Analyse the feasibility of using Earth Observation data to evaluate the optimal location in space for observing Earth as an exoplanet.

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August, 2022

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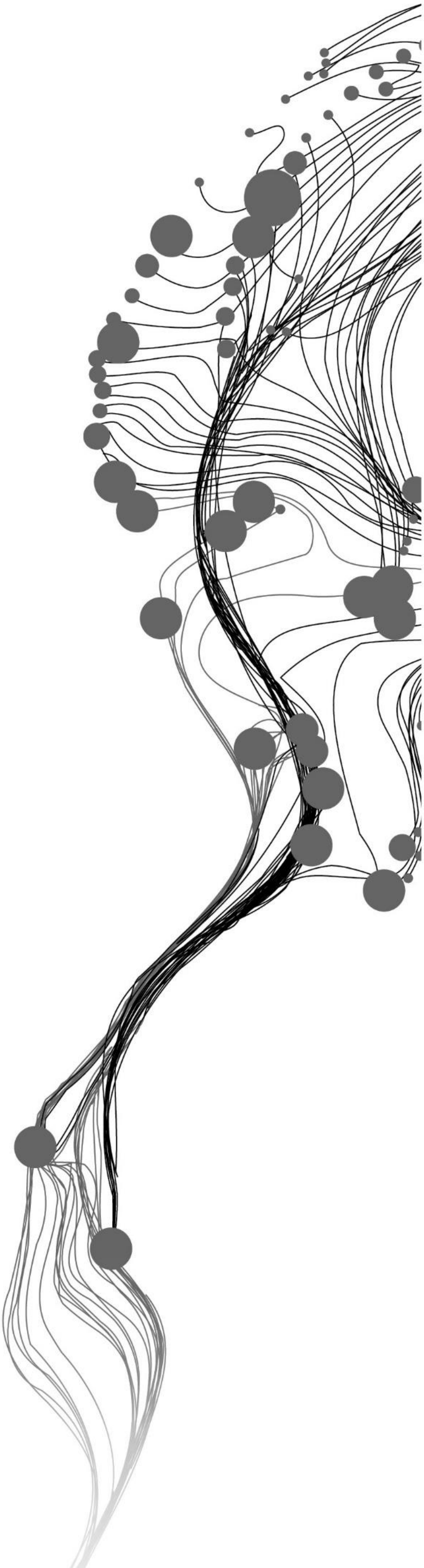

Analyse the feasibility of using Earth Observation data to evaluate the optimal location in space for observing Earth as an exoplanet.

NIMISHA VERMA
Enschede, The Netherlands, August, 2022

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Geoinformatics

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ABSTRACT

Observing Earth as an exoplanet allows us to study the features present on Earth using Polarimetry, which, in turn, allows the scientists to study the features present on different exoplanets. Various studies have focused on studying Earth as an exoplanet using computational models. However, research on using Earth observation datasets for these kinds of studies has not yet been done.

The main objective of this study was to understand if Earth observation datasets are feasible to observe Earth as an exoplanet and calculate the optimal location to observe Earth as an exoplanet. This research has observed that using the Earth observation dataset like MODIS, Landsat and Sentinel directly from the platform of Google Earth Engine does not provide a feasible solution. This is mainly due to limitations like partial coverage of Earth, missing metadata or availability of partial information. While it is possible to calculate the missing parameters separately, the limitations faced during the study were the spatial coverage of the image.

The study also focused on calculating the optimal location or orbit to observe Earth as an exoplanet. Through literature study, it has been confirmed that different features react differently in different phase angles. Hence, we require a wide range of phase angles to observe different features on Earth. During the study, we focused on the four Lagrange points L1, L2, L4, L5 and the Moon to calculate the phase angle for each orbit. It was observed that the trajectory of the Moon provides us with a high range of phase angles to observe Earth as an exoplanet.

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Although the journey at ITC might end on a different note than I had imagined, I would like to say through this letter that it has been a journey of a lifetime.

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1. INTRODUCTION

1.1. Space Exploration

Humans have always been interested in finding out if there is life beyond our planet. From ancient times when Galileo observed the different planets from his telescope to studying the cosmos using powerful telescopes like the Hubble, Kepler, etc., the search for life in the universe is an ongoing process. Apart from this, space exploration also helps us understand the origin of humankind and the possible future. In recent decades, space exploration has helped humankind advance in science and technology at an unprecedented rate. With the advent of satellites, information like weather, navigation, communication etc., are available to humans everywhere. Satellites like the Hubble or observation decks on Earth have provided us with images from deep space, which has helped humans expand their knowledge about the cosmos and other stars and planetary systems. Astronomers and scientists believe that observing other star systems and exoplanets is the key to understanding how Earth and the solar system developed and what might happen in the future.

Exoplanets are planets that revolve around stars other than our Sun. The first-ever exoplanet was discovered in 1992 around pulsar "PSR 1257" (Wolszczan and Frail, 1992), while the first exoplanet revolving around a sun-like star was found in 1995 named "51 Pegasi b" (Mayor and Queloz, 1995). After the first discovery, thousands of new exoplanets were discovered. The milky way galaxy is home to around 100 billion stars (or more). It is assumed that each star, on average, contains at least one planetary system (NASA's Planetary Science Communications team, 2021). Today, the NASA Exoplanet Archive holds more than 29000 exoplanet discoveries and is updated daily as more and more exoplanets are being discovered (Rajan et al., 2021). Studying exoplanets allows us to look beyond the perimeters of our solar system and discover planets with extreme characteristics. Some Exoplanets have pushed scientists beyond the plausible explanation of planet formation or places where they can exist. One example of a planet with an extreme atmosphere would be Kepler-10b, which orbits its star at a distance 20 times shorter than Mercury, giving it a revolution period of 1 Earth day (Batalha et al., 2011). Kepler-10b is a rocky planet, similar to Earth, but due to its proximity to its star, the surface temperature rises to 1,400 degrees Celsius (Batalha et al., 2011). The radiation from its star has stripped away the atmosphere from this planet (Batalha et al., 2011). Scientists have discovered many other extreme systems with exoplanets revolving around the stars in extreme conditions. Studying these exoplanets and the conditions surrounding them helps scientists develop a database of planets and their characteristics, and eventually find out if life can evolve on those planets. Of all the exoplanets, the Earth-like exoplanets are considered the most favourable because they may have conditions similar to Earth to host life as we know it.

Earth-like exoplanets are rocky planets revolving around their star in the habitable zone (Space.com, 2016). A habitable zone is an area around a star where it is just about right to sustain liquid water on the planet's surface and depends on the type of star it is revolving. Determining if the planet lies in the habitable zone, the distance from its star, stars type & composition, and the amount of dip in the star's luminosity when the planet transits in front of the star are considered. Some factors in determining if a planet is habitable are its ability to contain liquid water[1] , if the planet has an atmosphere, its estimated mass, chemical composition, among others (Rajan et al., 2021).

Over the years, scientists have devised various ways to find if an exoplanet is Earth-like. Seager (2003) mentions the methods used during the early days of exoplanet research – "Search for Earth-like planets by their gravitational influence on the parent stars", "Direct planet detection developments", "Observing Earth as an extrasolar planet", etc. Rajan et al., (2021) used a machine-learning algorithm to list exoplanets that have a similar attribute to the PHL[2]

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[1] The temperature and pressure on these planets should be exactly right to sustain liquid water.

[2] Planetary Habitability Laboratory – Online database of Potentially habitable planets

habitable exoplanets catalog, the stellar type of the stars and planet size comparison to understand if the planets are similar to Earth.

In recent years, the focus has been to study Earth as an extrasolar planet due to the ease of examining the signals. Studying Earth as an exoplanet can be done in two ways – through an Earth-like model or direct observation through remotely sensed data. Robinson et al., 2011 work with the observation data taken from the EPOXI Discovery Mission of Opportunity. EPOXI is the name provided to NASA's Deep Impact spacecraft[3] designed to study the interior composition of a Comet (NASA, 2010). The data from EPOXI is combined with information like the specular reflectance from the ocean, atmospheric effects like Rayleigh Scattering, gas absorption and temperature to develop an Earth-like model. Direct observation of Earth as an exoplanet is an alternative that is still in the initial phases. Scientists have been working on an initial concept of LOUPE – Lunar Observatory of Unresolved Polarimetry of Earth (Klindžić et al., 2021), a spectro-polarimeter to observe Earth from a location based on the Moon or near to the Moon.

A spectro-polarimeter generally consists of "a telescope that collects photons and images the object, a polarimeter to convert the polarisation of light into variation of the intensity, a spectrometer to resolve the spectral feature and photosensors to measure the intensity of the modulated intensity of light" (Ichimoto, 2019). Polarimetry is defined as "a technique to measure the polarisation of light which allows astronomers to infer information about celestial objects" ("Polarimetry | ESO," 2021). Polarisation of light occurs due to scattering by gas molecules, aerosol/cloud particles or reflection by a surface (Stam, 1982). Polarimetry is used with ground-based observations to differentiate planets from its' parent star. Future space telescopes are being designed to work with Polarimetry as it is an easier way to study planets outside of our solar system. Using Spectro-polarimetry to study exoplanets gives an advantage of not only examining the planet as a whole but also extracting information about its geomorphologies and biospheres (Klindžić et al., 2021).

1.2. LOUPE

LOUPE focuses on capturing the flux and polarisation data by observing Earth as a "spatially unresolved exoplanet". The flux of any planet is the total amount of energy radiated by that planet, and the polarization amount of any planet depends on the phase angle of observation. A phase angle is an angle between the star and the observer measured from the centre of a planet. Every feature depicts different behaviour when observed from various phase angles. Clouds can be observed through a low phase angle, while oceans need a larger phase angle. E.g., through numerical study, it is suggested that an intermediate to large phase angle can help identify an ocean by a change in colour of polarisation of a planet (Klindžić et al., 2021). LOUPE will be designed to work with a spectral range between 400-1000 nm and with a resolution of 5 nm (Table 1). The goal is to map the Earth multiple times per hour as a temporal resolution, and the mission is expected to last for about a year (Klindžić et al., 2021). The data collected from this mission will be used for a comparative study with the information collected from the exoplanets to understand if they are Earth-like.

Requirement	Minimum	Goal
Spectral Range	500-800 nm	400-1000 nm
Spectral Resolution	20 nm	5 nm
Temporal Sampling	Hourly	Multiple/hour
Mission Duration	1 month	1 + Years
Mass	< 1 Kg	300 g
Data Bandwidth	Around 50 MB/day	> 100 MB/day
Moving Parts	Protective Lid (Single Use)	Active pointing and protection

Table 1: Technical requirement for LOUPE - Minimum and goal (Klindžić et al., 2021)

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[3] NASA's Deep Impact mission for observation of a comet (DIXI) and Extrasolar Planet Observation and Characterization (EPOCh). Both names have been combined to create the name EPOXI.

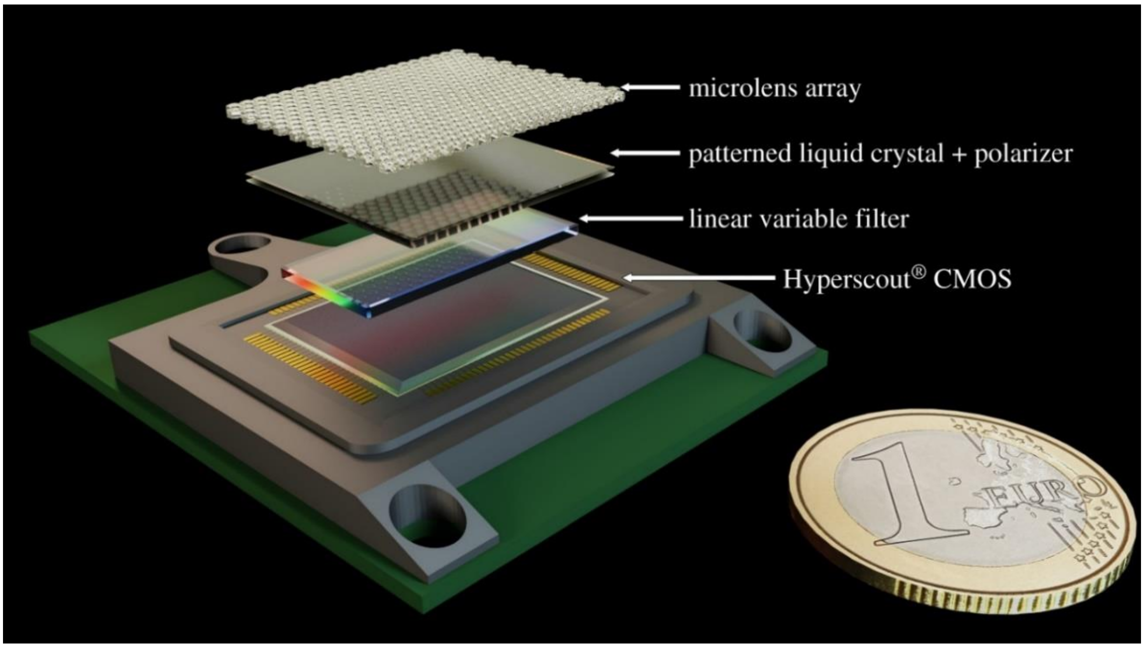


Figure 1: "A three-dimensional render of the current LOUPE concept, with a 1 Euro coin for scale" (Klindžić et al., 2021)

Presently, LOUPE is in the initial phases of development with instrumentation (Figure 1). Various studies related to LOUPE focus on understanding the most favourable phase angle to observe different features on Earth. However, actual research that can provide this information has not been done yet. Hosting LOUPE at an optimal location in space is a crucial part of this mission because it can provide us with the most favourable phase angles to capture the flux and polarisation of different features.

LOUPE is an instrument to be hosted in orbit around Earth and will be one of the first missions of its kind. An optimal location for LOUPE can be defined as the position in space from where we observe the most features on Earth. To find such a location, it is important to use the present resources like Earth Observation Data and use them to calculate the optimal location to observe Earth as an exoplanet. It is important to note that the optimal location might not be limited to one single point in space but can be spread out in orbit around Earth. However, one of the important things to note is that Earth Observation data is mostly parameterised for use at a certain distance and also to collect the atmospheric data for atmospheric correction. So far, no Earth observation data has been used to study Earth through a space domain. Therefore, there is a gap in understanding if it would be suitable for this study. Furthermore, relating the phase angle, illumination angle and the Earth observation data to understand what features are visible through them is also tricky as the Earth observation data is limited in how it can be modified. There is no present software that can directly perform these kinds of tasks.

The present study focuses on these research gaps to understand if the available Earth Observation resources to analyse and evaluate the optimal location in space are feasible enough. The study also focuses on the limitations present while conducting this kind of research. In order to evaluate the optimal location, this study focuses on the Lagrange orbit around Earth.

1.3. Orbits

As of 2021, there are more than 4,500 operational satellites in orbit around Earth (UCS, 2021), with new satellites being launched each year. Most satellites launched are used in Earth observation for various purposes like weather forecasting, GPS location and tracking, scientific research, military operations etc. These satellites orbit Earth at various distances. There are five kinds of orbits around Earth (ESA, 2020):

- Geo-stationary orbit (GEO)

- Low Earth Orbit (LEO)
- Medium Earth Orbit (MEO)
- Polar Orbit and Sun-Synchronous orbit (SSO)
- Transfer orbits and geo-stationary transfer orbit (GTO)
- Lagrange Points (L-points)

The most common and crowded orbit around Earth is "Low Earth Orbit (LEO)", which lies at a distance of about 160 to 1000 km from Earth's surface (ESA, 2020). Most satellites in this orbit are used for Earth observation due to their proximity to Earth, and the orbit in this region is not restricted to follow a strict path around Earth. Some satellites from this region are MODIS, Sentinel-3, Landsat series etc. Proximity to Earth's surface and the speed of the satellite decides their temporal resolution.

As for the Lagrange point, it is the position starting at a distance four times that of the Sun, i.e. 0.1 Astronomical Unit (1.5 million kilometres) (ESA, 2020). These are the points between Earth-Sun, where the gravitational field of both bodies combines in a way to allow the spacecraft to remain stable. Most satellites used to study other celestial bodies, individually or in relation to Earth, are placed in this orbit. One example is the James Webb Telescope (NASA, 2018). This distance allows for the observation of the target body without the influence of visible and infrared emissions of Earth. It is interesting to note that these locations provide for an anchored view (not to be confused with Geo-stationary observation) of the Earth rather than an orbital view (Figure 2).

There are five Lagrange points L1, L2, L3, L4 and L5 (NASA/WMAP Science Team, 2018). Of the five, only two provide for a stable orbit – L4 and L5. The orbits L1, L2, and L3 lie along the line connecting the two large celestial bodies, in this case, the Earth and the Sun. The stable Lagrange point – L4 and L5 are located at the end of two equilateral triangles of the large bodies at the vertices. L4 lies ahead of the orbit of Earth, and L5 is behind. L1 is the location facing the Sun, providing an uninterrupted view of the celestial body. At the same time, L2 is the orbit facing away from the Sun, currently home to the famous James Webb Space Telescope (NASA, 2018). Regular course and attitude correction is usually required for spacecraft hosted in these regions.

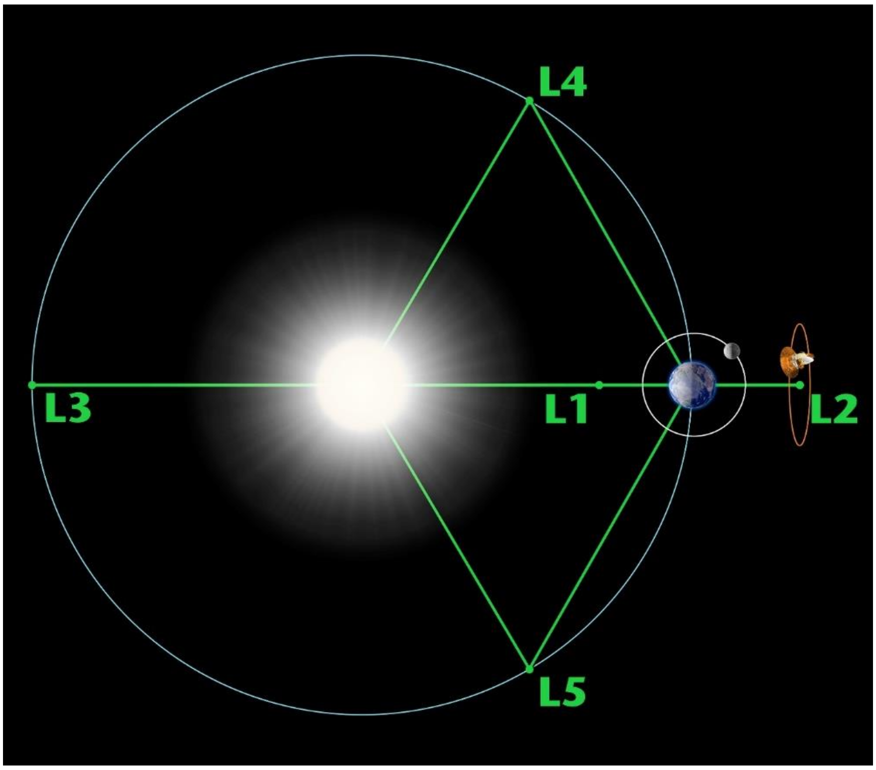


Figure 2: The five Lagrange point around Earth (NASA/WMAP Science Team, 2018).

Lagrange point provides for a very suitable orbit to launch LOUPE, eventually to observe Earth as an exoplanet. One of the challenges is combining the Earth observation data from Low Earth Orbit with that of Lagrange Point. So far, no study has been done to understand whether Earth Observation data are feasible enough to integrate with space research. Therefore, as initial research, it was essential to identify which satellite imagery is suitable for the study and the requirements to get suitable results.

1.4. Objective, sub-objective and research questions

Studying exoplanet, that too Earth as an exoplanet, comes as part of a space domain less explored so far. As mentioned already, studies have been done to analyse Earth as an exoplanet but using the Earth Observation dataset to study its feature and observe the behaviour of the planet has not been done yet. There are various questions and requirements yet to be explored to understand how we can use Earth observation data to study Earth as an exoplanet.

This research focuses on analysing the requirements and suitability to understand if Earth observation data is feasible enough to conduct a study like this.

1.4.1. Main objective

Analyse the feasibility of using Earth Observation data to evaluate the optimal location in space for observing Earth as an exoplanet.

1.4.2. Sub-objective

1.4.2.1. Evaluation of the available Earth observation data for a study related to the astronomical domain.

- Which Earth observation datasets are available and suitable for the study?
- Are Earth Observation data compatible to be used in these kinds of studies?
- What software/platform is available for this kind of study?

1.4.2.2. Evaluation of most favourable orbit for observing Earth as an exoplanet.

- What parameters are required to study a favourable orbit for observing Earth as an exoplanet?
- What results are most favourable, and how feasible is the calculated optimal location?
- How feasible is the defined optimal location based on the study done?

1.4.2.3. Understanding the possibilities and limitations of the study for further research.

- Being one of the first studies of its kind, what are the drawbacks faced during the study?
- What limitations are faced with open-source datasets for this kind of study?
- What possible steps can be taken to succeed in these kinds of studies?

2. DATASET AND STUDY AREA

As mentioned above, there are more than 4000 satellites in orbit around Earth (UCS, 2021). Of the satellites for Earth observation, many of them are available as an open-source dataset which allows the user to download the images free of cost using the website or the API. The satellite images present as open-source are available both in raw format or as a product like NDVI layer, Surface reflectance etc. One example is the MODIS satellite imagery which provides both the raw images as well as end products (NASA, 2014). The images available as products mostly comes with Metadata and documentation on how the processing was done.

To study Earth from outer space, we require the reflectance from the Top Of Atmosphere (TOA), namely either TOA Radiance or TOA Reflectance. TOA Radiance is the radiance captured from a certain area and has W/(m^2 sr um) as a unit. TOA Reflectance, on the other hand, is the ratio between the incoming and reflected radiation and hence, is unitless (Ray, 2013). TOA Radiance is a unit whose value depends on the region being observed and can vary based on the absorption and reflectance of the radiance from that area. On the other hand, TOA Reflectance being a ratio, is independent of such parameters. While observing Earth as an exoplanet, we want to avoid such miscalculations based on the changes in absorption; hence, TOA Reflectance seems a better choice.

Therefore, we require a dataset with "TOA reflectance" values for the present study. During the research, MODIS and Landsat were considered based on the requirements. However, due to limitations discussed later in the "Results" chapter, we work with Sentinel 3 OLCI EFR dataset. Although it does not provide us with TOA Reflectance, the dataset provides us with TOA Radiance, which can then be used for further calculation.

2.1. Dataset

2.1.1. Sentinel 3 OLCI EFR:

Sentinel-3 is a joint mission by ESA and EUMESAT where its primary mission is "to measure sea surface topography, sea and land surface temperature, and ocean and land surface colour with high accuracy and reliability to support ocean forecasting systems, environmental monitoring and climate monitoring" (Bourg et al., 2021). Sentinel-3 orbit uses a high inclination orbit (98.65°) for the coverage of ice and snow parameters for high latitudes. It is a near-polar, sun-synchronous orbit at an altitude of 814.5 km and crosses the equator at 10:00h mean Local Solar Time (Bourg et al., 2021). The spacecraft carries four main instruments:

- OLCI – Ocean and Land Color Instrument
- SLSTR – Sea and Land Surface Temperature
- SRAL – SAR Radas Altimeter
- MWR – Microwave Radiometer

Copernicus Sentinel-3 OLCI (Ocean and Land Color Instrument) is an imaging spectrometer with 21 spectral bands (Bourg et al., 2021). Its wavelength ranges from 0.4 μm to 1.02μm with a spatial resolution of 300 m, and it provides global coverage almost every two days. OLCI products are available in four types and can be freely downloaded at 'https://scihub.copernicus.eu'. The visible bands from Sentinel-3 OLCI EFR (GEE, 2020) dataset are used for the present study - Red, Green and Blue:

- Oa08_radiance - Chl (2^nd Chl abs. max.), sediment, yellow substance/vegetation
- Oa06_radiance - Chlorophyll reference (Chl minimum)
- Oa04_radiance - High Chl, other pigments

The band specification is available in Table 2.

Name	Description	Wavelength centre (nm)	Resolution (m)
B01	Aerosol correction, improved water constituent retrieval	400	300
B02	Yellow substance and detrital pigments (turbidity)	412.5	300
B03	Chlorophyll absorption maximum, biogeochemistry, vegetation	442.5	300
B04	Chlorophyll	490	300
B05	Chlorophyll, sediment, turbidity, red tide	510	300
B06	Chlorophyll reference (minimum)	560	300
B07	Sediment loading	620	300
B08	2nd Chlorophyll absorption maximum, sediment, yellow substance / vegetation	665	300
B09	Improved fluorescence retrieval	673.75	300
B10	Chlorophyll fluorescence peak, red edge	681.25	300
B11	Chlorophyll fluorescence baseline, red edge transition	708.75	300
B12	O_2 absorption / clouds, vegetation	753.75	300
B13	O_2 absorption / aerosol correction	761.25	300
B14	Atmospheric correction	764.375	300
B15	O_2 absorption used for cloud top pressure, fluorescence over land	767.5	300
B16	Atmospheric / aerosol correction	778.75	300
B17	Atmospheric / aerosol correction, clouds, pixel co-registration	865	300
B18	Water vapour absorption reference. Common reference band with SLSTR. Vegetation monitoring	885	300
B19	Water vapour absorption, vegetation monitoring (maximum REFLECTANCE)	900	300
B20	Water vapour absorption, atmospheric / aerosol correction	940	300
B21	Atmospheric / aerosol correction, snow grain size	1020	300

Table 2: Sentinel 3 Band Specifications (Bourg et al., 2021).

2.2. Study Area:

The study area for this research was the complete view of the Earth as would be visible from space. As mentioned in the introduction (1.3 Orbits), the Lagrange point lies farther from Earth than the Moon. It is from this distance that we study to find which location provides the highest range of phase angle to study Earth as an exoplanet. We also consider the orbit of the Moon for the study of phase angle.

Figure 3: Image of the Earth rising over the Moon from Apollo 8 (NASA, 2007).

3. METHODOLOGY

Due to the study being a first of its kind in this field, there are no pre-existing scripts or methodology used for the present research. The methodology consists of steps, processes and software deemed the most suitable to get the desired result. Still, various roadblocks and limits were faced throughout the research, which is discussed further in the later sections (Discussion).

The methodology consists of two parts:

- Google Earth API – Processing and Generation of the image.
- Python – Generation, calculation and further processing of the image to evaluate the favourable point for observing Earth as an exoplanet.

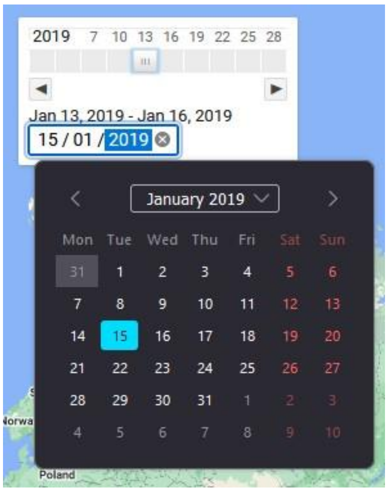
3.1. Google Earth Engine (GEE)

Google Earth Engine (GEE) is a cloud platform that allows its users access to resources for processing a large number of geospatial datasets. Although it is not open-source, the platform is freely available for everyone as an extension of Google services and works with JavaScript code. Many of the satellite images from Landsat and Sentinel are readily available on GEE, and it also allows you to work with your data. Some features available on GEE are filtering, creating mosaics, clipping images, classification (supervised and unsupervised) etc.

Sentinel-3 OLCI TOA Radiance dataset is freely available for use on the GEE platform, which is called using the script already provided with the dataset. It also contains the information to calculate the TOA radiance for each layer. We work on creating a script to call the image based on the user's input for date selection, mosaicking the images, reducing the image's resolution and exporting it out from the platform for further usage in Python script.

A "date-slider" functionality is added to the script to allow the user to select the date of interest for a mosaiced image generation. The "date-slider" automatically chooses three days around the specified date to generate the Earth's overview.

Eventually, the image was exported to be stored in a Google Drive folder. There are three options to export the image after the script – Google Drive, Cloud Storage or ee.Asset. Google Drive was chosen for this study as it is the easiest option. The "Export.image.toDrive" functionality was used to export the image to the drive. It is important to note that the coordinate system has to be redefined (using the same coordinate system as the original image) in this section; otherwise, the image might not have the same coordinate system observed while working on the GEE platform. The folder on Google Drive was then synced with a folder on a local drive to make the image accessible for use.



Jan 13, 2019 - Jan 16, 2019

15 / 01 / 2019

Figure 4: Image of the DateSlider function - Selection between 13-01-2019 - 16-01-2019.

3.1.1. Processing of the dataset and generation

The selected image was processed based on the information provided along with the dataset for calculating TOA radiance for each band. In addition to the calculation, the script contained a section to reduce the image's resolution. It is evident that the resolution with which we can observe Earth will decrease as we go further away from Earth. Furthermore, while observing exoplanets, the resolution sometimes spans one pixel or two, making it important to observe Earth in fewer pixels. Therefore, the spatial resolution of the sentinel image is reduced from 300m to 25 km during the processing of the image. It is further reduced to 250 km while exporting the image. The reason to perform this in 2 steps is to reduce the processing time for both data display and export and decrease the processing time with the python script as well.

3.2. Python API

Pycharm is a Python IDE used to create and run scripts using Python Language ("JetBrains Product Documentation," 2022). The Pycharm Community Edition – provided by the Faculty of ITC, University of Twente, is used for this research.

Python was used in the second part of this research to read the image, calculate the TOA Reflectance and then plot the possible path and locations for observation through LOUPE. The libraries used for the process are – Numpy, Pandas, GDAL, SPICE and matplotlib. Numpy is a library used to create and work with multi-dimensional arrays, and it also provides the capabilities of mathematical operations like algebra, transform, matrix etc. Numpy is used to read the TIFF image, which is stored as an array of values, while pandas are a python library used for data manipulation and analysis. GDAL library is designed to work with vector and raster geospatial data formats. It provides the functionality to read the raster images, the image coordinates, the properties of the image etc. Other libraries are also used in the script depending on the requirement, like math, DateTime etc., to read or convert the information to the datatype as required.

The script is mainly divided into four parts –

- Importing, reading and converting the image to NumPy array.
- Calculation of the path and phase angle based on the location of pixels.
- Calculation of the TOA reflectance.
- Calculate the phase angle and TOA reflectance to understand the optimal location (if any).

3.2.1. Importing, Reading and Converting the image to a Numpy Array

One of the most popular libraries available to deal and work with TIFF images is GDAL. "GDAL is a translator library for raster and vector geospatial data formats released under an MIT style Open Source License by the Open Source Geospatial Foundation. As a library, it presents a single raster abstract data model and single vector abstract data model to the calling application for all supported formats." (Warmerdam and Rouault, 1998).

The script uses the GDAL library to read the TIFF image, read the image properties and call the individual bands. As the image is available in a pixel format, the TOA Radiance from each pixel is read after individual bands are converted into an array. Furthermore, the GDAL library is also used to calculate the corresponding Latitude/Longitude in decimal format for the image coordinates. The build-in functionality GetGeoTransform() is used to read the pixel width, pixel width, possible row rotation, possible column rotation, and the location of the top-left corner of the top-left pixel. To convert the image coordinate to a real coordinate, we define a function "pixel2coord", which takes each pixel from the image and calculates the real-world coordinate based on the information obtained from GetGeoTransform() functionality.

It is important to note that the coordinates available via Google Earth Engine are in the (Longitude – Latitude) format to read the correct information while calculating the location. In our usual practice, we are habituated to reading the coordinates as Latitude/Longitude, which might result in wrong values being calculated. While reading the image, it is essential to note that the x-axis defines the columns and hence, the longitude, while the y-axis denotes the rows, thus, latitude. The Latitude/Longitude is stored in a Dataframe defined as "Final Dataframe" – a Pandas Dataframe containing all the calculated parameters required. The TOA Radiance from each pixel is also appended to this dataframe.

3.2.2. Calculation of the Path and the Phase angle based on the location of each pixel

As the data section explains, the Lagrange point is at a distance of 1.5 million kilometres. It means that this orbit is at a distance even further than the Moon, which sits at a distance of around 384,000 km. Very few satellites or spacecraft are deployed in this region, and none of them is designed for Earth observation. This results in a limitation where we are unaware of what to expect when observing Earth from this distance. Hence, it is important to have some calculated path for these Lagrange points or Moon that LOUPE might follow to observe Earth.

We work with SPICE – a tool created by NASA and used in the study of astronomy, planetary science etc., to calculate the orbits concerning the Lagrange point and Moon. "The Navigation and Ancillary Information Facility (NAIF), acting under the directions of NASA's Planetary Science Division, has built an information system named "SPICE" to assist NASA scientists in planning and interpreting scientific observations from space-borne instruments, and to assist NASA engineers involved in modelling, planning and executing activities needed to conduct planetary exploration missions." (NAIF, 2018)

"Spice" toolkit is available directly in C, Fortron, IDL, Matlab and Java native Interface language from the NAIF team. However, it is not directly available for use in the Python environment. Spice can be used in the Python environment via Third-Party interfaces. Spice is available as Spiceypy library for python users (Annex et al., 2020). Spice toolkit comes with some pre-installed deployments referred to as kernels. These kernels include information about the celestial bodies like the path, rotation speed, relative location, etc., and are used in numerous space missions. Some examples of what Spice can be used for are – Positions and velocities of the planet, satellites, comets, asteroids and spacecrafts, Shape, size and orientation of planets, satellites, comets etc. It can also be used to determine the orbits or paths of spacecrafts, orientation and field-of-view of spacecraft for possible space missions. Spice tool is open-source and is available to everyone.

Spice tool is used to calculate the various positions and possible orbits around the Earth from the four Lagrange locations in space – L1, L2, L4 and L5. L3 point sits on the opposite side of the Sun, i.e. the other end of the Earth; therefore, we do not consider the location in this study.

Using the "spkpos" function (NAIF, 2018), we calculate the possible path in the Lagrange point for hosting LOUPE (NAIF, 2018). This tool takes in parameters like the target body (Lagrange orbit), the time in epoch, reference frame, observing body (Earth), and position of the target (Latitude, Longitude). The functionality "illumf" (NAIF, 2018) is used to calculate the phase angle. It takes the computational method (Ellipsoid), the target body (Earth), the illumination source (Sun), the time in epoch, the Body-fixed target body frame, observing body (Lagrange orbit), the position of the target body (latitude, longitude) as an input for the calculation of different parameters. An epoch is the Ephemeris time (et) based on the orbital motion of the celestial body. The time provided in the script was converted from UTC to Epoch for further calculation using the built-in function "datetime2et". It is essential to make this conversion as the time calculation in astronomy is done in Ephemeris time.

A reference frame is used in Spice to define the centre of any object being studied. For, e.g. for a spacecraft orbiting the Earth, the reference frame has to have Earth as the centre. However, when calculating the viewpoint from a spacecraft, and the observing body is Earth, the centre has to be defined within the spacecraft to make the viewpoint from the spacecraft. Spice already has a reference frame created for Earth and Moon. Many inter-planetary mission uses Spice to calculate the possible path, understand or modify the predicted path or view them.

The output created from this functionality is described below.

The parameters calculated from the "illumf" functionality:

- Target Surface Point Epoch -
    - The target surface point epoch is dependent on the lat/long provided.
- Vector from observer to target surface point -
    - The vector provides parameters to calculate the distance between an observer and target body, the relative position of the observed to that of the target body, and to convert the reference frame from a fixed to a time-dependent reference frame.
- Phase angle -
    - A phase angle is an angle between the target's location and that of the observer. The units are in radian, and the range is [0, pi].
- Illumination source incident angle. The unit is in radian.
- Emission angle – the range of emission angle is [0, pi].
- Visibility and Illumination logical flag – Indicating if the target surface is visible and illuminated.

3.2.3. Calculation of TOA Reflectance

Top of Atmospheric (TOA) reflectance is "The reflectance measured by a space-based sensor flying higher than the Earth's atmosphere" (Shippert, 2013). It can be used to observe Earth as it would be visible from Space without the apparent atmospheric correction done to remove distortion observed via aerosol presence, clouds etc. Furthermore, TOA reflectance calculation is possible for almost every satellite image using the Metadata attached to that particular image.

TOA Reflectance is calculated using the TOA radiance (depends on the band), solar zenith angle, solar irradiance and the Earth-Sun distance in the astronomical unit. The formula used for this step is given below (Marino, 2017):

Equation 1: TOA Radiance to TOA Reflectance.

$$\rho_\lambda = \frac{\pi * L_\lambda}{ESUN\lambda * \ \theta_\lambda}$$

Where,

$$\rho_\lambda = Planetary\ TOA\ Reflectance\ [unitless]$$
$$\pi = Mathematical\ constant - 3.14\ [unitless]$$
$$L_\lambda = Spectral\ radiance\ at\ the\ sensor's\ aperture\ [W/(m^2 sr\ um)]$$
$$ESUN\lambda = Mean\ solar\ spectral\ irradiance\ [W/(m^2\ um)]$$
$$\theta_\lambda = Solar\ Zenith\ Angle$$

Usually, the information about the solar zenith angle and mean solar spectral irradiance is provided along with the Metadata of the image. However, this information is unavailable for Sentinel 3 TOA radiance image on Google Earth Engine. Therefore, we calculate these two parameters based on the acquisition date from the Sentinel 3 TOA Radiance image on Google Earth Engine.

The Solar Zenith angle and the irradiance are calculated using the "pvlib" library for Python. "pvlib" provides functions for simulating the performance of photovoltaic energy systems (Holmgren et al., 2015). It has various modules that can calculate parameters like irradiance, solar position, atmospheric pressure or airmass etc.

We focus on the irradiance module and the solar position module for the present study. The irradiance module contains functions for calculating the global horizontal irradiance, direct normal irradiance, diffuse horizontal irradiance, and total irradiance under various conditions (Holmgren et al., 2015). The irradiance needed for Top of Atmospheric Reflectance (TOA) is called Extraterrestrial radiation – the intensity of the Sun at the Top of the Atmosphere. The unit, as mentioned above, is Watt per square meter. The sun irradiance varies through the year and, due to changing sun intensity in general, varies between years as well. Therefore, it is essential to consider both things while calculating Solar irradiance.

The function "get_extra_radiation" from pvlib is used to calculate sun irradiance. It considers the DateTime and year to calculate the solar irradiance. Another parameter required is called the solar constant (= 1366.1). A solar constant is the average radiation received at a distance of 1 astronomical unit from the Sun. As for calculating the solar zenith angle, the function "solarposition.get_solarposition" from pvlib was used. It takes the time, latitude, longitude, altitude and temperature as an input and provides the output containing the zenith, azimuth, elevation and the equation of time. It is important to note that since the image is a mosaic of the complete Earth, the Sun Zenith angle spanned the whole of 180°. The sun zenith angle till 90° indicates Noon; therefore, to acquire the correct results, we subtract the calculated value for sun zenith from 180° for angles beyond 90°. This is because the Sun Zenith angle is the location of the Sun against a normal, which means that the angle cannot be more than 90°. These calculated results are then fed as an input to calculate each band's TOA reflectance, which is then stacked together to create a new image.

4. RESULTS

The results can be divided into three parts based on the research and processing done in the study:

- Evaluation of data suitability.
- Understanding and calculation of the TOA reflectance.
- Evaluation of the phase angle for viewing the Earth from space.

4.1. Evaluation of the data availability and data suitability

As mentioned in the dataset section, we require a dataset with TOA reflectance parameter that can give us an overview of the Earth as visible from the Top of Atmosphere. Furthermore, a dataset which can provide this information with different layer visibility would be an extremely suitable dataset for the study. At present, Google Earth Engine offers a wide range of data products available for use ranging from Landsat to MODIS and Sentinel. Most of the images available on the Google Earth engine are already processed images with product information for the direct use of the layer.

4.1.1. MODIS Datasets

During the initial phase of this research, we chose MODIS dataset as the primary dataset to focus on due to the availability of several layers providing different features on Earth, namely clouds, ocean, aerosols etc. However, during the later stages of the research, it was understood that the MODIS layers present within GEE are all processed information which will not be suitable for the study as rolling back the images to their original pixel values is not possible. For eg.: there are multiple layers present in the MODIS satellite images. Still, due to the processing done on the images, it is not possible to consider them for the study. In the image below (Figure 5), we can see that the layer shows the possible snow coverage of the entire Earth. However, other areas are removed from the image and hence, are represented as a dark pixel. Therefore, it was required to look at other datasets which could be suitable for the

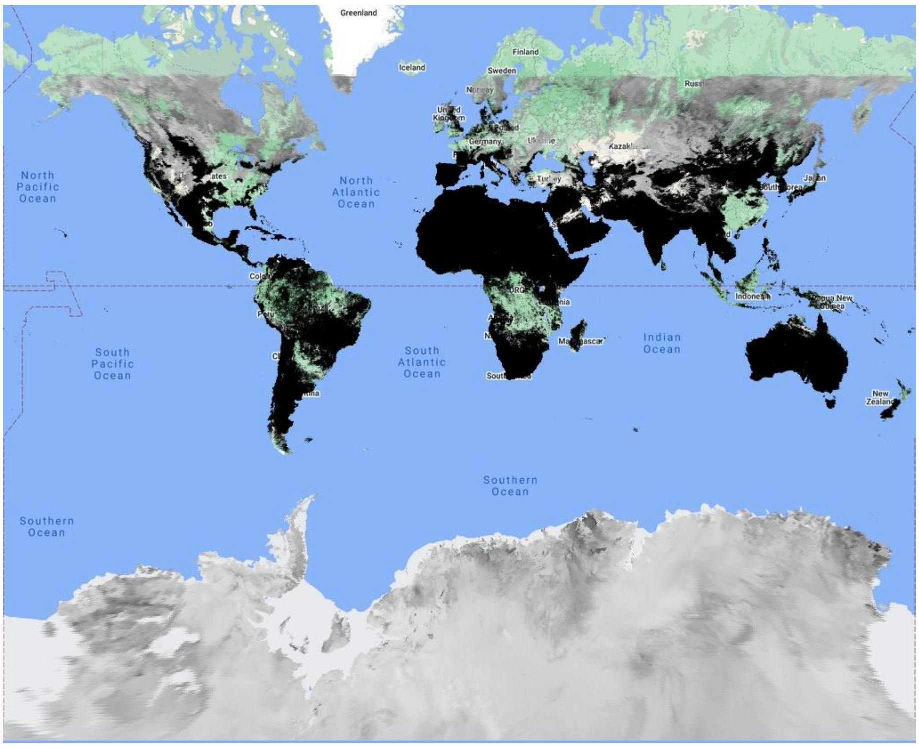


Figure 5: MODIS Terra snow cover - Google Earth Engine.

study. Datasets already containing the TOA reflectance was the first choice of the study to reduce the processing of the images.

4.1.2. Landsat 8 Datasets

Landsat 8 images have a temporal resolution of 16 days and complete one rotation of Earth every 99 mins (Department of the Interior U.S. Geological Survey, 2016). Although Landsat is one of the most suitable datasets to work with, the temporal resolution does not provide us with complete coverage of the Earth. Below are the two images taken as a 3-day resolution period and a 30-day resolution period from Google Earth Engine.

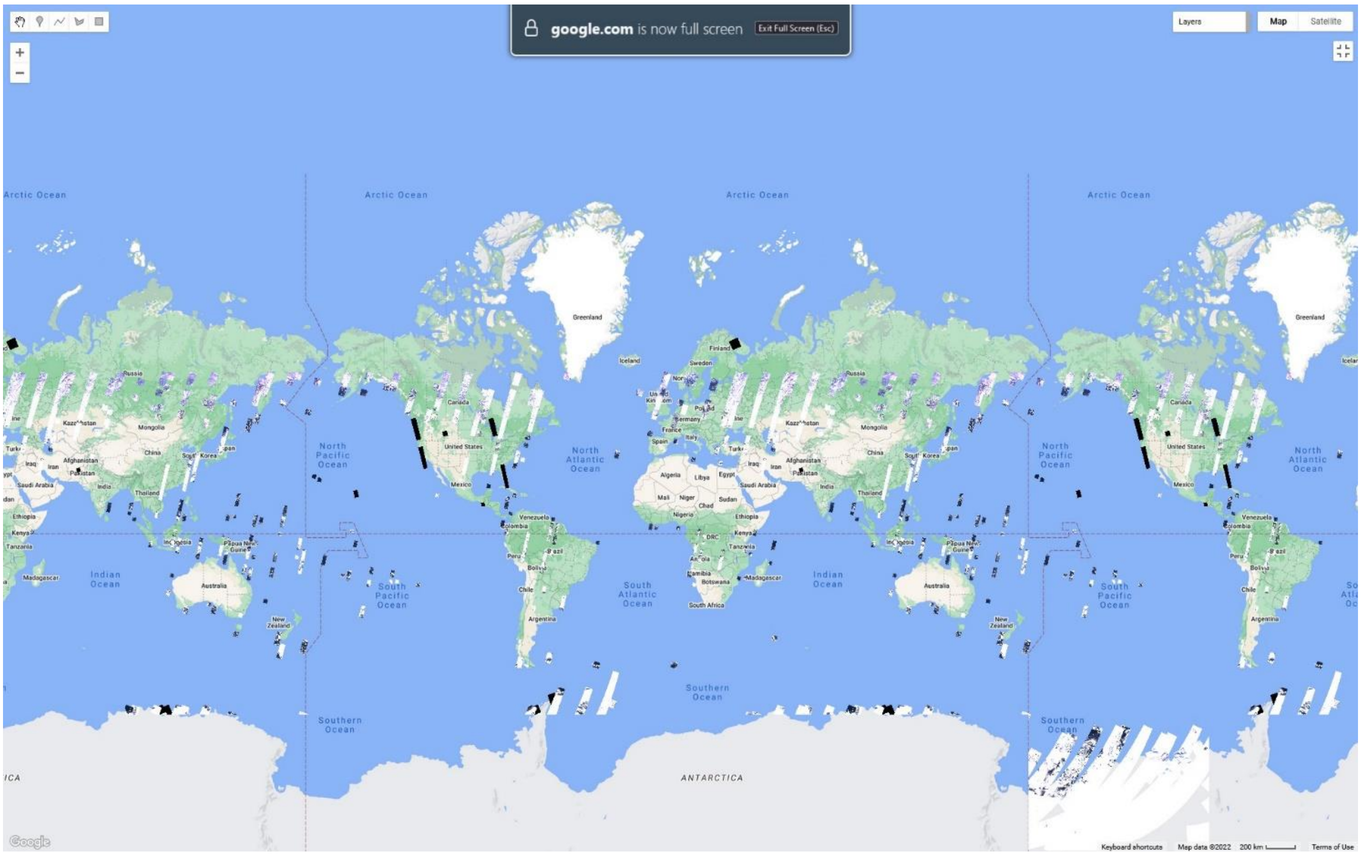


Figure 6: Landsat 8 dataset with a temporal period of 3 days - Google Earth Engine.

As seen in the two images (Figure 6 and Figure 7), images from the Landsat did not create complete coverage of the Earth. It is essential to have a dataset through which we can create a mosaic covering the entire Earth, to understand how different features might behave when viewed from phase angles. There are substantial gaps observed for the Landsat dataset in the three days temporal resolution image, and the 30 days temporal period image also displays a gap around significant parts of Africa and Asia.

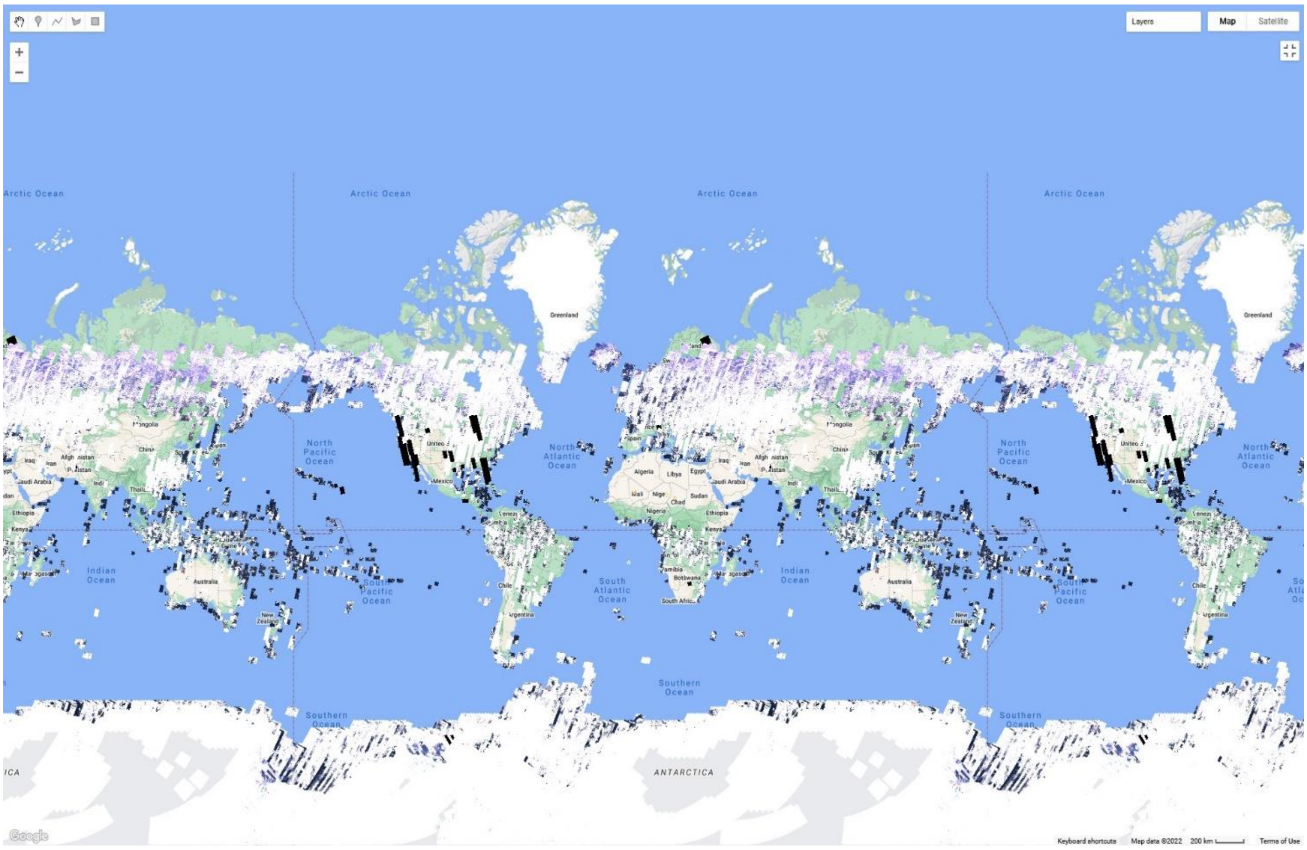


Figure 7: Landsat 8 dataset with 30 days temporal period - Google Earth Engine.

4.1.3. Sentinel 3 OLCI EFR

Sentinel-3 OLCI TOA Radiance dataset is freely available on the GEE platform along with the script, which can be used to call the bands and view the results.

Sentinel 3 image has a temporal resolution of about two days, covering the complete Earth. However, we observed some gaps near the equatorial region of the created map when taking images with two days of temporal resolution (Figure 9 and Figure 10). To overcome this and create an overview of the Earth, a three-day temporal resolution was taken, which creates a complete overview of Earth, including the clouds, ocean, lands etc. It can be seen from the image (Figure 8) that there is partial or no coverage in the polar region; however, Figure 9 shows some coverage in the southern part. This is due to multiple images being considered while creating a mosaic where some images have a partial observation dataset from the Antarctic circle while others don't. It has been observed that the dataset coverage shifts from north to south and vice-versa throughout the year (Figure 9 and Figure 10). This means that we get partial coverage of both the poles but not at the same time. It can also be seen that Figure 9 is grainier than Figure 8, which is the result of the downscaling of the image from 300 m to 25 km.

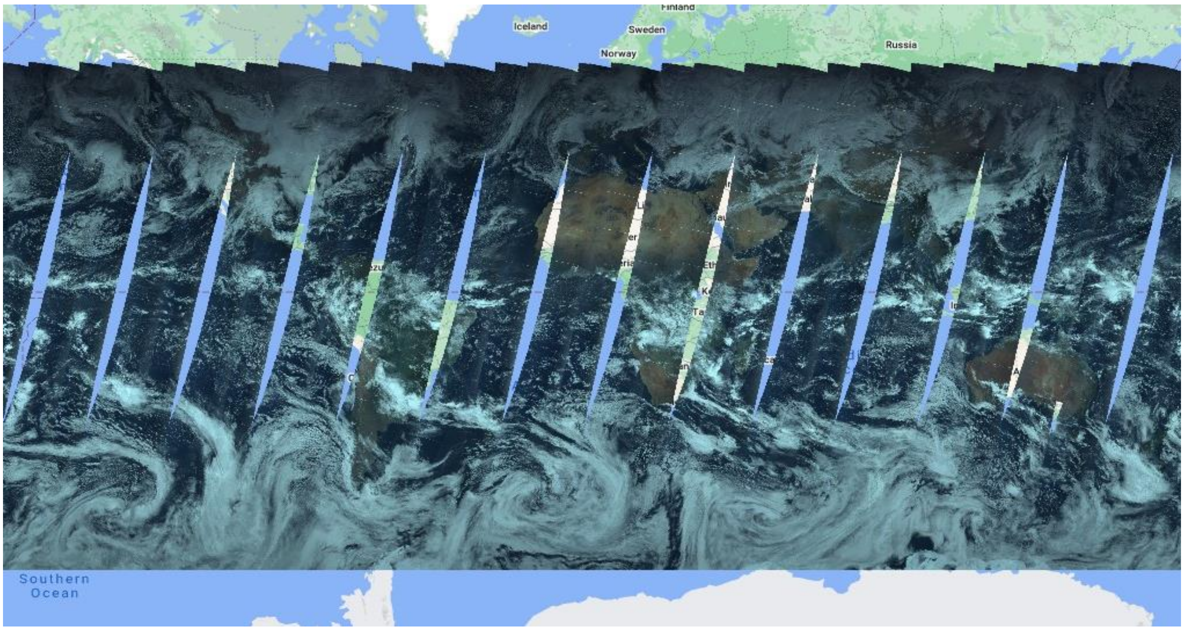


Figure 8: Sentinel 3 dataset with 2 days temporal period - Google Earth Engine.

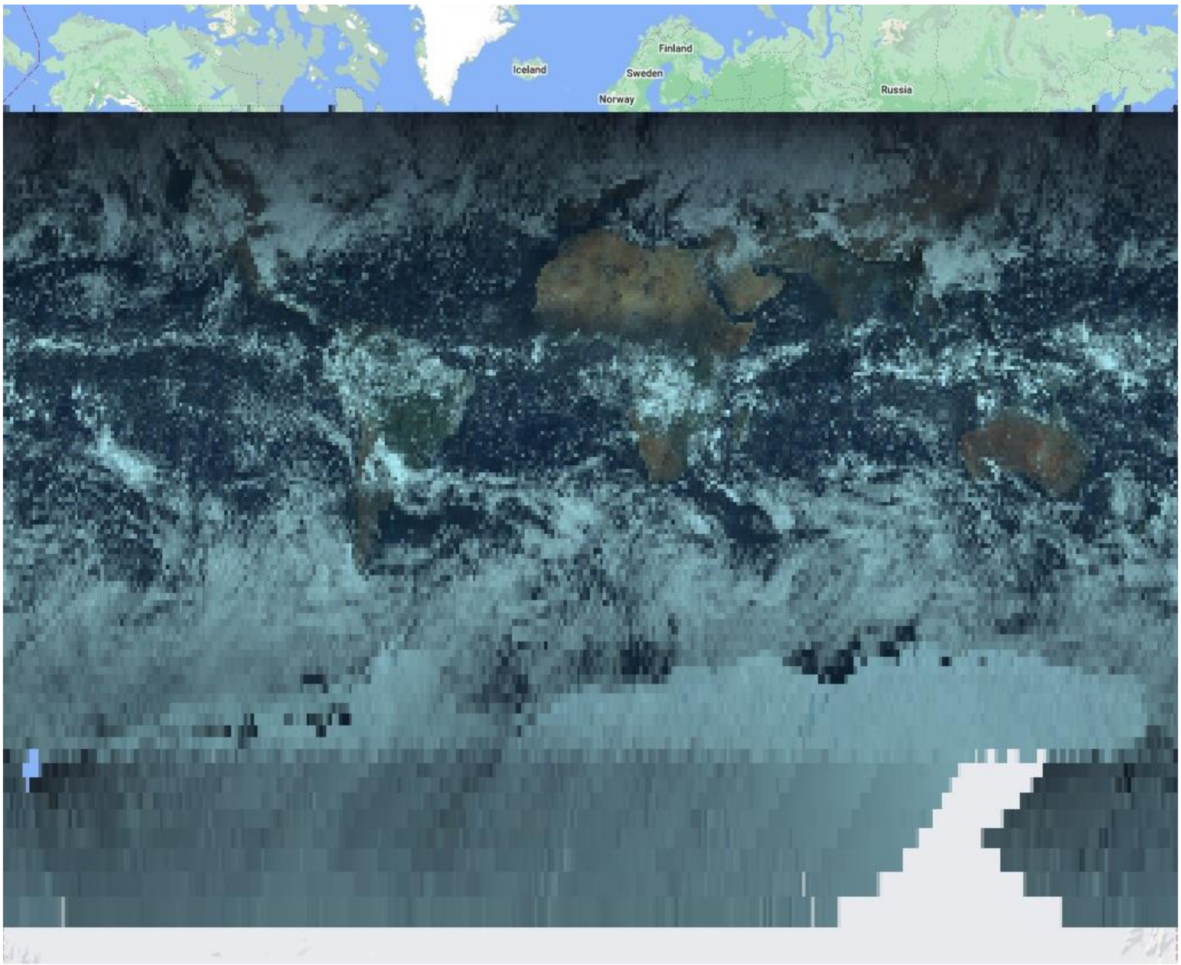


Figure 9: Sentinel 3 dataset with 3 days temporal period and 25 km resolution - Jan 2019.

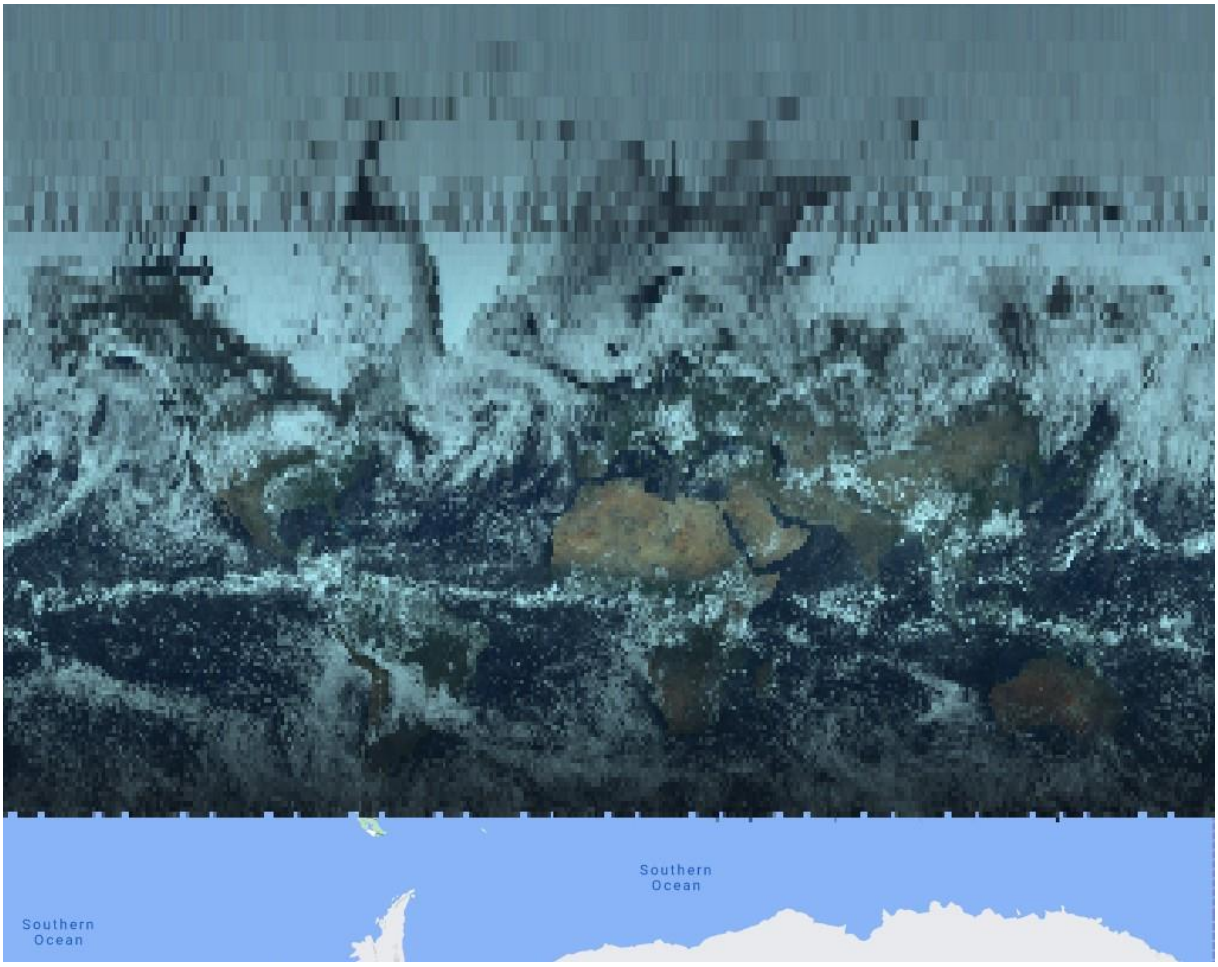


Figure 10: Sentinel 3 dataset with three days temporal period and 25 km resolution - May 2019.

The created image was then exported from Google Earth Engine to Google Drive and stored as a GeoTIFF file. The pixel size is reduced to 250 km/pixel from 25 km/pixel to decrease the number of pixels to be calculated via the Python script in the post-processing.

4.2. Understanding and the calculation of TOA Reflectance

As explained already, the calculation of TOA reflectance was done in a non-conventional way where each parameter is calculated rather than taken from the Metadata. Many a time, parameters are averaged enough to provide an overview of the values present from that day. For e.g. the irradiance value for the Sun is taken from one of the three-day temporal period of the acquisition date.

The Sentinel image already comes with the calculated TOA Radiance on GEE. The values from the GEE are scaled for each band, and the unit is "W m^-2 sr^-1 µm^-1" (GEE, 2020). Below you can see the image as visible through the python script using the function "imshow" of matplotlib (Figure 11). It can be seen from the image that although it is pixelated, we can still identify some features on Earth, namely clouds, water and land.

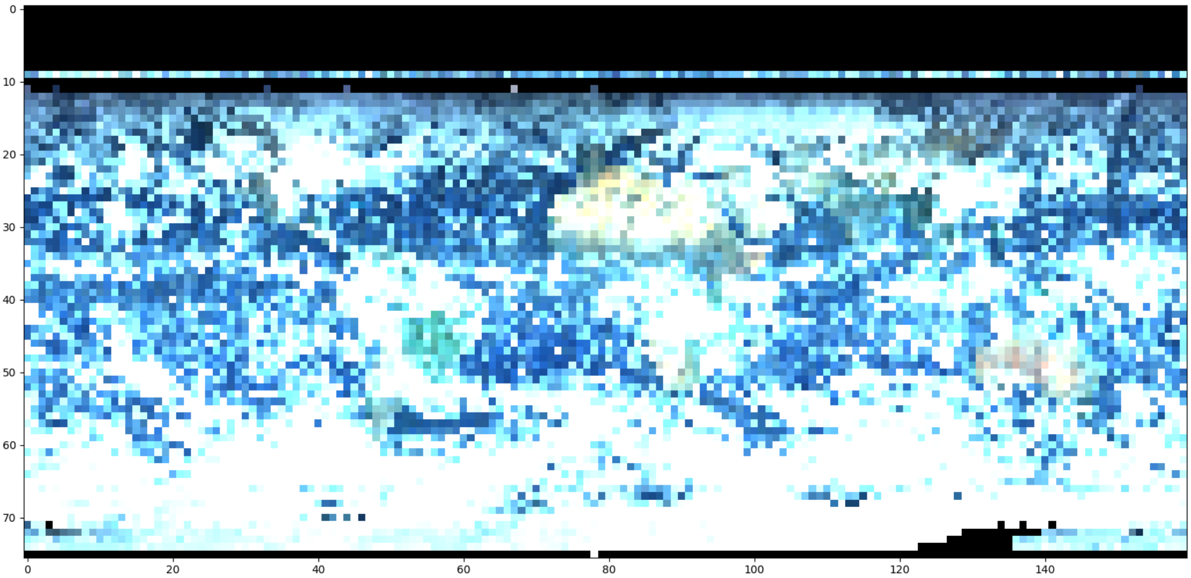


Figure 11: TIFF image as visible through Python's "imshow" functionality.

The image's histogram from Figure 11 can be seen in Figure 12 with all three bands combined and Figure 13 with individual bands. As can be seen from the figures, most pixels have values from 0 to 1. It is important to note that this image also contains "Nan" value pixels. Hence, reading the pixels' max and min values results in "nan" unless specified otherwise.

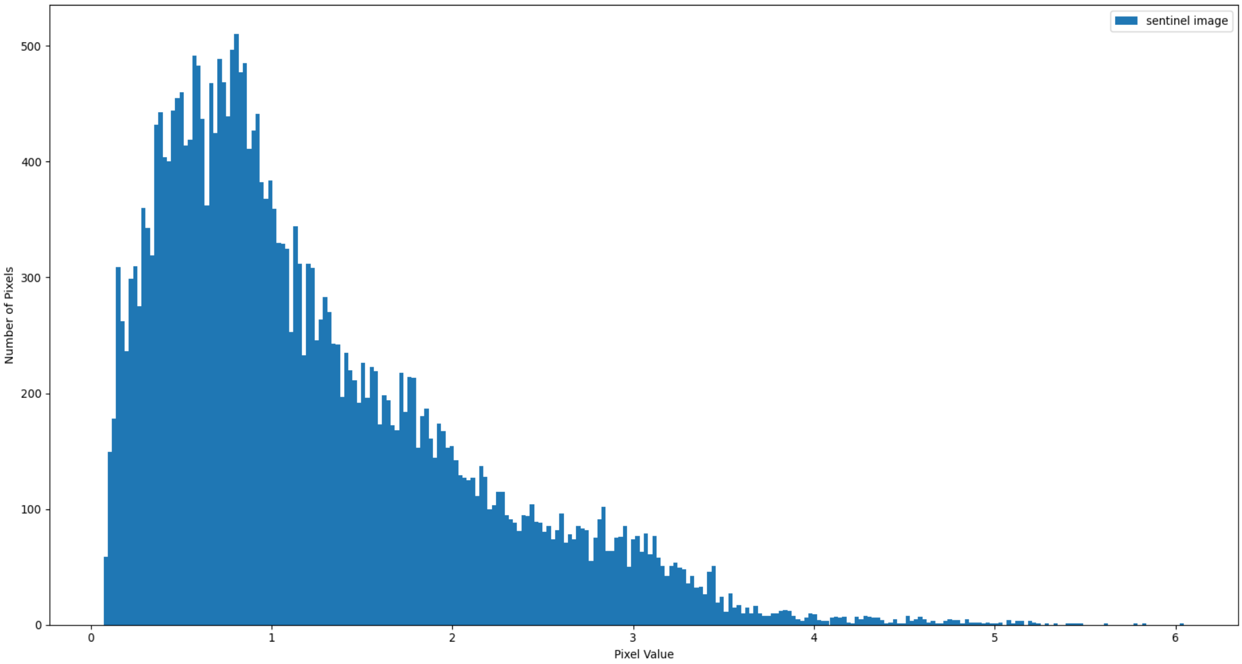


Figure 12: Histogram - All three bands combined.

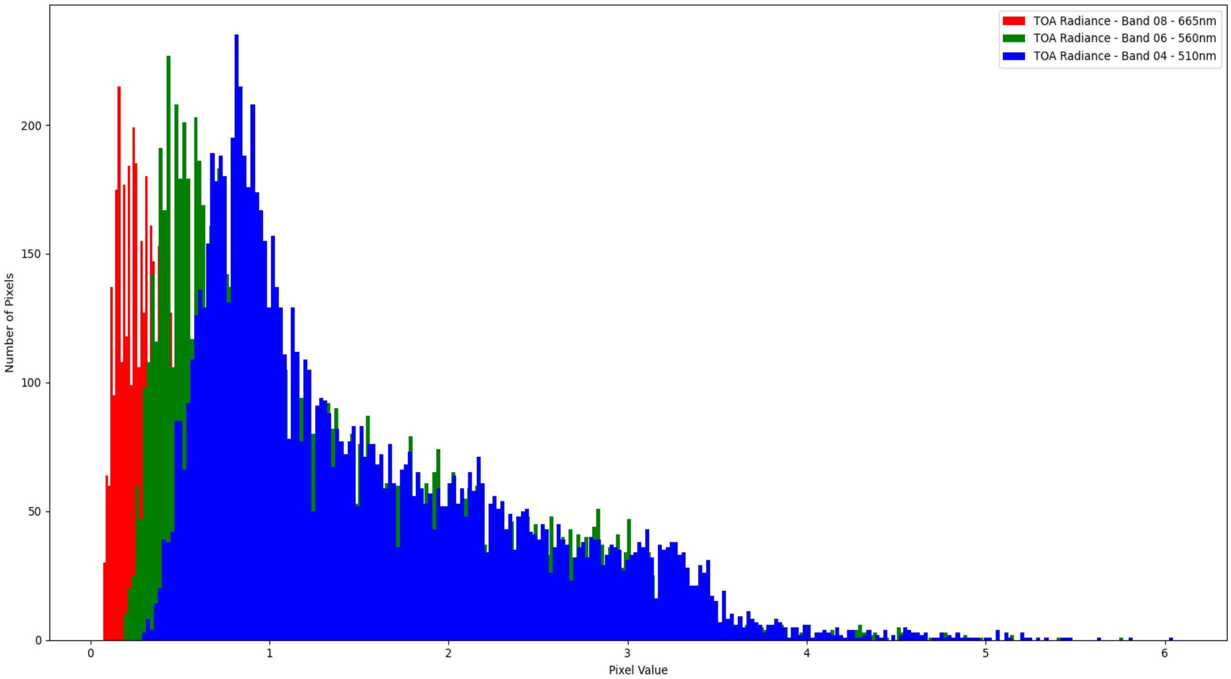


Figure 13: Histogram - For each band of the GeoTIFF image.

The image pixels have been extracted using the GDAL library, which is then used in a function created to calculate the Latitude and Longitude of each pixel. The latitude and longitude are in degree. The location information is then used to calculate the Sun Zenith angle.

The value for the Sun Zenith angle before Noon is between 0° to 90°. After that, the angle has to be subtracted from 180° to calculate the actual Sun Zenith angle for each location to avoid negative values. As for satellites, the Sun Zenith angle is captured along with the image and usually stored in the Metadata. The Solar Zenith angle for the image was calculated for each pixel.

As for the Solar Irradiance, the graph below displays the calculated solar irradiance via python.

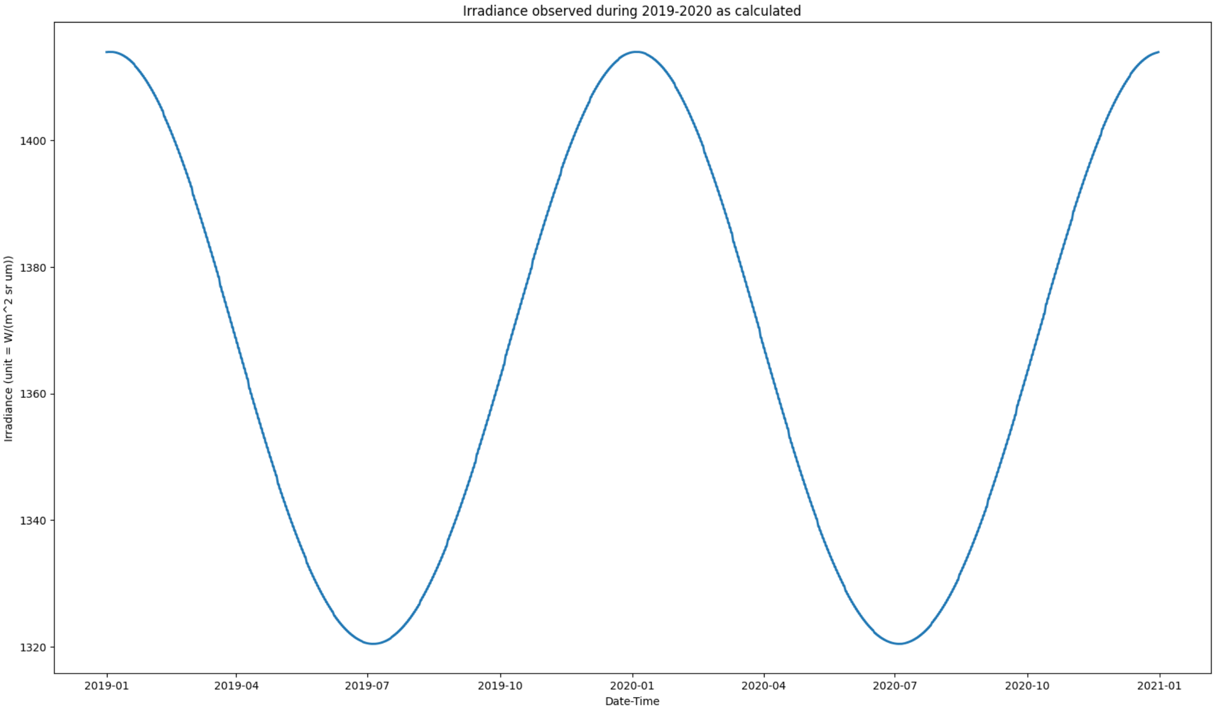


Figure 14: Sun Irradiance as calculated for different dates over 2019-2020.

As mentioned in the Methodology, sun irradiance was calculated using the pvlib library (Holmgren et al., 2015). TOA Reflectance was computed using the Sun Zenith and the solar irradiance, after which a TIFF image was created. Figure 15 shows the histogram created of the TOA reflectance values calculated. As can be seen from the image, most of the pixels have a value of around zero or just above zero.

However, we get a blank image when creating an image out of the values calculated.

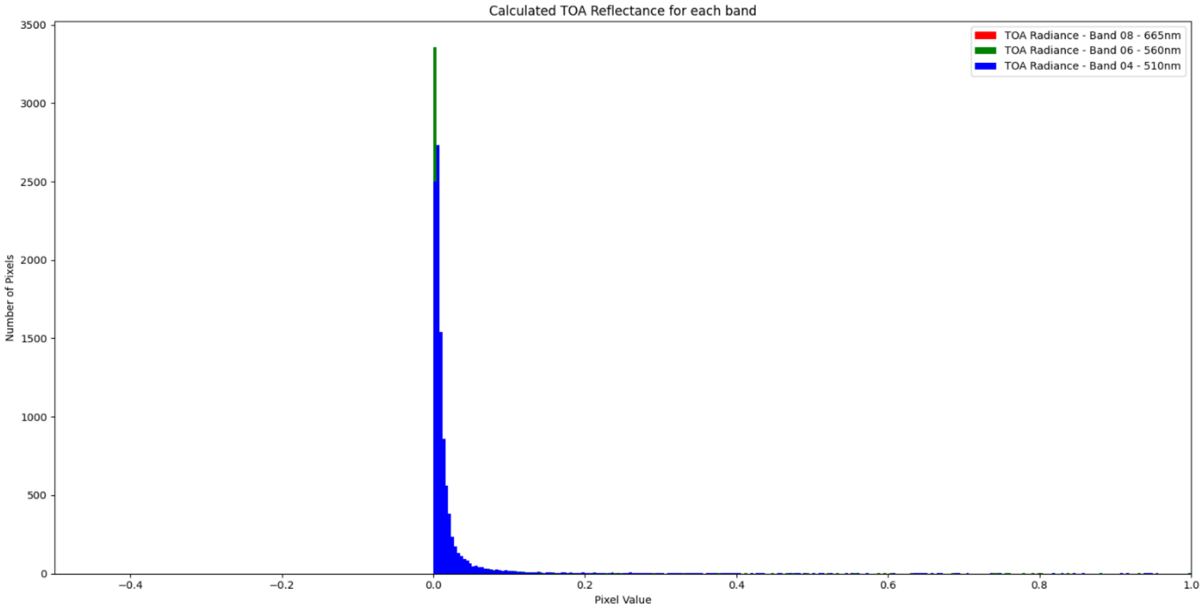


Figure 15: Histogram of the calculated TOA Reflectance.

4.3. Evaluation of the phase angle (in degree) for viewing the Earth from space.

LOUPE has been designed to work with Polarimetry, a requirement based on observing an object using Phase Angle. As has already been explained, different features react differently to each phase angle between 0° to 180°, eventually highlighting distinct features for observation (Klindžić et al., 2021). In the present study, we have five orbits analysed to understand which provides the most varied range of phase angles to study Earth as an exoplanet.

Figure 16 shows the possible orbits of Lagrange points L1, L2, L4, L5 and Moon. With the current focus by the LOUPE team on the L1 point, studying it and other Lagrange points provides a complete overview of different phase angles that can be used through each point. As seen in Figure 16, the orbit of the Lagrange point is at a further distance than the Moon. The distance of each Lagrange point is about 1.5 million kilometres. It is to be noted that the orbit of the Moon is visible as a point and L1 and L2 are not visible because the L4 and L5 orbit lies at a 60° angle from the Earth-Sun plane.

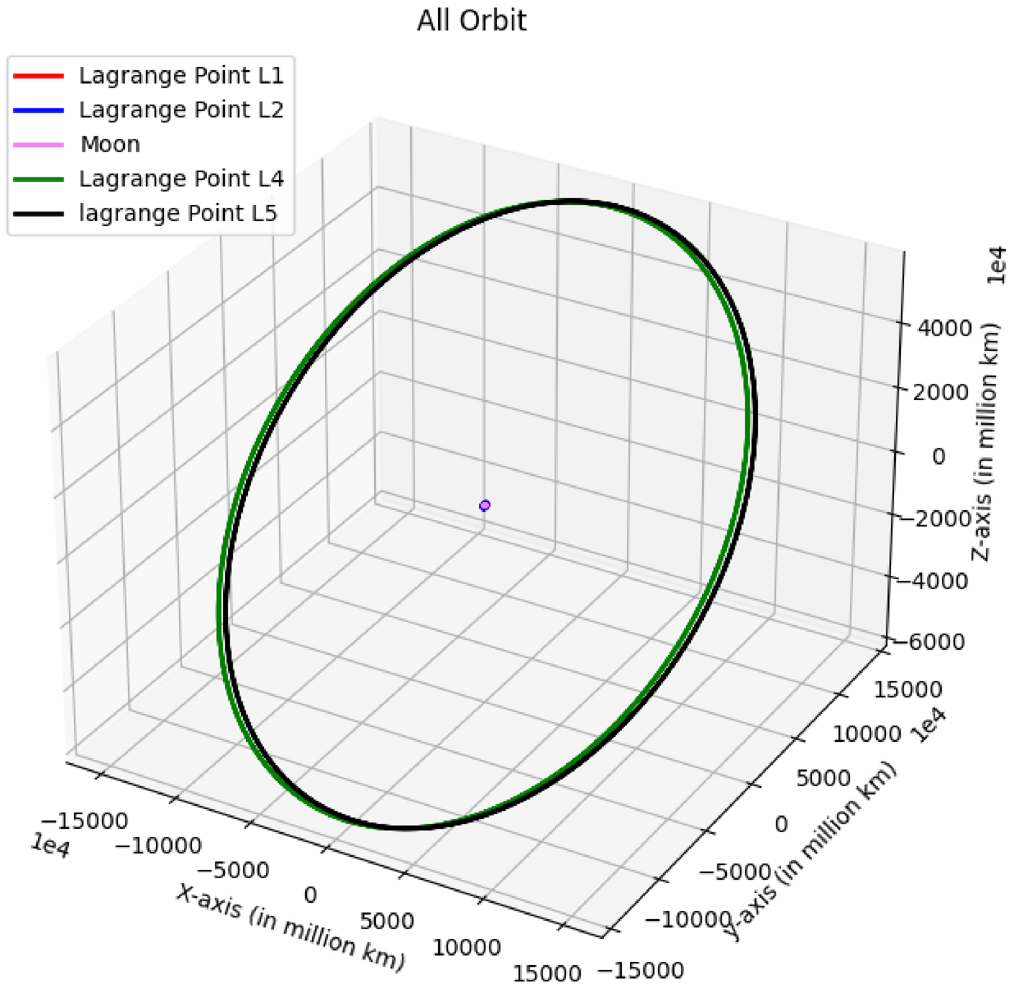


Figure 16: Orbit of Lagrange points and Moon.

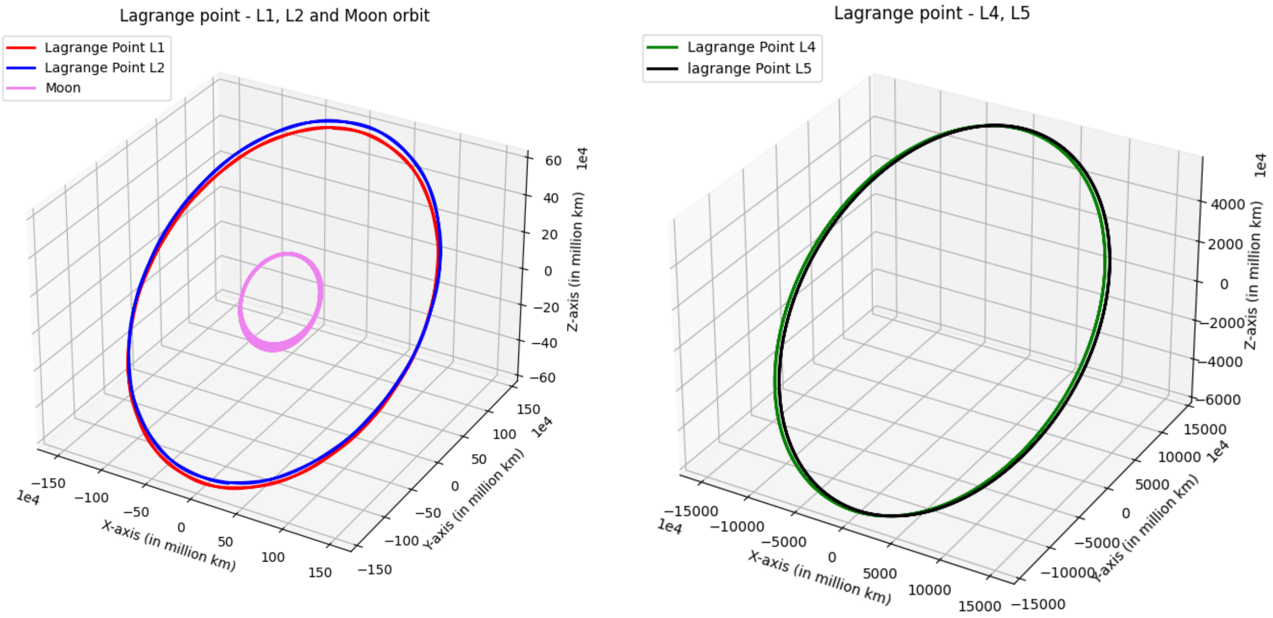


Figure 17: (a) Orbit of Lagrange point L1, L2 and Moon. (b) Orbit of Lagrange point L4 and L5.

Figure 17 depicts the path of each Lagrange point and the Moon. The orbit of L1 and L2 is an unstable orbit that requires periodic modification to the orbital parameters simply because of the distance, whereas the L4 and L5 orbits are stable orbits for the launch and usage of spacecraft. However, the mere distance of the L4 and L5 makes it challenging to be able to observe Earth as an exoplanet.

The table below, part of the complete table, describes the phase angle (in degrees) for viewing Earth from each orbit. Based on the calculation, we can see that all the Lagrange point shows a very narrow phase angle range, hardly ever changing through the year. Furthermore, Lagrange points L1 and L2 have phase angle at the very end of 0° to 180°. While the orbit of L4 and L5 do provide a phase angle of around 59° to 61°, the Moon offers a range of phase angles spanning the whole 0° to 180°.

	Date	L1	L2	L4	L5	Moon
1	2019-01-01 00:00:00	0.147777	179.8381	59.99262	60.00575	58.03642
2	2019-01-01 12:18:43	0.137022	179.849	59.99248	60.0055	51.92778
3	2019-01-02 00:37:27	0.125973	179.8601	59.99246	60.00536	45.91458
4	2019-01-02 12:56:10	0.111198	179.8751	59.99236	60.00512	39.92206
5	2019-01-03 01:14:53	0.0983	179.8882	59.99237	60.005	34.01606
6	2019-01-03 13:33:36	0.080242	179.9066	59.99232	60.00477	28.12476
7	2019-01-04 01:52:20	0.066159	179.9209	59.99236	60.00467	22.31352
8	2019-01-04 14:11:03	0.045675	179.9419	59.99236	60.00446	16.51441
9	2019-01-05 02:29:46	0.031091	179.9568	59.99243	60.00438	10.79606
10	2019-01-05 14:48:29	0.00982	179.9792	59.99248	60.00421	5.121231
11	2019-01-06 03:07:13	0.006544	179.9938	59.99258	60.00416	1.218292
12	2019-01-06 15:25:56	0.029156	179.9819	59.99267	60.00401	6.398494
13	2019-01-07 03:44:39	0.042375	179.9685	59.99279	60.004	11.96295
14	2019-01-07 16:03:22	0.065415	179.945	59.99291	60.00389	17.55932
15	2019-01-08 04:22:06	0.07735	179.9328	59.99305	60.00391	23.10952
16	2019-01-08 16:40:49	0.099459	179.9103	59.99321	60.00385	28.67617
17	2019-01-09 04:59:32	0.109454	179.9001	59.99336	60.00389	34.20212
18	2019-01-09 17:18:15	0.129833	179.8794	59.99355	60.00388	39.75222
19	2019-01-10 05:36:59	0.137394	179.8717	59.99371	60.00396	45.27463
20	2019-01-10 17:55:42	0.155305	179.8536	59.99391	60.00398	50.83349
21	2019-01-11 06:14:25	0.160029	179.8489	59.99407	60.00409	56.38157
22	2019-01-11 18:33:08	0.174803	179.8339	59.99429	60.00416	61.98178
23	2019-01-12 06:51:52	0.176367	179.8324	59.99444	60.00429	67.59133
24	2019-01-12 19:10:35	0.187416	179.8213	59.99466	60.00441	73.27141
25	2019-01-13 07:29:18	0.185582	179.8233	59.9948	60.00456	78.98333
26	2019-01-13 19:48:02	0.192414	179.8165	59.99501	60.00471	84.78595
27	2019-01-14 08:06:45	0.187037	179.8221	59.99513	60.00488	90.64405
28	2019-01-14 20:25:28	0.189281	179.8199	59.99533	60.00506	96.61322
29	2019-01-15 08:44:11	0.180331	179.8291	59.99542	60.00524	102.6607
30	2019-01-15 21:02:55	0.177768	179.8318	59.9956	60.00544	108.8374
31	2019-01-16 09:21:38	0.16536	179.8444	59.99566	60.00562	115.1116
32	2019-01-16 21:40:21	0.157968	179.852	59.99581	60.00584	121.5278
33	2019-01-17 09:59:04	0.1424	179.8678	59.99582	60.00602	128.0535
34	2019-01-17 22:17:48	0.130402	179.88	59.99593	60.00624	134.7246
35	2019-01-18 10:36:31	0.112203	179.8984	59.99591	60.0064	141.5062
36	2019-01-18 22:55:14	0.096107	179.9147	59.99597	60.00662	148.423
37	2019-01-19 11:13:57	0.076063	179.9349	59.9959	60.00676	155.4372
38	2019-01-19 23:32:41	0.05668	179.9544	59.99591	60.00696	162.5603
39	2019-01-20 11:51:24	0.035849	179.9755	59.99579	60.00705	169.7511
40	2019-01-21 00:10:07	0.014248	179.9972	59.99575	60.00722	176.9975
41	2019-01-21 12:28:50	0.006844	179.982	59.99559	60.00728	175.6702
42	2019-01-22 00:47:34	0.028756	179.9595	59.99551	60.00741	168.3705
43	2019-01-22 13:06:17	0.04772	179.9404	59.99531	60.00741	161.0769
44	2019-01-23 01:25:00	0.069656	179.9182	59.99519	60.0075	153.8163
45	2019-01-23 13:43:43	0.085749	179.902	59.99497	60.00745	146.6106

Table 3: Calculated phase angle (in degrees) for each Lagrange point and Moon.

5. DISCUSSION

Remote sensing and Earth observation have become essential to tracking, understanding and predicting possible Earth phenomena around Earth like weather, climate change etc. All these have become possible with the availability of numerous satellites currently orbiting Earth at various distances from Earth's surface. As has been mentioned, most Earth observation satellites orbit Earth at a distance of about 600 km to 1000 km, with the exception of Geo-stationary satellites, which orbit Earth at a distance of 36,000 km that is not only used for Earth observation but other purposes as well.

5.1. Evaluation of data availability and suitability

One of the main reasons to study Earth as an exoplanet is to investigate different features visible on Earth and understand how they can be seen through different phase angles. With numerous satellite data available through Earth Observation, it can be seen as an easy task to pick out the datasets which can be used for this purpose. However, one limitation was that these Earth observation datasets are designed or parameterised to observe Earth from a certain distance. Most of the data available as open-source are processed images with atmospheric correction, aerosol correction, and cloud masks, which are used to remove the influence of atmosphere and clouds from the image to read the features on the ground and sea. Satellite images used to study clouds and atmosphere create a separate layer for each component.

5.1.1. MODIS

One of the most important parts of this study was understanding if the Earth observation datasets are suitable for studying Earth as an exoplanet. When observing Earth from a distance in space, it is vital to understand how it looks above the atmosphere, including the atmospheric influence and the presence of clouds, aerosol particles, etc. With the initial research, it seemed feasible to include different layers created for various features to ease the possibility of identifying different reflectance. For this reason, MODIS data was considered during the initial part of this research simply because of the presence of different kinds of data products. It comes with layers focused specifically on atmospheric characteristics, aerosol layer, cloud layer etc.

However, each layer is defined using parameters that suit the given feature, limiting the possibility of combining them. While trying to combine the MODIS terra and Aqua images for surface reflectance and snow cover, it was evident that combining the two layers might not be possible due to the difference in characteristics of the two layers. While one layer took the RGB layer as a parameter with other spectrum ranges, the snow layer values were computed and retrieved from a snow mapping algorithm that uses NDSI and other criteria to calculate the snow cover (Hall and Riggs, 2016).

Due to these differences in parameters for each layer, it is also not possible to calculate the TOA reflectance, which is an essential requirement of the research. TOA Reflectance is computed using the Pixel's DN values or the TOA radiance layer. While TOA Radiance also provides us with the radiance values from above the atmosphere, it depends on the surface area it covers, while TOA Reflectance is independent. MODIS Images, available on GEE, do not provide us with either the TOA Reflectance or TOA Radiance parameters. Furthermore, the values from the end product can also not be used for calculating TOA Radiance.

5.1.2. Landsat 8

TOA reflectance datasets are available from the Landsat series. Multiple Landsat satellites like Landsat 5, Landsat 7, Landsat 8 and Landsat 9 provide the TOA Reflectance dataset on Google Earth Engine. Furthermore, the image comes with complete metadata equipped with each image, providing us with all the essential components for further analysis. This eliminates the possibility of performing manual calculations for the image.

However, due to the temporal resolution of Landsat, none of the datasets provides us with complete coverage of Earth, even when taking a time period of one month. As seen in the images from the Results section, Landsat data have gaps in the global coverage of Earth. While Landsat can prove to be an easy solution with the TOA reflectance layer, with the current requirement to observe the complete Earth and its different features, Landsat does not seem compatible with providing a complete overview.

5.1.3. Sentinel 3 OLCI EFR

Some of the advantages of using the Sentinel 3 layer for this study was that the dataset provided us with TOA radiance values which can be used to calculate the TOA Reflectance. As mentioned in the results section, the Sentinel dataset showed gaps around the equator using a two-day time frame; however, complete coverage can be obtained using a three-day timeframe for sentinel 3. But one disadvantage of using this dataset is that the Sun Zenith angle and the solar irradiance are not provided as the Metadata for this dataset. This limits the possibility of calculating the TOA Reflectance directly from the Google Earth Engine platform. This information is available as part of the Metadata for sentinel image if downloaded directly from the Sentinel repository.

5.1.4. Polar regions datasets

One of the features which stands out while looking at Earth is the availability of water and ice. The Antarctic region is mostly covered with snow/ice throughout the year, while the arctic circle has the presence of ice through the winter season. It is one of the distinct features present on Earth as these snow/ice is formed from liquid water and can be termed a vital feature to study while studying Earth as an exoplanet. Another limitation this research faced was the unavailability of unprocessed, visible range satellite datasets of the polar regions.

There are various datasets available from Polar regions for usage in different studies that can be downloaded and processed further. However, there are limited datasets available on GEE from the polar regions, most of which are either RADAR or DEMs (GEE, 2022). These datasets are the results from the polar datasets captured which are not directly available on GEE. We also looked at the possibility of downloading and using the polar datasets, but there are limited datasets available from the polar regions which can provide us with TOA reflectance values. Therefore, the partial coverage from the Sentinel 3 dataset has been considered to study the polar region.

5.2. Google Earth Engine

Google Earth Engine as a platform provides an easy-to-use interface for users with extensive datasets and scripts on the platform to perform operations related to remote sensing and Earth observation. The datasets available on GEE range from Landsat imagery, MODIS, and Sentinel to processed datasets like the DEM, the NDVI etc. GEE helps the user process big datasets without the hassle of storing them on your local computer, as satellite images usually require considerable memory for storage. This was one of the reasons Google Earth Engine was chosen as a platform for this study.

We worked with several satellite images stitched together and processed to create an overview of the Earth based on the date and time chosen within two years – 2019-2020. To avoid the possibility of creating a data repository and data management, we worked with Google Earth Engine. However, there are also quite a few limitations present while working with Google Earth Engine. As mentioned in the last section, although GEE has a vast data repository, it does not directly indicate that the available datasets are feasible for every study. Limited functionality and information are

attached to some of the datasets, which limits the possibility of processing the image online and exporting the desired information for further processing when the image is taken offline.
Another limitation faced during the present study was the limited availability of the Google Earth API for Python. Google Earth API for Python is an ongoing project of GEE which allows the user to integrate the functionality of GEE on Python. Due to limited functionality available for the platform, it is not possible to take the complete script offline to work within the python environment. Hence, it is not suitable to integrate currently.

5.3. TOA Reflectance calculation

Calculating the parameters and the TOA reflectance for the mosaic layer is one of the main objectives of this study. With the limitations faced on the Google Earth Engine platform, we moved to Python to calculate the TOA Reflectance.

The results show that we calculated some parameters required to calculate the TOA Reflectance, namely Sun Zenith Angle and Sun Irradiance, and the TOA radiance was present in the layer. With the libraries for python, it is quite a simple task to calculate the sun zenith and irradiance for the given location. With the latitude/longitude available, we only needed the time to calculate both parameters. Table 4 describes the parameters of the Sentinel 3 image created via GEE and used for further calculation.

Parameters	**Value**
Size	160x76
Coordinate System	WGS 84
Type	GeoTIFF
Original Spatial Resolution	300m
Spatial resolution - Downscaling	25km
Pixel Size	250km
Number of Pixel	Column = 160, Row = 76
	Total = 12,160
Temporal period	3 days
Time Period	2019-2020
Bands	RGB
Geometry	
-179.6630568, 85.3399520	179.6630568, -85.3399520
-179.6630568, -85.3399520	179d39'47.00"W, 85d20'23.83"S
-179.6630568, -85.3399520	179d39'47.00"E, 85d20'23.83"N
179.6630568, -85.3399520	179d39'47.00"E, 85d20'23.83"S

Table 4: The parameters used for the Sentinel 3 image.

However, it should be noted that the temporal resolution of the image was taken to be three days, and the time provided for calculating the Sun Zenith angle and Sun Irradiance was one of the days from those three days. It means that the Sun Zenith angle and the Sun irradiance were calculated based on one day from the selected three days. The formula (Equation 1: TOA Radiance to TOA Reflectance.) helps calculate the TOA reflectance based on one image and its parameters. In contrast, the Sentinel image is a mosaic of images over time. Considering that each parameter has been calculated for the same time (in UTC), calculating the solar zenith angle averaged over only one day would cause an error in the result.

These errors in calculation can be understood from the histogram (Figure 15) of the calculated TOA Reflectance of each band. Although the values of TOA reflectance are supposed to lie between 0 and 1, which the graph donates, the computed values are mostly either "NaN" or contain a value of 0. The resultant image also is a blank image created using the GDAL library. This indicates that the calculated TOA Reflectance using the current process has a significant error margin, resulting in an image with incorrect values for each pixel.

5.4. Phase angle and optimal location

Another part of the study's main objective was to identify the optimal location to observe Earth as an exoplanet. Phase angle, as described above, is an angle between the source of the light onto the target body and the observing body.

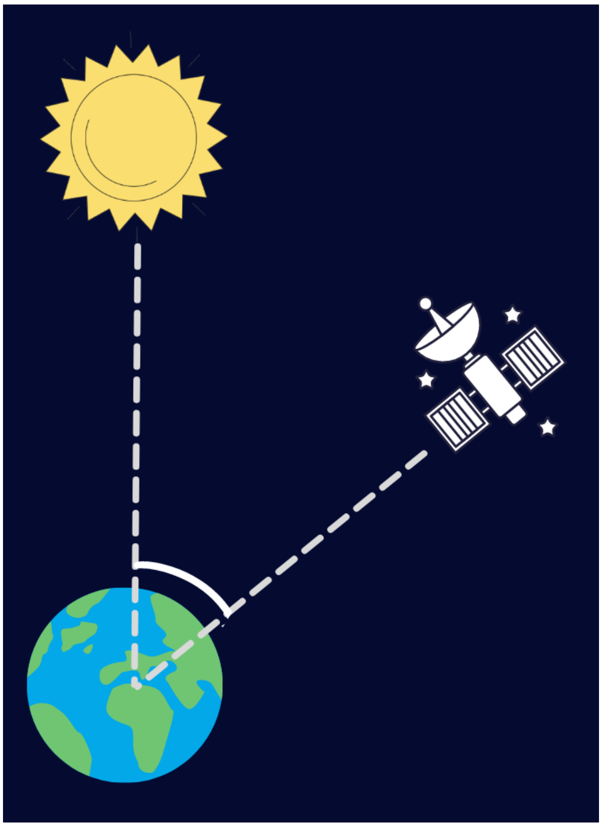


Figure 18: Phase angle between the observer and the surface of illumination for a planet.

Phase angle is very much dependent on the location you are viewing the object from. As described in the results section, a phase angle may have slight variation over a time period if viewed from a constant location but will have a varied range (in the case of the Moon) when the object is changing location as compared to that of the target body.

As seen in the image in Figure 19, the orbit of L1 does not provide much of a variation because the location of observation is fixed. Another drawback of using the trajectory of L1 would be the sun glint. This orbit is usually used to observe the Sun as it provides a direct and unobscured view of the Sun. However, it might pose an issue while observing Earth. As for the L2, this orbit offers a clear view of the Earth or space without extreme sun glint. But, as with L1, L2 also will be hosted at the same position relative to Earth.

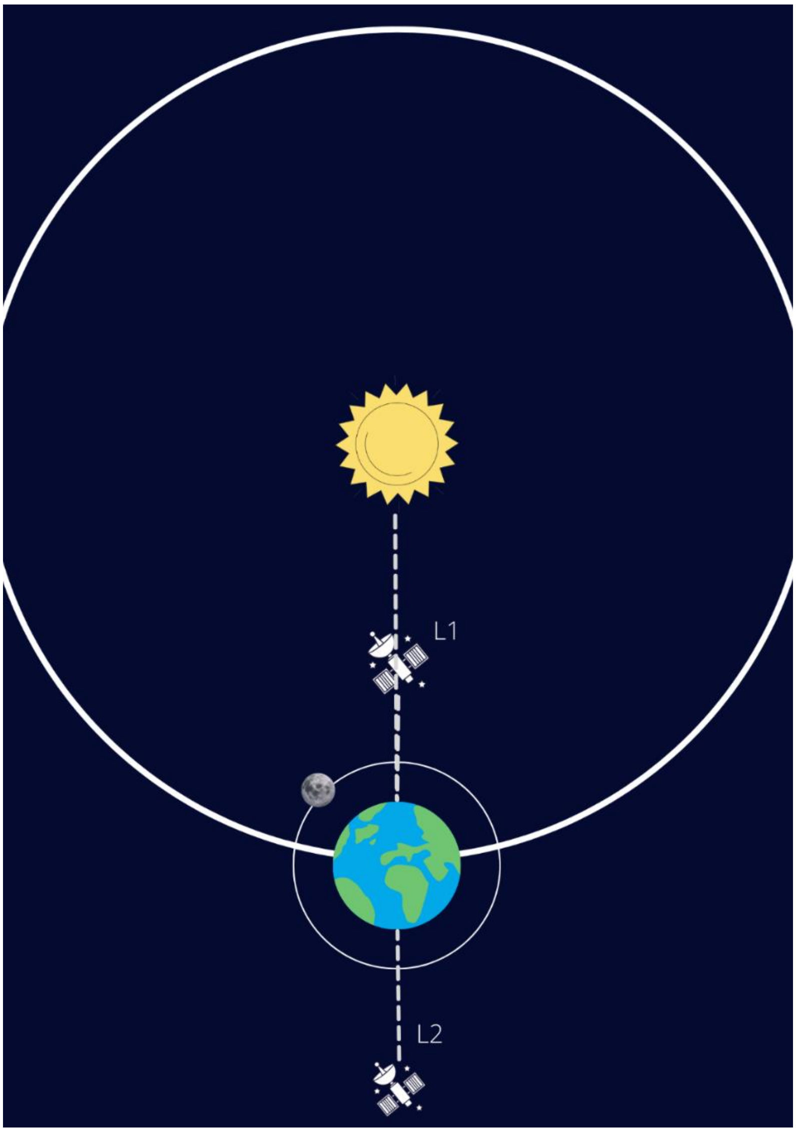


Figure 19: The L1 and L2 Lagrange point around Earth.

It is interesting to note that the orbit of L1 and L2 is fixed as compared to Earth but is not limited to one particular location on Earth. As seen with the James Webb Telescope, the satellite does revolve at its position compared to Geostationary orbit. At the Lagrange point, the Earth and the satellite orbit each other but remain at the same position relative to each other.

As for the L4 and L5 orbit, the Lagrange point L4 and L5 sit at an angle of 60° from the Earth-Sun plane.

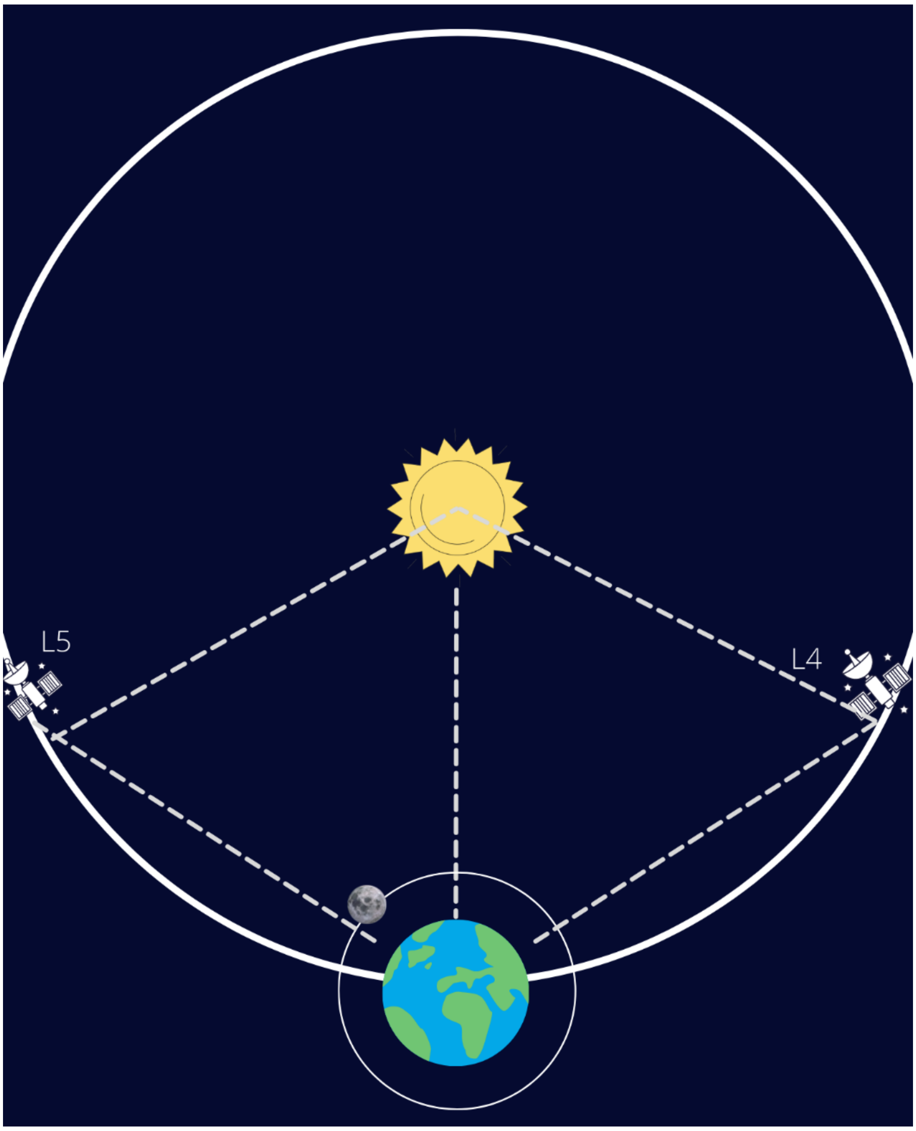


Figure 20: L4 and L5 Lagrange point from Earth.

In terms of L4 and L5, the distance and the angle at which these points exist from Earth proves to be a limitation in observing Earth as an exoplanet. These two orbits provide for a very stable orbit around Earth, and a phase angle between 59° and 61°, which may prove helpful, but the very limitation of L1 and L2 orbits applies here too. The position of these two points compared to the Earth remains constant and may not provide a wide range of possibilities for observing Earth's features.

As for the orbit of the Moon around Earth, it is seen from the table provided in the results section that we can observe Earth using a wide range of phase angles using this orbit. It has been discussed multiple times already in this thesis that studying different features on Earth using a wide range of phase angles would be the most suitable for LOUPE. The minimum phase angle calculated for Moon is 1.218 °, while the maximum is 178.766°.

According to these results, it can be said that the most suitable orbit to observe Earth would be that of the Moon to understand how Earth features behave in different phase angles. The image below depicts the trajectory of the Moon around Earth (Saraf et al., 2011).

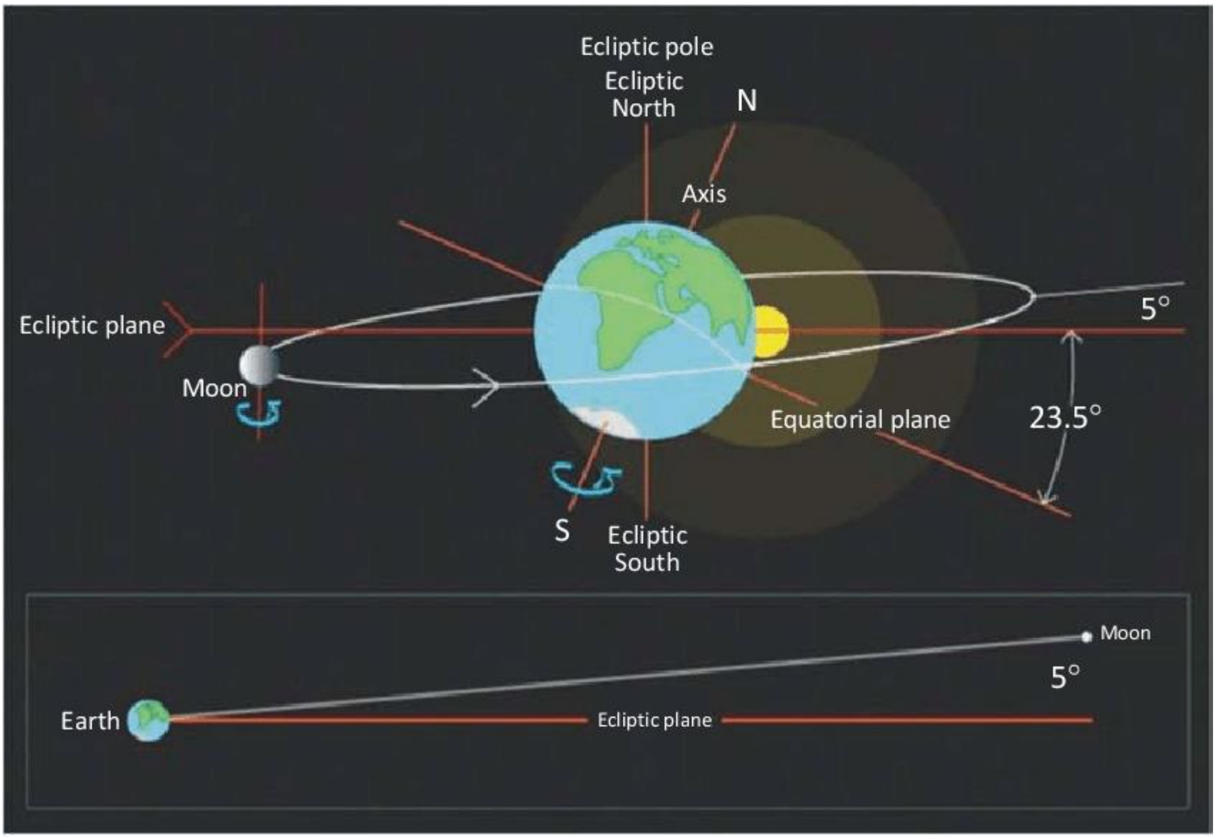


Figure 21: Moon's orbit around Earth (Saraf et al., 2011).

6. CONCLUSIONS AND RECOMMENDATIONS

The present research aimed to understand if the Earth Observation datasets are suitable to study Earth as an exoplanet and calculate the optimal location from where we can observe Earth as an exoplanet. The attempt to understand this requirement was based on understanding Earth observation datasets and testing the limits to which they can be modified to yield relevant results. Due to the study being a first of its kind, there was no methodology defined which can be followed for this kind of study. Hence, the attempt was made based on the present knowledge and requirements at the time of the research.

It was found during the research that the current resources, namely, the Google Earth Engine and the data repository on it, provide limited support in conducting a study of this domain. Although the platform provides us with a wide variety of satellite imagery and processed products available at our disposal, GEE as a platform has less flexibility or limited opportunity to modify the already available dataset. Furthermore, it was also understood from the study that taking an average or separately calculating the parameters which depend on the Metadata of individual datasets is not a favourable solution.

Limitations faced with the dataset availability on Google Earth Engine as a platform gives us insight that even with open-source, there are limitations to what the dataset can be used for. The dataset availability seems to be one of the major setbacks faced during this study. It was understood from the study that while the Earth observation datasets provide us with the possibility to conduct these studies, combining the two domains of Earth Observation and space exploration requires much more research and dataset compatibility study. As for the platform to be used for an analysis like this, online open-for-all platforms might be a solution if it offers the possibility to conduct the pre and post-processing of the image; however, if part of the processing has to be undertaken elsewhere, these online platforms might not be the most suitable.

Furthermore, it was observed during the study that the Earth observation datasets have to be modified quite a lot based on the requirements from a space exploration perspective. On the one hand, we were able to analyse and suggest that the orbit of the Moon would be the most feasible location to observe Earth as an exoplanet. On the other, limitations faced during the processing of Earth observation data proved as an impossible challenge to observe features on Earth using the various phase angles.

It is important to note here that the study has considered many parameters based on the understanding and possibility of the solution. However, much more research is required to understand its feasibility. Requirements related to the parameters and theories regarding studying the Earth using the phase angle require a much deeper understanding of how light reacts to the phase angle and the physics concerning Polarimetric observation of an object.

A lot of limitations can be observed through the present study, which helps us to understand why conducting research by combining two domains can be difficult. However, with the current progress within the Earth observation datasets and space research, it can be of interest for quite a few people to understand how Earth may look if we observe it from a different perspective.

While conducting a study like this, we also understand that while a lot of research is required and studies like this may face a lot of roadblocks than previously thought, it is also a domain which may help us move ahead with our research in the space domain. However, such studies may require quite a large amount of resources and an understanding of various domains. Therefore, to conduct a follow-up study, it is essential to understand the basic requirement and capabilities of the study while also having a proper understanding of the limitations that the current resources present in front of us.

6.1. Recommendations

To conduct a follow-up study for proper usage and viewing of the different features on Earth, it is important to understand and pinpoint the limitations faced during the present study.

6.1.1. Data suitability study

From the present study, it is pretty evident that very few datasets can be used to conduct a study like this. Also, using the datasets available on the online platform may come with their own set of limitations, which can prove to be quite tricky to deal with. Therefore, performing these studies with datasets available with the required information is recommended, mostly found with imagery available for download. There are various datasets available for download, which comes with the required Metadata to be used for further processing and can be combined to create an overview of the Earth.

However, the compatibility of these datasets should be studied in advance. With multiple datasets providing different coverage of the Earth at different points, it is recommended to consider the required parameters for each layer based on the Metadata available for each of them. This may make it easier to combine the images and have the correct values for each pixel for further analysis.

Furthermore, it is also required to research which platform, online or software-based, would be suitable to conduct a study like this. With the present research, we see that GEE as a platform has its own set of limitations with data processing. Therefore, it is recommended to use the platform which provides functionality for Earth observation and space domain. Or, the compatibility of the results should be checked if different platforms are being used. It should be noted that each satellite imagery takes around 300 Mb of space based on the type. Hence, a recommendation would be to consider that while downloading, processing and storing the data. Although it can be said that using software to reduce the processing time for these studies might be a feasible solution, it is not an easy answer as to which platform provides the most robust techniques required in a study like these.

6.1.2. Studying different features using phase angle

From the present study, we can understand that the orbit of the Moon provides us with the maximum range of phase angles to study Earth as an exoplanet. However, due to limitations in the results from the Earth observation data, it was not possible to study the features seen on Earth using these phase angles.

To conduct a study for different features, it is recommended to understand various parameters required while observing them using phase angle. Studying different features using phase angles requires a good knowledge about how light is inferred when looked through using Polarimetry and how different phase angles might affect the visibility of various features.

It is recommended that the follow-up study considers this information and understands the compatibility of the obtained results to the requirement of Polarimetry before studying different features on Earth using the results from the present research.

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