vis3c and d1231 shows that this type of cloud is not common over non-polar ocean.

5. CONCLUSIONS

In order to make full use of the absolute radiometric precision of the AIRS data, cold bias due to clouds has to be minimized. The high spectral resolution of AIRS can be used to design spectral cloud filters. A spectral cloud filter is described which has a yield ranging from 15-25 percent, but has a residual cold bias of the order of 0.5K during the day, 0.8K at night, for surface sensitive channels. The bias is due to cloud contamination. For day time data the correlation between the cold bias and the reflected light in the 0.75 to 0.95 micron AIRS vis3 channel indicates 3% scattered cloud cover about 2km above the surface. If the spectral cloud filter is combined with a spatial coherence filter with a 0.5K threshold, the residual cold bias drops to about 0.2K, and the yield of "cloud-free" spectra drops from 15-25% to 1-2% of the data.

In the limit of a perfect spatial coherence filter and for a perfect vis3 filter, the bias relative to the rtg.sst is consistent with 0.2K absolute radiometric accuracy claimed for AIRS.

ACKNOWLEDGEMENTS

This work was carried out at California Institute of Technology, Jet Propulsion Laboratory, funded under NASA contract and sponsored by NASA HQ code Y. The excellent radiometric performance of AIRS would not achieved without the dedication of the calibration teams at JPL and BAE.

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