Earth as an Exoplanet. I. Time Variable Thermal Emission Using Spatially Resolved Moderate Imaging Spectroradiometer Data

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Abstract

Among the more than 4000 exoplanets known today, some terrestrial planets have been detected in the so-called habitable zone of their host stars and their number is expected to increase in the near future, energizing a drive to understand and interpret the eagerly awaited wealth of data to identify signs of life beyond our solar system. So far, Earth remains the best and only example of a habitable (and inhabited) world. Although, it seems extremely unlikely that any other exoplanets will be true Earth twins, it is important to explore and understand the full range of spectral signatures and variability of Earth in order to inform the design of future instruments and missions, and understand their diagnostic power as well as potential limitations. In this work we use Earth observation data collected by the MODIS instrument aboard the Aqua satellite. The complete data set comprises 15 years of thermal emission observations in the 3.66–14.40 \( \mu \text{m} \) range for five different locations on Earth (Amazon Rainforest, Antarctica, Arctic, Indian Ocean, and the Sahara Desert). We then determine flux levels and variations as a function of wavelength and surface type (i.e., climate zone and surface thermal properties) and investigate whether periodic signals indicating Earth’s tilted rotation axis can be detected. Our findings suggest that (1) viewing geometry plays an important role when thermal emission data is analyzed as Earth’s spectrum varies by a factor of three and more depending on the dominant surface type underneath; (2) typically strong absorption bands from CO\textsubscript{2} (15 \( \mu \text{m} \)) and O\textsubscript{3} (9.65 \( \mu \text{m} \)) are significantly less pronounced and partially absent in data from the polar regions implying that estimating correct abundance levels for these molecules might be challenging in these cases; and (3) the time-resolved thermal emission spectrum encodes information about seasons/planetary obliquity, but the significance depends on the viewing geometry and spectral band considered.

1. Introduction

Since the first detection of an exoplanet around a Sun-like star in 1995 (Mayor & Queloz 1995), the research field of exoplanets has grown rapidly. As of today, 25 years after the first discovery, there are over 4000 confirmed exoplanets in more than 3000 planetary systems (Alei et al. 2020). Among these discoveries, some terrestrial planets have already been found orbiting in the so-called habitable zone (HZ) of their host stars such as planets e, f, and g in the TRAPPIST-1 system, LHS 1140 b, Proxima Centauri b, Kepler-442b, or TOI-700d (Montet et al. 2015; Anglada-Escudé et al. 2016; Dittmann et al. 2017; Gillon et al. 2017; Gilbert et al. 2020). In the future, their number is expected to increase further, primarily thanks to dedicated missions such as the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) and PLAnetary Transits and Oscillations of stars (PLATO; Rauer et al. 2014) and ongoing or upcoming radial velocity surveys such as Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs (CARMENES; Quirrenbach et al. 2014) or EXtreme PREcision Spectrograph (EXRES; Jurgenson et al. 2016) and High Accuracy Radial Velocity Planet Searcher 3 (HARPS3; Young et al. 2018).

The long-run goal is the characterization of the atmospheres of temperate terrestrial exoplanets in order to assess their habitability and search for indications of biological activity. With the aim of detecting Earth analogs around other stars, a particularly interesting class of exoplanets will be terrestrial planets with thin N\textsubscript{2}–H\textsubscript{2}O–CO\textsubscript{2} atmospheres that orbit within the HZ of their host stars. Characterizing these planets and searching for traces of life requires the direct detection of their signal. The first space telescope capable of detecting potential atmospheres of terrestrial exoplanets is expected to be the James Webb Space Telescope (e.g., Morley et al. 2017; Krissansen-Totton et al. 2018; Tremblay et al. 2020), which is scheduled to launch in 2021. From the ground, the 30–40 m Extremely Large Telescopes may provide us with the first images and high-resolution spectroscopy data of a few terrestrial exoplanets, once they are online in the mid- to late 2020s (e.g., Quanz et al. 2015; Snellen et al. 2015). However, none of the currently planned missions or projects are capable of detecting and characterizing the atmospheres of a statistically meaningful sample of temperate, rocky exoplanets, and the exoplanet community has to wait for future missions like the Habitable Exoplanet Observatory (HabEx; Gaudi et al. 2020), Large Ultraviolet Optical Infrared Surveyor (LUVOIR; the LUVOIR Team 2019), or Large Interferometer For Exoplanets (LIFE; Quanz et al. 2018).

For the time being, Earth remains the best—and only—example of a truly habitable and inhabited world, offering a unique opportunity to study the remote characterization of potential habitability. Despite the vast diversity of exoplanets (e.g., Batalha 2014; Burke et al. 2015) and the significant changes in the spectral appearance of Earth over the past 4.5 Gyr (e.g., Kasting & Catling 2003; Kaltenegger et al. 2007; Meadows 2008; Arney et al. 2016; Reinhard et al. 2017; Rugheimer & Kaltenegger 2018), it seems unlikely that any
other exoplanet will be a true Earth twin. Nevertheless, it is still useful to explore and understand the full range of spectral signatures and variability of Earth (e.g., due to the presence of oceans, clouds, surface inhomogeneities, or polar caps) in order to fine tune the design of future instruments and missions and understand their diagnostic power as well as potential limitations.

A key challenge arises from the fact that we will observe exoplanets from distances of—typically—at least several parsecs so that even with the most powerful telescopes conceived today they will remain spatially unresolved point sources. So, ideally, in order to study Earth as an exoplanet disk-integrated data should be used. However, such data taken from a remote vantage point and showing the entire disk are limited as they are only obtained from a handful of spacecraft sources. So, ideally, in order to study Earth as an exoplanet this is the longest continuously recorded time baseline from one satellite constellation using the same instrument for investigating Earth’s thermal emission in the context of exoplanet science.

2. Methods

2.1. Locations and Surface Types

In order to investigate the thermal emission and time variability of Earth, we have focused on specific surface types with different thermal properties and from different climate zones that represent our planet’s appearance from afar. Although Earth shows a wide variety of surface characteristics, on large scales it is dominated by oceans, deserts, ice, and vegetation. In addition, clouds are also typically covering ~67% (King et al. 2013) of Earth. A comprehensive review about clouds and their effects on Earth’s climate can be found in Kondratyev (1999) and references therein. In this paper we examine the following five locations: (1) Amazon Rainforest, (2) Antarctica, (3) Arctic, (4) Indian Ocean, and (5) Sahara Desert, as shown in Figure 1. For every location we also investigate the difference in thermal emission between day and night.

The patch for the Sahara Desert covers the area between 10–30° N latitude and 0–30° E longitude. The time when the satellite was above this region varied over the 15 year period between 12:05–12:45 UTC and 01:00–02:00 UTC for the day and night measurements, respectively. The patches for the Amazon Rainforest were taken between 17:25 UTC–18:05 UTC and 05:10 UTC–05:40 UTC. For the Indian Ocean, we analyzed a patch lying below the equator between ~10 and ~25° S latitude and 65–90° E longitude. Here the time varied between 08:15–08:40 UTC for the day and 20:00–20:20 UTC for the night measurement. For the Arctic and Antarctica, the satellite was above the target regions between 06:00–10:35 UTC and 16:30–18:55 UTC, respectively. Due to Earth’s axial tilt the two polar data sets naturally include day and night measurements.

To ensure that single-surface-type measurements are consistent over the full time baseline, some patches had to be cut as described in Section 2.2. Since we are interested in how Earth’s appearance varies over time, we do not specifically select or deselect any data frames that are dominated by clouds. Instead, the cloud-induced variability in Earth’s thermal emission is implicitly included in the analyses.

In order to interpret our analyses in the context of exoplanet science we assume (1) that for an exoplanet the surface types investigated here are dominating the hemisphere that is observed, and (2), related to this, that the integration time in order to collect the exoplanet data is short compared to the
rotation period of the planet so that smearing effects, i.e., the mixing of various surface types, are negligible.

2.2. Data Retrieval and Processing

We used data collected by MODIS, a cross-track, multi-disciplinary scanning radiometer with a total of 36 spectral channels measuring visible and infrared bands in the wavelength range of 0.4–14.4 μm. Approximately 40 data products are produced from the MODIS data with horizontal spatial resolutions at nadir of 250, 500, and 1000 m, providing the most detailed spatial information of all instruments aboard the Aqua satellite (Parkinson 2003). The instrument employs a conventional imaging spectroradiometer concept, consisting of a cross-track scan mirror and collecting optics, and a set of linear arrays with spectral interference filters located in four focal planes. The optical arrangement provides high radiometric sensitivity (12 bit) imagery throughout the channels. With a temporal resolution of 5 minutes, MODIS achieves a maximum swath of 2330 km by 2030 km at the equator due to a ±55° scanning pattern. This leads to low-latitude data gaps between successive orbits, preventing full global daytime or nighttime coverage within a day. Although these data gaps are filled in on subsequent days, the full global coverage is obtainable every two days. However, due to Aqua’s operation height of 705 km and due to its Sun-synchronous, near-polar and circular orbit, it revolves Earth in 99 minutes with a repeat cycle of 16 days. Therefore, our target locations were monitored twice per month, resulting in 360 data points per location after 15 years of observation.

We investigated the calibrated at-aperture radiance for 16 thermal channels (see Table 1) with a spatial resolution of 1000 m that were measured twice per month between 2003 January and 2017 December. The data originate from a Level-1B product called MODIS/Aqua Calibrated Radiances 5-Min L1B Swath 1km (MYD021KM) collection number 6.1 (LAADS DAAC), which was accessed over NASA’s EARTHDATA Engine.

| Table 1
| Summary of All Thermal Channels of MODIS |
| Primary Use | Channel | Bandwidth (μm) |
|-------------|---------|----------------|
| Surface/Cloud Temperature | 20 | 3.660–3.840 |
| | 21 | 3.929–3.989 |
| | 22 | 3.929–3.989 |
| | 23 | 4.020–4.080 |
| Atmospheric Temperature | 24 | 4.433–4.498 |
| | 25 | 4.482–4.549 |
| Cirrus Clouds/Water Vapor | 27 | 6.535–6.895 |
| | 28 | 7.175–7.475 |
| Cloud Properties | 29 | 8.400–8.700 |
| Ozone | 30 | 9.580–9.880 |
| Surface/Cloud Temperature | 31 | 10.780–11.280 |
| | 32 | 11.770–12.270 |
| Cloud Top Altitude | 33 | 13.185–13.485 |
| | 34 | 13.485–13.785 |
| | 35 | 13.785–14.085 |
| | 36 | 14.085–14.385 |

Note. Channel 26 covers the 1.360–1.390 μm range and does not probe Earth’s thermal emission. Therefore, it is not listed below. Taken from https://modis.gsfc.nasa.gov/about/design.php.

After downloading the corresponding data from the servers, the files were read and the band specific scaled integers (SI_B) were converted into spectral radiances (L_B) with physical units of W m⁻² μm⁻¹ sr⁻¹ according to Equation (1) (MODIS User Guide 2017),

\[ L_B = \Gamma_B (SI_B - \Theta_B), \] (1)

where \( \Gamma_B \) and \( \Theta_B \) refer to radiance scales and radiance offsets for a specific band \( B \), respectively, which are computed inside Level-1B products and are written as attributes to the scientific data sets. In the MYD021KM Level-1B product, the radiance measured in each channel were generated in 32 bit floating-point format and scaled to a range of [0, 32767]. Any value larger than 32,767 represents invalid or unusable data and was removed from the data sets.

3 https://doi.org/10.5067/MODIS/MYD021KM.061
4 https://search.earthdata.nasa.gov
The first iteration through this process revealed that in some years the patches of the selected locations were slightly drifting. These drifts are caused by orbital maneuvers which are well known (e.g., Lin et al. 2019). In order to solve this issue we had to custom clip the concerning patches to show the exact same location for each passage. While only a few frames of the Sahara Desert had to be slightly cut, an effort was made to cut the two polar regions patches in a way that the geographical pole lies in the center. As a result, roughly 50% of the Arctic patch had to be clipped to just show the polar cap, thus, instead of having the usual 1354 by 2030 pixels the scene is composed of 600 by 2030 pixels. None of the Amazon Rainforest or Indian Ocean patches had to be cut as they all showed scenes composed of vegetation and water (and clouds), respectively.

3. Results

3.1. Spectral Energy Distributions

A key diagnostic for investigating the (atmospheric) properties of an exoplanet is its SED. In Figures 2–5 we show the SEDs of all target locations including their day and night comparisons (note the different scales on the y-axes). In Table 3 we provide the mean values for all SEDs in tabulated form. The horizontal lines indicate the average radiance measured in every channel over the 15 year observation period and the error bars in the y-direction correspond to the standard deviation. The blue shadings indicate the bandwidth of each channel.

For the North Pole, summer was defined as from April to September and winter from October to March and vice versa for the South Pole. As expected, we find the hottest region, the Sahara Desert, with the highest radiance values followed by the Indian Ocean, Amazon Rainforest, Arctic, and, finally the coldest target location, Antarctica. Throughout the channels and over the entire observation period of 15 years, the Sahara Desert also shows the largest difference between day and night measurements where the flux differs by 30% in channel 31 (10.78–11.28 μm). The Indian Ocean data lies in between this range and overall shows a smaller dispersion which could be due to the oceanic large thermal inertia (heat capacity) making them more resistant to temperature changes.

We note the very low level of variations at the shortest wavelength for the two poles and the Indian Ocean which can...
Table 2
Overview of the Resulting Effective Temperatures after a Blackbody Curve Was Fitted to Every Single Measurement’s SED of a Target Location and the Weighted Arithmetic Mean and the Standard Error of the Weighted Mean Were Calculated from the Set

| Target Location           | Effective Temperature (K) |
|---------------------------|---------------------------|
| Sahara Desert             | 278.01 ± 0.31             |
| Indian Ocean              | 267.92 ± 0.21             |
| Amazon Rainforest         | 260.52 ± 0.20             |
| Arctic Summer             | 249.18 ± 0.16             |
| Antarctica Summer         | 233.83 ± 0.06             |
| Sahara Desert Night       | 264.39 ± 0.20             |
| Indian Ocean Night        | 266.82 ± 0.20             |
| Amazon Rainforest Night   | 255.83 ± 0.17             |
| Arctic Winter             | 236.75 ± 0.12             |
| Antarctica Winter         | 219.00 ± 0.02             |

Note. For the Arctic, summer and winter were defined as from April to September and October to March, respectively, and vice versa for Antarctica.

largely be attributed to the overall low flux levels. In general, comparing the radiance from the equatorial regions to that from the polar regions, the flux differs by up to a factor of about two and three during the day and night, respectively. However, this strongly depends on the channel and location considered.

In order to estimate the effective temperature of each target location, we fitted a blackbody curve to every single measurement’s SED and calculated the weighted arithmetic mean and the corresponding standard error of the weighted mean from the total set. The results are shown in Table 2. Although no comparable results were found that cover the same observation period, the obtained estimates compare well with the results of Schwieterman & Rowland 2005; Hanel et al. 1972; Petitcolin & Vermote 2002; Hearty et al. 2009.

Four out of five locations, the Sahara Desert, Indian Ocean, Amazon Rainforest, and the Arctic, show similar spectral absorption features in their SEDs. The first feature around 4.475 μm in channel 24 (4.433–4.498 μm) corresponds to the CO2 band centered at 4.3 μm (Catling et al. 2018). It is followed by a clearly visible ozone absorption band at 9.65 μm and between channel 33 and 36 (13.2–14.4 μm), for the three equatorial regions, the plots show a continuous decrease which indicates the next absorption band due to CO2 centered at 15 μm (e.g., Figure 3 in Catling et al. 2018; Schwieterman et al. 2018).

The two polar regions behave rather differently from each other as the South Pole displays a seasonal dependence when the drop in variability in channel 30 (centered on the ozone band at 9.65 μm) relative to channels 29 and 31 is compared. During the Southern Hemisphere summer, the resulting SED for Antarctica (shown in Figure 5) is missing the dominant ozone absorption feature at 9.65 μm. An existing but less pronounced ozone feature is, however, observable during winter. Due to the missing ozone absorption feature in the summer data, the SED of Antarctica has a shape similar to that of a perfect blackbody with a temperature of 233.83 K ± 0.06 K. Also, both polar regions show an upturn in flux toward the end of the observed wavelength range by MODIS.

A reason for the difference in the depth of the ozone absorption feature between the two poles could be the fact that ozone is less abundant in the Southern Hemisphere. Although, a thinning of the ozone layer has been observed over other regions (e.g., Butchart 2014, and references therein), such as the Arctic as well as northern and southern midlatitudes, the most severe ozone loss was registered to be occurring in springtime over Antarctica due to chlorofluorocarbons, known as CFCs, that lead to the depletion of the ozone layer (Molina & Rowland 1974). Figure 6 shows an ozone abundance data set for both polar regions over the same 15 year time baseline used in our SED analysis. The data set was provided by NASA’s Ozone Watch. The 15 year Arctic ozone abundance average is calculated to be 347.53 Dobson Units (DU) and 269.88 DU for the Antarctica, indicating that there is on average 22% less ozone around the South Pole compared to the North Pole within that time period.

Despite the fact that such a shape, and thus temperature, would originate from high altitude clouds, this can be ruled out due to the long observation period. While less ozone is certainly present in the atmosphere above Antarctica, we primarily attribute the lack of a clear absorption feature to the temperature structure of the atmosphere at this location rather than due to differences in abundance. Balloon soundings showed that 90% of the atmospheric ozone resides in the stratosphere between 10 and 17 km and about 50 km with a peaking abundance around 20–25 km. At this altitude the average temperature above the South Pole over a 40 year period is roughly ≈221 K (NASA Ozone Watch). With the surface temperature being similar to the temperature at the altitude of the peak ozone abundance, the absorption feature may not be seen due to the missing contrast in thermal emission.

The observed upturn in channel 36 (14.085–14.385 μm) in the SEDs for both polar regions appears to be a characteristic signature of these types of locations. For the poles, it has been known for years that surface-based temperature inversions exist (e.g., Hudson & Brandt 2005) which are major drivers of some aspects of their climates, including atmospheric radiation. Given that the snow-surface emissivity is greater than the atmospheric emissivity, the inequality in emissivities results in a temperature inversion when the absorbed energy from solar radiation at the surface is small. In this case, some features can appear in emission. Hence, the increase in channel 36 indicates the emission of CO2 centered at 15 μm.
In order to investigate whether the planet’s obliquity can be inferred from Earth’s thermal emission, we decompose the spectral radiance time series into components of different frequencies using Fourier analysis. Specifically, we performed a discrete Fourier transform (DFT) on the data to produce a power spectrum, also known as PSD. Since the PSD is the measure of a signal’s power content versus frequency, finding trends in the data related to the orbital period would be a strong indication for a tilted spin axis. Figure 7 gives an example of the variations in spectral radiance. It shows the time series of the observed spectral radiance in channel 31 (10.78–11.28 μm) for the patches over the poles revealing a cyclic behavior. Due to Earth’s obliquity, the poles show higher (lower) spectral radiance readings at the North (South) pole during summer, as seen from the Northern Hemisphere. The mean radiance level over the 15 year period is indicated by the dashed horizontal lines. The mean spectral radiance difference between the two poles is 1.87 W m⁻² μm⁻¹ sr⁻¹.

3.2. Power Spectral Densities

In order to investigate whether the planet’s obliquity can be inferred from Earth’s thermal emission, we decompose the spectral radiance time series into components of different frequencies using Fourier analysis. Specifically, we performed a discrete Fourier transform (DFT) on the data to produce a power spectrum, also known as PSD. Since the PSD is the measure of a signal’s power content versus frequency, finding trends in the data related to the orbital period would be a strong indication for a tilted spin axis. Figure 7 gives an example of the variations in spectral radiance. It shows the time series of the observed spectral radiance in channel 31 (10.78–11.28 μm) for the patches over the poles revealing a cyclic behavior. Due to Earth’s obliquity, the poles show higher (lower) spectral radiance readings at the North (South) pole during winter. Fitting a sine function to the data revealed a periodicity of ~365.25 days, which is very close to the official sidereal year with ~365.2564 SI days (International Earth rotation & Reference systems Service 2014). A comparison on the average radiance of the different surface types shows that land masses emit more radiation than ocean or ice covered areas, which is in agreement with previous studies (e.g., Hearty et al. 2009; Gómez-Leal et al. 2012; Hurley et al. 2014).

A DFT was applied to every channel for each target location using python’s numpy nifty.fft module which calculates the one-dimensional n-point DFT with the efficient fast Fourier transform algorithm. As it is a common practice to express the significance of an enhancement by quoting the number of standard deviations it differs from the mean value of the signal, Figure 8 shows cycles per year on the x-axis and the significance of a possible signal on the y-axis. It should be noted that the following discussion is based on the results where a DFT is applied to a data set with a time baseline of 15 year. The results of a one year baseline are discussed further below.

Although the PSDs are noisier for the equatorial regions compared to the polar regions throughout all available thermal channels, 92% of all channels and locations including night measurements show a well-defined peak (3σ and more) at 1 cycle per year as displayed in Figure 9. The polar regions show overall peaks of 10σ or more as well as whole integer repeats which can be interpreted as harmonics, thus artifacts of the method. For these two locations, all thermal MODIS channels seem to be appropriate for looking for evidence of planetary obliquity in the MIR spectrum. Even though some bands are location and surface-type dependent, we find four channels (20–23, 03.66–04.08 μm) that produce strong signals (7σ and above) showing evidence of planetary obliquity independent of target location and surface type. These channels are primarily used for surface and cloud temperature measurements as stated in Table 1.

The Sahara Desert (a water-poor region), shows a strong signal (above 11σ) for the first six channels (20–25, 03.66–04.55 μm) that are primarily used for surface, cloud, and atmospheric temperature measurements, followed by five channels (29–32 and 34, 08.40–12.27 μm, and 13.49–13.79 μm) that deliver an intermediate signal strength (above 6.5σ) and five channels (27–28 and 33, 35–36, 06.54–07.48 μm, and 13.19–14.39 μm) with less signal strength (below 4.22σ). These bandwidths are primarily used for cirrus clouds, water vapor detection, and cloud-top altitude detection.

Besides from the above mentioned channels 20–23 that produce strong signals (11.83–12.15σ), we can deduce from the Indian Ocean (water-rich region) PSDs that channels 27, 28, and 36 also produce strong signals (above 7σ) as well as that another four channels (30, 33–35) do show a peak at 1 cycle per year but with a low sigma reading (below 4.15σ), implying that in the case of observations of a water-dominated hemisphere at similar latitude bandwidths covering water absorption bands are less appropriate for detecting evidence of planetary obliquity via thermal emission monitoring.

Since it is unlikely to observe a rocky, temperate exoplanets around a Sun-like star sufficiently frequently along its orbit over a time baseline of 15 years, we investigated the signal strength behavior for an observation period of only one year. The same DFT analysis was performed separately on each year. For channels that did not show a peak at one cycle per year ±5%, the peak was retrieved from the signal at that orbital period. For each channel, the average of its signal strength throughout the 15 years and the corresponding standard deviation was calculated. The result of the analysis is shown in Figure 10.

After 1 year of observations, the Arctic data set showed up to 3σ signals for all channels except for channel 27 (06.54–06.90 μm) which was the most variable channel in terms of radiance fluctuations. This is likely to be the result of undetectable cirrus clouds. Due to the relative large noise level and a very low reading (1.71σ) in the year 2010, it shows the largest error bar out of the 16 channels. Only nine channels (24–28, 30, 33–36) lie above the 3σ threshold for the Antarctic target location. Overall the channels show more noise than the matching channels of the Arctic data set, resulting in larger standard deviations.

The three equatorial regions display the same behavior for one year of observation as for 15 years of observation. Especially for channels 27 and 28 in the Sahara Desert and Indian Ocean data sets, as discussed above. None of the channels exceeded the 3σ threshold for the locations in question considering only one year of observation. Their large standard deviations indicate the variability in spectral radiance due to a mixture of cloud coverage and change in seasonal insolation. For these latitudes however, the signal is probably
dominated by clouds as they affect the measurements more due to a larger contrast between surface and top of cloud temperature. For the polar regions on the other hand, the signal is not dominated by clouds but by the change of seasonal insolation. Indeed studies suggest that cloud coverage varies with distance from the equator where the cloudiest regions are.

Figure 8. Calculated power spectral density for the Antarctica data set. The figure shows cycles/year on the x-axis and the significance ($\sigma$) of the signal on the y-axis. The green and red dashed lines correspond to the signal’s mean and $\pm 1\sigma$ value, respectively. Due to the clear periodicity in the spectral radiance signal caused by Earth’s obliquity, a relatively clean PSD with a noise level well below $1\sigma$ can be calculated for the polar regions. All channels show a strong peak (above $11.2\sigma$) at 1 cycle/year and are therefore indicating a tilted rotation axis of Earth. Due to the well-defined peaks, all channels are appropriate for looking for evidence of planetary obliquity in the MIR spectrum for the polar regions.

Figure 9. PSD analysis for 15 consecutive years of observation to infer the existence of seasons. The figure shows the 16 thermal channels on the x-axis and the significance $\sigma$ on the y-axis. The red line indicates the $3\sigma$ threshold and the error bars correspond to the channel specific standard deviation. All channels can be used to infer seasons for the polar regions and the Amazon Rainforest as well as the majority of the channels for the Sahara Desert and Indian Ocean.

Figure 10. Same as Figure 9 but now showing the mean significance when 1 year of data is analyzed. Although the trends remain the same independent of the observation time, only the Arctic seems to be showing evidence of a tilted rotation axis throughout all thermal channels after 1 year of observation. For Antarctica, the result is wavelength-dependent and suggests nine favorable channels. The differences between day and night measurements for the three equatorial regions are statistically insignificant.
the tropics and temperate zones, and the sub tropics and the polar regions have between 10% and 20% less cover (e.g., Rossow & Zhang 1995; Rossow & Schiffer 1999; Warren et al. 2007). Furthermore, the results show that the difference between day and night measurements for the three equatorial locations is statistically insignificant in this type of analysis.

While the methodology to infer obliquity in the reflected light is well established (e.g., Kawahara 2016; Schwartz et al. 2016; Farr et al. 2018), we cannot yet provide quantitative statements on the planet’s obliquity based on our results. The underlying idea of our analysis is that by re-observing the planet several times along its orbit (and ideally over more than one orbital period) we can link the observed periodicity in the SED with the orbital period. Therefore we can identify whether a planet has seasons and hence a tilted spin axis. Additional and more quantitative conclusions require disk-integrated data and additional modeling. We hope to address this in future research.

### 4. Summary and Conclusions

We investigated the thermal emission and time variability of five single-surface-type target locations on Earth: (1) Amazon Rainforest, (2) Antarctica, (3) Arctic, (4) Indian Ocean, and (5) Sahara Desert. We constructed Earth observation data sets containing calibrated spectral radiances from 16 discrete channels between 3.66 and 14.40 μm over a time baseline of 15 years including separate data sets for daytime and nighttime emission of all five locations. The data were collected between 2003 and 2017 by MODIS aboard NASA’s Earth observing satellite Aqua which observed every target location twice per month, resulting in 360 measurements per location. From each data set, we derived SEDs and used Fourier analysis to look for evidence of planetary obliquity in the measured spectral radiance variations. By fitting blackbody curves to the SEDs, we estimated the effective temperature for each target location. Since all our results are based on a time baseline of 15 consecutive years, we compare the time variability results to an observation time of 1 year in order to investigate whether it is still possible to detect evidence of Earth’s tilted rotation axis.

Key results from the inferred SEDs include the following.

1. As expected, Earth’s thermal emission cannot be represented by a single SED. Hence, viewing geometry plays an important role when analyzing exoplanet thermal emission data. At Earth’s peaking wavelength, the flux between the equatorial and polar regions varies on average by a factor of about two and three during the day and night, respectively.

2. Despite the coarse spectral resolution, the inferred SEDs showed differences in the strengths of absorption features in the atmosphere. Regions close to the equator and toward the North Pole show more dominant O₃ and CO₂ absorption features than the South Pole.

3. Given how seasonally variable the atmospheric structure and composition is in Antarctica, its SED changes over half of an orbit significantly when the ozone feature at 9.65 μm is compared between summer and winter. The lack of a clear ozone absorption feature during summer should be considered as it could lead to a false negative interpretation when searching for biosignatures in exoplanets that are viewed pole-on.

4. The derived effective temperatures averaged over a 15 year observation period are:

   (a) 278.01 K ± 0.31 K, 267.92 K ± 0.21 K, and 260.52 ± 0.20 K for the three equatorial regions the Sahara Desert, Indian Ocean, and Amazon Rainforest during the day and 264.39 K ± 0.20 K, 266.82 K ± 0.20 K, and 255.83 ± 0.17 K during the night, respectively.

   (b) For the two poles we received 249.18 ± 0.16 and 236.75 ± 0.12 for the Arctic and 233.83 ± 0.06 and 219.00 ± 0.02 for Antarctica during summer and winter, respectively.

Key results from the time variability study over the 15 year observation period are as follows.

### Table 3

| Locations         | Sahara Desert | Indian Ocean | Amazon Rainforest | Arctic | Antarctica |
|-------------------|---------------|--------------|-------------------|--------|------------|
| Day               | Night         | Day          | Night             | Summer | Winter |
| 20                | 1.19          | 0.25         | 0.43              | 0.30   |            |
| 21                | 1.33          | 0.36         | 0.55              | 0.44   |            |
| 22                | 1.42          | 0.35         | 0.54              | 0.43   |            |
| 23                | 1.23          | 0.40         | 0.53              | 0.46   |            |
| 24                | 0.16          | 0.11         | 0.13              | 0.12   |            |
| 25                | 0.62          | 0.37         | 0.40              | 0.38   |            |
| 27                | 1.46          | 1.39         | 1.58              | 1.52   |            |
| 28                | 3.07          | 2.85         | 3.09              | 2.99   |            |
| 29                | 9.17          | 6.21         | 7.00              | 6.79   |            |
| 30                | 6.66          | 4.90         | 5.41              | 5.30   |            |
| 31                | 10.29         | 7.23         | 7.59              | 7.40   |            |
| 32                | 9.49          | 6.91         | 7.08              | 6.91   |            |
| 33                | 5.47          | 4.79         | 4.83              | 4.76   |            |
| 34                | 4.17          | 3.92         | 3.97              | 3.94   |            |
| 35                | 3.56          | 3.34         | 3.39              | 3.37   |            |
| Channels          | 3.00          | 2.93         | 2.95              | 2.94   |            |

Note. All values are stated in physical units of W m⁻² μm⁻¹ sr⁻¹.
1. Applying a DFT to the data sets showed that a periodicity of Earths thermal emission can be observed, providing a strong indication for a tilted spin axis, and therefore seasons.
2. Specifically, 92% of the combined 128 thermal channels show a well-defined peak at 1 cycle/year:
   (a) The polar regions displayed a signal strength of at least 10σ for all channels. Therefore, pole-on view measurements are ideal for probing seasonal variations.
   (b) The equatorial regions showed a signal strength of at least 7σ for 72 out of 96 thermal channels, including the night measurements.

Key results from the time variability study over a one year observation period are as follows:
1. For an observation time of 1 year (~24 data points), the strength of the periodicity signal decreases significantly. For the equatorial regions none of the investigated channels reached a 3σ signal, and the day and night difference is found to be statistically insignificant. For the polar regions, it is possible to observe signs of obliquity in the thermal emission but the significance depends on the spectral band considered.
2. Compared to the 15 year observation period, the trends of the data distribution are unchanged.
3. Comparing the nature of variability between the equatorial and polar regions, we find that the measurements are dominated by clouds in equatorial regions and by changes of seasonal insolation in polar regions.

Our analyses emphasize the power of thermal emission data for the characterization of habitable terrestrial exoplanets, but they also caution us to be careful in the analysis and interpretation. Depending on viewing geometry and underlying dominant surface type, the same planet may appear significantly different. It seems that seasons could be inferred from thermal emission data, but that will require a significant amount of observing time. Still, combing the information from all channels investigated here may allow one to infer the existence of seasons with high confidence in a case where ~20 data points are available that are roughly evenly spread over the planet’s orbital period. The results obtained in this work should be considered as the first steps toward disk-integrated MIR observations of Earths spectra (e.g., Hearty et al. 2009) in order to explore characteristics that may appear in newly detected exoplanets in the future. The derived data sets could serve as a basis for such further investigations. Furthermore, combining the optical and near-infrared channels of MODIS, that were not considered here, with the thermal emission data would allow us to investigate, for instance, the specific influence of various cloud types on certain channels in order to refine atmospheric models.

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