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The Radio Frequency Interference Environment Behind the Moon between 0.3 - 30 MHz

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Summary

In the study of several processes in the universe, observations at low frequencies (0.3 MHz – 30 MHz) will give valuable information. These observations cannot be done on the Earth's surface due to the obstruction and scintillation by the Earth's atmosphere at low frequencies. Therefore observations have to be done in space. To protect observing satellites in space from radio interference from Earth, the Moon might be used as a shield. It is however not known how well the Moon can function as a shield, and therefore several sources of interference and propagation mechanism are examined in this literature research.

The Radio Frequency Interference (RFI) produced by the Earth has several sources. To determine the amount of RFI behind the Moon, these sources are looked into. The first source that is examined is artificial radio communication. These transmissions are used for broadcasting, navigation systems and many more applications. Another source of RFI that is looked into is lightning. During lightning discharges, which globally occur 40-50 times per second, RFI is produced. The third main source that will be examined is Auroral Kilometric Radiation (AKR) which is produced at a high altitude in the auroral zones.

An important aspect which has to be accounted for is the location where the RFI is produced. The AKR is produced above the ionosphere, and therefore does not have to propagate through it. Lightning and artificial transmissions however do have to propagate through the ionosphere, which will attenuate signals especially at the lower frequencies. This attenuation also depends on whether it is daytime or night time.

To end up at an observer behind the Moon, the RFI also has to propagate behind the Moon. Various propagation mechanisms are looked into to determine the most important propagation mechanism. First, direct line-of-sight (LOS) is discussed. This is especially important for AKR, since AKR is produced at a high altitude above the Earth.

When the Moon is between the source and observer, diffraction may occur. Diffraction can be modelled as Fraunhofer diffraction for the far-field, and Fresnel diffraction for the near-field. The final propagation mechanism that will be discussed is surface wave propagation, which will use the surface and the atmosphere as a waveguide to travel past the horizon. Surface wave propagation can be separated in sky wave propagation and ground wave propagation.

It appeared that AKR is the most important source, and ground wave propagation is the most important propagation mechanism to get to an observer behind the Moon. Therefore AKR and ground wave propagation are further examined to determine their influence on the amount of RFI behind the Moon.

From the information collected about the different sources and propagation mechanisms it can be concluded that the Moon can act as a shield against RFI produced by the Earth. Due to the very low conductivity of the Moon's surface, interference will be much weaker than the Galactic Background Radio Noise when not in LOS, and therefore proper observations can be conducted behind the Moon.

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1. Introduction

To get a better understanding of the universe, radio astronomy observations in the 0.3-30MHz band are of great interest. For example in the study of the early universe, between 0.38 and 400 million years after the big bang. The observation of signals below 30MHz cannot be done on the Earth's surface, because these signals cannot propagate through the Earth's ionosphere properly [1]. Therefore, the observations below 30MHz have to be done in space. The Orbiting Low Frequency Array (OLFAR) project for example aims to develop a radio telescope consisting of multiple satellites to conduct these observations.

The signals that need to be observed are very weak. To prevent terrestrial radio frequency interference (RFI) disturbing these signals, a Moon orbit or the Earth-Moon Lagrangian point behind the Moon (L2 point) might be used. When the satellites are behind the Moon, the Moon can act as a shield against the RFI produced by the Earth. This will reduce the amount of RFI coming from Earth, but the amount of reduction, and the size of the area of reduction behind the Moon is not known.

Due to diffraction, the RFI might bend around the Moon, and still have significant presence at locations where there is no direct line of sight to Earth, especially at the lowest frequencies. The amount of RFI presence behind the Moon due to diffraction is not known, while it is an important factor for radio telescopes like OLFAR. The research question of this assignment is to determine the influence of RFI produced by the Earth on the amount of interference behind the Moon, especially between 0.3 MHz and 30 MHz.

To do this, various aspects of RFI produced by the Earth and the interaction with the Moon have to be examined. For example the influences of the polarisation of the signals, the surface wave propagation, the frequency dependency and the conductivity of the Moon's surface have to be accounted for. Various types of diffraction and propagation will be looked into. The source of RFI which is expected to have the most influence will be further examined. Important factors like the frequency range and emitted power will have to be accounted for. Also the different propagation mechanisms will be looked into, and the propagation mechanism which is expected to have the most influence will be examined thoroughly.

The final result of this literature research will be a summary of the different RFI sources (Section 2.1) and propagation mechanisms (Section 2.2) that might influence the amount of RFI behind the Moon. For the source which is expected to have the most influence, AKR, a more detailed estimation of the influence on the amount of Earth-produced RFI behind the Moon will be made in Chapter 3. This will also be done for the propagation mechanism which is expected to have the most influence (ground wave propagation) in Chapter 4.

2. Preliminary research

To get more insight in the Radio frequency interference (RFI) behind the Moon, it first has to be determined how this RFI is produced, and how it propagates to the locations behind the Moon. There are multiple sources of RFI, but it is unknown which source has the most influence. There are also multiple propagation mechanisms that cause RFI produced by the Earth to be present behind the Moon. In this chapter, the various sources and propagation mechanisms are looked into to estimate which source and which propagation mechanism are the most important. These are then examined in more detail in the subsequent chapters.

2.1. Sources of radio frequency interference

The RFI produced by the Earth has three main sources. The power and the frequency range of these sources are important for the determination of the amount of RFI that will be observed behind the Moon. Another important aspect which has to be accounted for is the location where the RFI is produced. RFI produced high above the atmosphere results in a much smaller cone of RFI shielding behind the Moon than if the RFI is produced at the Earth's surface. The three sources that will be examined in this section are Auroral Kilometric Radiation (AKR), artificial radio transmissions and lightning discharges. To be able to reach the Moon, the RFI produced by sources near the Earth's surface first has to propagate through the atmosphere. Especially the Ionosphere has a great influence on radio waves. So before looking at the sources themselves, the ionosphere will be examined.

2.1.1 The Ionosphere

During daytime, radio waves at frequencies up to 30MHz are absorbed by the ionosphere. The ionosphere is part of the atmosphere, which can be split in several layers as shown in Figure 1. Due to solar radiation, gas molecules are ionized and an electron is set free, resulting in a positive ion. The ionosphere is named after these ions, but it is the electrons that affect the radio waves [2].

The ionosphere can be split in several layers, which are also shown in Figure 1. The lowest layer is the D-layer at an altitude of 50 to 80 km. The density of the air at this altitude is still high, and therefore ions and electrons recombine relatively quickly. During night time, when solar radiation is blocked by the Earth, electron and ion levels fall quickly and the D-layer effectively disappears. This also goes for the E-layer. The F-layer exists of two layers (F1 and F2) which combine to one layer during night time, but do not disappear.

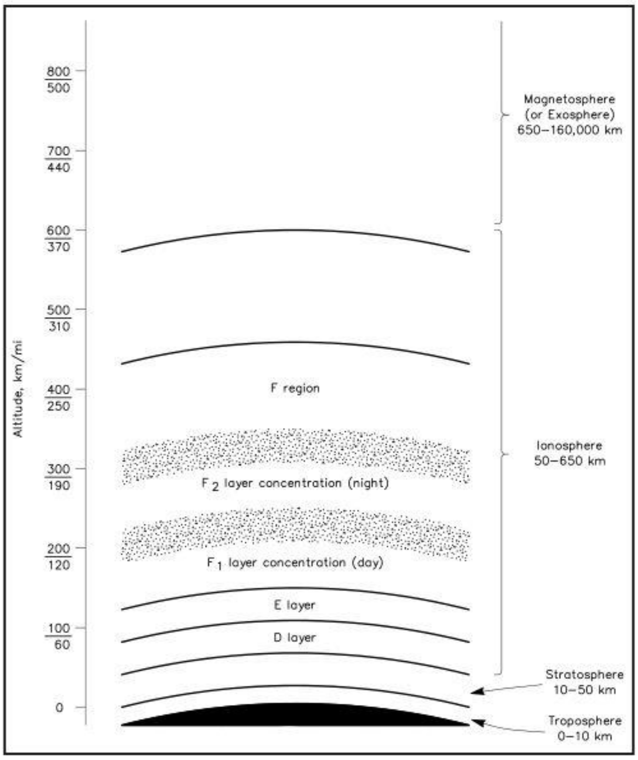


Figure 1: Different layers of the Earth's atmosphere [2]

Radio waves originating from the Earth's surface first reach the D-layer. Due to the large amount of electrons, radio waves are attenuated by the D-layer. The amount of attenuation depends on the inverse square of the frequency, which means that especially low frequencies will be attenuated. The attenuation is so large that during daytime the radio waves below 10 MHz are effectively blocked by the D-layer, and will not be significant enough to be further accounted for.

During night time, there is no D- and E-layer. Radio waves originating from the Earth's surface will then reach the F-layer. The F-layer also contains electrons, but far less than the D-layer. So instead of attenuating, the electrons tend to re-radiate the signal. Parts of the signals are radiated back to Earth. This "reflection" is used for AM radio broadcast transmissions to reach past the horizon. Parts of the radio waves are also re-radiated into space, and will contribute to the RFI behind the moon.

How much the interference from the Earth's surface is attenuated by the ionosphere, depends on the critical frequency for vertical incidence reflection (f_0). This is the cut-off frequency of the ionosphere. The attenuation of signals below this frequency increases extremely fast, up to thousands of decibels when only 0.1 MHz below f_0. The changes of f_0 over time suggest that the ionospheric shielding is effective up to at least 10 MHz on the sunlit side of the Earth, and up to at least 3 MHz at the night time side of the Earth[3].

2.1.2 Artificial radio transmissions

An important source of RFI is artificial radio transmission. These transmissions are used for mobile radio communication, broadcasting, radar, navigation systems, communication satellites and many more applications. The frequency range of interest, 0.3 to 30MHz, is especially used for AM radio broadcasting, maritime mobile and (maritime) radio navigation [4].

Artificial radio transmissions are produced on the Earth's surface. To reach the Moon, these signals first have to propagate through the ionosphere (Section 2.1.1). This will attenuate these signals a lot at especially the lower frequencies. Radio transmissions below 3 MHz are effectively blocked by the ionosphere, therefore only artificial radio transmissions above 3 MHz will be accounted for. The strength of the interference above 3 MHz at Moon distance can be up to 30 dB above Galactic Background Radio Noise.

2.1.3 Lightning

Another main source of RFI that will be looked into is lightning. On the entire Earth, there are approximately 40 to 50 lightning discharges per second [5]. Every lightning discharge generates an electromagnetic wave so powerful that it can be detected more than 10.000 km away [6]. Therefore it might also be strong enough to be observed in space. The interference generated by a lighting discharge is a very sporadic impulse, but due to the large amount of impulses (40-50 per second) it can be observed from space as a constant noise source.

The RFI generated by lightning originates close to the Earth's surface, and therefore it has to propagate through the ionosphere too (Section 2.1.1). This will attenuate the RFI produced by lightning, just like the artificially produced RFI. The attenuation is strong especially at the lower frequencies. The RFI at these frequencies is effectively blocked, as explained in Section 2.1.1, and will therefore not be significant enough at Moon distance. At higher frequencies however, the attenuation by the ionosphere is not so very high anymore, and some interference will propagate past the ionosphere. This is also visible at 3.93 MHz on the data of the RAE-B satellite (Figure 2) [10].

It appears that the frequency of the RFI produced by lightning is especially between 0.1 and 10 kHz, which is below the 0.3MHz-30MHz range of interest for this assignment. The RFI produced by lightning that does appear in the frequency range of interest is approximately of the same strength as the artificial produced radio waves (+ 30dB). At Moon distance, the strength of the interference of lightning and artificial radio waves combined can be up to 30-40 dB above Galactic Background Radio Noise[7].

2.1.4 Auroral kilometric radiation

The third main source that will be discussed is Auroral Kilometric Radiation (AKR). AKR radiates at the frequency band of 100 kHz to 600 kHz. This is only a small part of the frequency band of interest, but due to its high power it might saturate the receivers and is therefore very important. Furthermore, planets with a magnetosphere, like Jupiter and Saturnus also emit AKR. Even exo-planets might emit AKR if they have a magnetosphere. So the observation of low frequencies from space can also contribute to the detection and examination of exo-planets. Therefore this part of the frequency range is important despite the fact that it is only a small part of the frequency range of interest.

The AKR is the result of interaction between solar winds and the Earth's magnetosphere. This interaction takes place at an altitude of two times the radius of the Earth (R_E) above the Earth's surface, which is above the ionosphere. This means that the ionosphere only attenuates the radiation directed to the Earth's surface. The AKR directed towards the Moon does not travel through the Earth's ionosphere and is therefore not attenuated by it. The high altitude of 2 R_E also decreases the size of the cone behind the Moon where there is no direct line of sight (LOS) to the source. This effect on the LOS will be further examined in Section 2.2.1.

The AKR is mainly emitted from the auroral zones, which is a circular ring between 10° and 20° latitude around each magnetic pole. The AKR is beamed out in a narrow plane tangent to the magnetic field of the Earth [8]. This is also in the direction of the Moon.

Seen from the direction of the Moon, the AKR is the most dominant source of radio waves at a frequency of 100 kHz-600 kHz [9]. At peak intensity, the total power emitted in this frequency range exceeds 10^9 W, and the frequency can be up to 1 MHz. The intensity of the AKR is also clearly visible in the data of the RAE-B satellite, which measured radio waves in an orbit around the Moon. A graph of the intensity of the RFI observed by the RAE-B satellite can be found in Figure 2 [10].

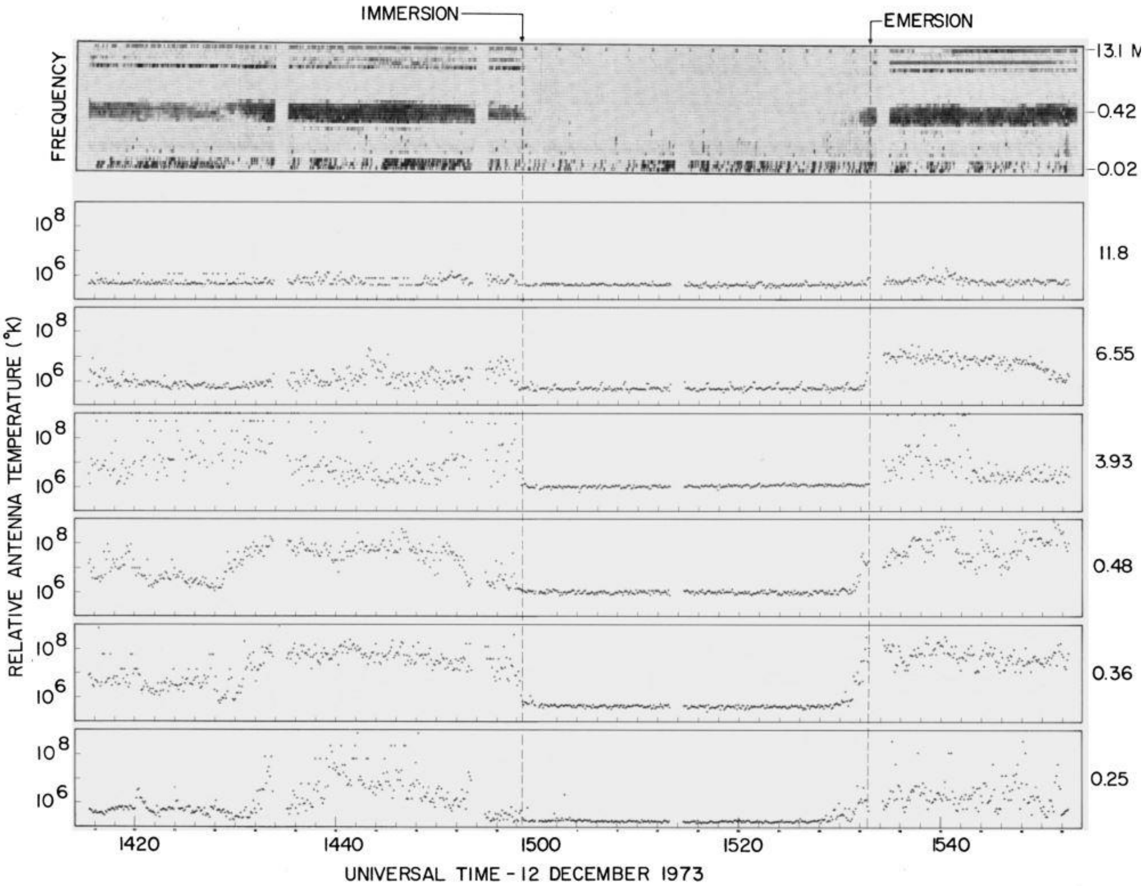


Figure 2: Relative antenna temperature observed by the RAE-B Explorer [10]

The upper graph displays the dynamic spectrum of the observed intensities over time. The other plots display intensity vs. time at a single frequency. From immersion to emersion the Moon was in between the satellite and the Earth. The short noise pulses observed every 144 seconds are due to interference from the satellite itself. In the upper plot of Figure 2, the AKR can be seen very clearly as a dark band between 0.18 MHz and 0.60 MHz. In the intensity plots at 0.36 and 0.48 MHz it is visible that AKR is already received before the Earth is in the LOS. This is because the AKR is produced at a high altitude.

The emission of AKR is continuous, but its strength varies over time due to solar bursts [11]. This is also visible in the upper plot of Figure 2. Around 1425 UT, the intensity of RFI at the AKR frequency band is much smaller than at 1445 UT. The strength of the AKR interference at Moon distance can be up to 70 dB above the Galactic Background Radio Noise [3].

2.2 Propagation mechanisms

The RFI produced by the various sources on Earth all have influence on the amount of RFI behind the Moon. However, for the RFI to be observed behind the Moon, the waves first have to propagate behind it. Multiple propagation mechanisms might achieve this. To determine which propagation mechanism has the most influence, various aspects of the different propagation mechanisms, and properties of the Moon have to be examined. Examples are the influence of the frequency of the RFI, and the conductivity of the Moon's surface.

There are roughly four propagation mechanisms that might influence the amount of RFI observed behind the Moon. First, there is the direct wave which has a straight path between source and observer. A direct wave to an observer behind an object is only possible when the source is bigger than the shielding object, which is true for the Earth and the Moon. The second and third propagation mechanisms are forms of diffraction: Fresnel diffraction for the near-field and Fraunhofer diffraction for the far-field. The final propagation mechanism that will be examined is surface wave propagation, which uses the surface as a waveguide to bend around objects.

2.2.1 Direct wave

The first mechanism is the direct wave, which is just a straight propagation path between the source and receiver. For a direct wave, the source has to be in line of sight (LOS) of the receiver. Behind an object this might be the case when the source is bigger than the shielding object. Since the Earth is bigger than the Moon, this is also the case for the RFI produced by the Earth. Behind the object there will be a cone shaped area where there is no LOS to the source. A schematic showing the Earth, the Moon and the cone without a LOS is shown in Figure 3. How big this cone will be is determined by the size of the source and its altitude.

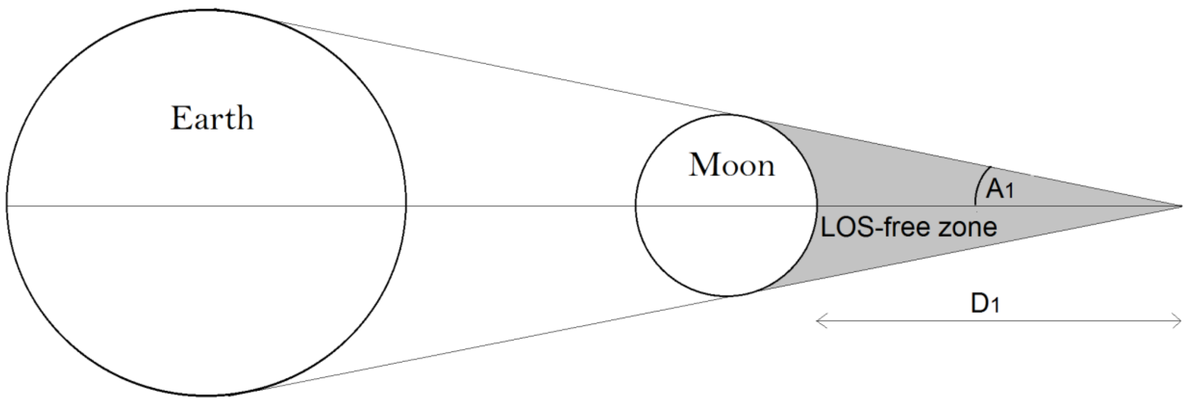


Figure 3: A schematic drawing of the LOS-free zone behind the Moon.

The length and angle of the LOS-free cone can be calculated by solving the geometric problem in Figure 4. In this figure, R_M is the radius of the Moon, R_E is the radius of the Earth, D_C is the length of the cone and D_{EM} is the distance between the Moon and the Earth. The angle of the cone's peak is A_1. The calculations of D_C and A_1 can be found in Appendix A. For RFI produced at the surface of the Earth, the length and angle are calculated to be: $D_C = 1.441 \cdot 10^5$ km and $A_1 = 0.69°$. The length of the cone is a bit smaller than half the distance between the Earth and the Moon. The Earth-Moon L2 point is at $0.6152 \cdot 10^5$ km, which appears to be within the LOS-free cone.

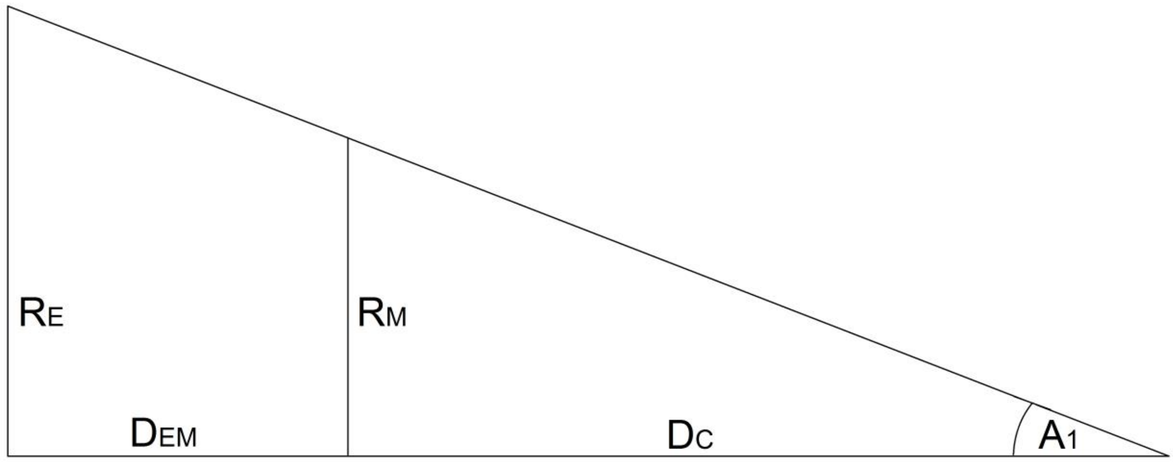


Figure 4: The geometric representation used to solve the length and angle of the LOS-free zone

When the source of the RFI is high above the Earth's surface, R_E will have to be adjusted. This results in a smaller area without a LOS to the source. This is the case for auroral kilometric radiation. The altitude of the radiation (2 times the radius of the Earth on average) has to be added to the radius of the Earth. The calculations for the length and angle of the LOS-free cone can be found in Appendix B. With a cone angle of 2.59°, the length of the cone has become $0.3845 \cdot 10^5$ km. Since the Earth-Moon L2 point is at $0.6152 \cdot 10^5$ km, this means that the L2 point is not within the LOS-free cone. The AKR produced in the magnetosphere can therefore directly propagate to an observer at the L2 point, without any shielding from the Moon.

2.2.2 Diffraction

When the source is not in the LOS of the receiver, there is still interference from RFI produced by Earth. This is because the radio waves will bend around an object due to diffraction. When the path of a wave is blocked by an obstacle, some of the waves are scattered around the object creating a pattern with bands of high and low intensities. An example of an intensity plot of a diffraction pattern is shown in Figure 5, where the incoming wave is blocked by a circular disk.

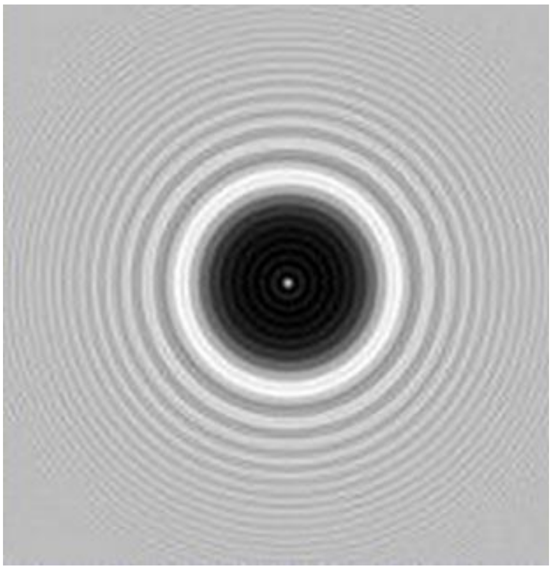


Figure 5: The diffraction pattern resulting from a circular obstacle [13]

These effects can be modelled using the Huygens-Fresnel principle. According to the Huygens-Fresnel principle every point that is reached by a wave becomes a new source of a spherical wave. This is also the reason why a small aperture in a wall appears to be a new light source when illuminated from the other side. Diffraction can be modelled in two different ways: Fraunhofer diffraction and Fresnel diffraction. Which of these two models of diffraction gives the best approximation depends on the distance between the observer and the shielding object, which is discussed next.

Fraunhofer diffraction

Fraunhofer diffraction is used to calculate the diffraction pattern at a large distance compared to the size of the diffracting object. In general, Fraunhofer diffraction is used when the squared radius of the shielding object (*r*) is smaller than the wavelength (λ) times the distance between the shielding object and the receiver (*d*) [12]:

$$r^2 < \lambda d$$

For both the L2 Earth-Moon Lagrange point and a Moon orbit (for example the RAE-B satellite) this is not true. Another restriction is that the waves approaching the diffracting object should be parallel and monochromatic. This is also not true for the RFI produced at Earth. Therefore Fraunhofer diffraction equations are not applicable to our scenario.

Fresnel diffraction

The other way to model diffraction is Fresnel diffraction, which is used to calculate the near field of diffraction around an object. The near field is where the squared radius of the shielding object (*r*) is larger than the wavelength (λ) times the distance between the shielding object and the receiver (*d*):

$$r^2 > \lambda d$$

This equation holds for both the L2 Earth-Moon Lagrange point and a Moon orbit.

An interesting property of the near field behind a round object is the Poisson's spot. At this spot right in the middle of the shadow of a round object, there is a significant peak of intensity. This is due to the fact that all the diffracted waves have travelled the same distance, and therefore they have the same phase. Because all the waves are in phase, their intensities will add up [13]. The Poisson's spot is also clearly visible in Figure 5. Since the L2 point is right in the middle behind the Moon, this might have a great influence.

To apply Fresnel diffraction, the Moon has to be approximated by a round disk. The disk's edge can however be made more rough to get a better approximation.

The mountains on the Moon are not much taller than 5 km. Since the radius of the Moon is 1737.5 km, this is an edge roughness of less than 0.3%. In Figure 6, the relative intensity of waves behind a circular object with an edge roughness of 1.25% is shown. This is more than the 0.3% edge roughness of the Moon, but the Poisson's spot is still very significant with an intensity of more than half the original intensity without obstacle.

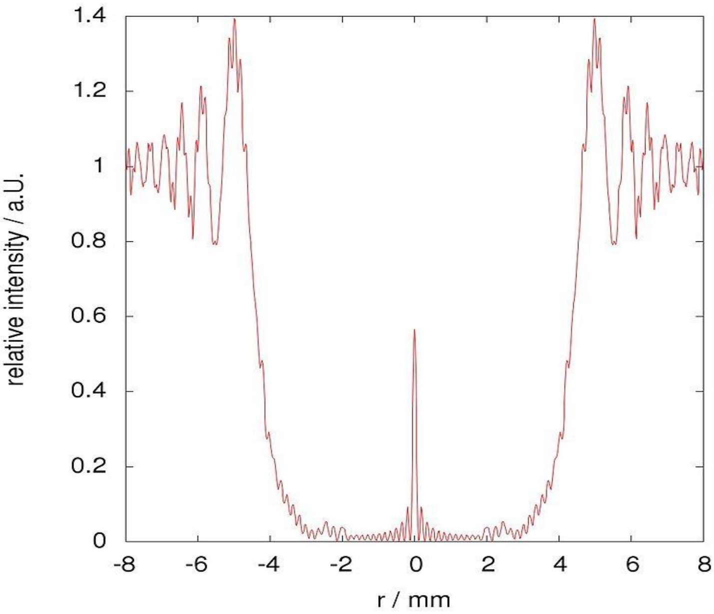


Figure 6: intensity of observed waves behind a circular object [13]

An important requirement for Poisson's spot and for Fresnel diffraction calculations in general, is the incoming wave which should be modelled as a plane wave. The RFI produced at Earth has many different sources at different locations, resulting in an incoming wave at the surface of the Moon that cannot be modelled as a plane wave.

For one single source at a time, the incoming wave at the Moon might be a plane wave, and may therefore result in a Poisson's spot. For the many different sources on Earth, this would result in multiple small Poisson's spots behind the Moon, which will blend together, resulting in an expectation of the spatial RFI distribution that is continuous. For an observation satellite in a Moon orbit, this might result in a significant level of RFI.

2.2.3 Surface wave propagation

Another propagation mechanism is surface wave propagation. On Earth, surface wave propagation can be separated in sky- and ground wave propagation. With sky wave propagation, the radio wave propagates through a three layer waveguide consisting of the surface, the lower atmosphere and the ionosphere. With ground wave propagation, the propagation will be along a two layer waveguide only consisting of the surface and the atmosphere. The Moon does not have a considerable ionosphere, and therefore the sky wave propagation can be neglected. Ground waves however, will propagate along the surface of the Moon with two layers consisting of the Moon's surface and space.

Ground waves are subject to the same attenuation factors as "normal" direct waves, but in addition, they also suffer from ground losses. Due to ohmic resistive losses in the conductive surface, and the dielectric properties of the surface, the radio waves heat up the ground and will therefore suffer ground losses.

When a radio wave is propagating along the Earth or Moon's surface, it will not propagate in a straight line but it tends to follow the curvature of the surface. While propagating along the surface, the part of the wave-front that is close to the surface will slow down due to the dielectric properties of the surface. [2] This will cause the wave-front of the entire signal to tilt downwards towards the surface, and therefore be able to propagate beyond the horizon of the surface. A schematic drawing of this process is shown in Figure 7.

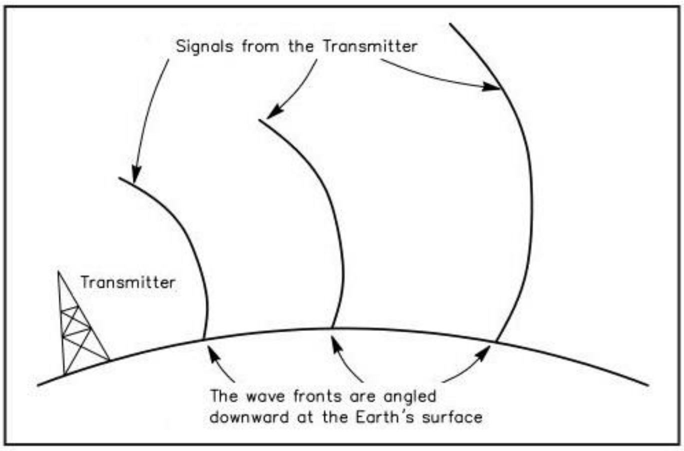


Figure 7: Ground waves following the curvature of the surface [2]

The amount of attenuation during ground wave propagation depends on several factors like the conductivity, the frequency of the radio wave and the roughness of the surface. The attenuation of the ground waves increases rapidly as the frequency increases. For frequencies above 3 MHz the ground wave propagation can be completely neglected. The lower frequencies, for example from the AKR, are attenuated a lot less and can therefore not easily be neglected.

The surface of the Moon is very rough because there is no wind or water causing erosion, while there are many asteroid impacts because the Moon does not have a significant atmosphere. Small rocks and bumps (<100 m) in the surface do not have much influence because the radio waves will just diffract around them. The large hills and craters however, will attenuate the radio waves a lot more especially due to their steep hills.

2.3 Conclusions of the preliminary research

In this Chapter several sources of RFI and propagation mechanisms are looked into. An overview of the main sources can be found in table 1. From the information collected about these sources and propagation mechanisms, the source and propagation mechanism which are expected to have the most influence are chosen to be researched in more detail in the following chapters.

The most important propagation mechanisms are the direct wave and ground wave propagation. Satellites at locations with a direct LOS to an RFI source will suffer too much from the interference, and these locations should therefore not be used. This is for example the case for AKR at the Earth-Moon L2 point, which is therefore unsuitable. When a satellite is not in the LOS, ground wave propagation is the most important propagation mechanism to cause interference. Due to the low conductivity and the roughness of the Moon's surface RFI will be attenuated a lot, but the strength of the RFI might still be large enough to cause interference during observations. The amount of attenuation during ground wave propagation should be further examined.

The Fraunhofer and Fresnel diffraction models are not suitable for this assignment, because the waves approaching the Moon are not parallel and monochromatic.

There are roughly two sources that contribute to the amount of interference at Moon distance in the 300 kHz to 30 MHz range: AKR and surface produced RFI. The surface produced RFI contains both man-made radio signals and interference produced by lightning which are very similar in frequency range and strength.

The AKR mainly interferes at frequencies between 100 - 600 kHz, but can also be up to 1 MHz. In the direction of the Moon, the AKR is the most dominant source of RFI. The AKR is produced at an altitude of two times the radius of the Earth (R_E), which reduces the LOS-free zone behind the Moon. Due to the high altitude, the AKR does not have to propagate through the ionosphere to reach the Moon. Therefore the presence of the AKR at Moon distance is very significant.

The surface produced RFI does have to propagate through the ionosphere first. The attenuation due to the ionosphere depends on the time of the day. During daytime, all the interference below 10 MHz is effectively blocked, while during night time, only the interference below 3 MHz is blocked. The strength of the surface produced RFI at Moon distance is already lower than the RFI produced by AKR, and due to the relatively high frequency it is attenuated even more during ground wave propagation. Above 3 MHz, the attenuation of the ground wave propagation is so high that it can be neglected. Therefore surface produced RFI will not contribute significantly to the interference during occultations, and does not have to be examined further.

In the next two chapters, AKR and ground wave propagation will be further examined to get a better estimation of their influence on RFI behind the Moon.

Source	**Frequency range (MHz)**	**Strength at Moon distance relative to background radiation**	**Altitude**
Auroral Kilometric Radiation	0.1 - 1	+ 70 dB	1 – 3 R_E
Artificial Radio Transmissions	0.003+ (3+)*	+ 30-40 dB	Low
Lightning discharges	10Hz – 10 (3 – 10)*	+ 30-40 dB	Low

* = Seen from space due to attenuation by the ionosphere

Table 1: Overview of the main sources of RFI based on preliminary research

3. Auroral Kilometric Radiation

During the preliminary research various sources have been examined (Section 2.1). From the preliminary research it is concluded that the Auroral Kilometric Radiation (AKR) is the most important source due to its high power and high altitude. To get more insight in this source of RFI, and the effect on the amount of RFI behind the Moon, the AKR will be further examined.

The strength of the AKR interference at Moon distance can be up to 70 dB above the Galactic Background Radio Noise. The frequency range of the AKR is usually between 100 – 600 kHz, but will sometimes peak up to 1MHz.

AKR is produced at an altitude of 1 – 3 times the radius of the Earth. At the beginning and the end of an occultation by the Moon, the source of AKR at this higher altitude will still be in line of sight while the Earth itself is not visible. Therefore, the RFI due to AKR will be observable for a longer period of time than RFI produced at the surface of the Earth. This is also visible in the data of the RAE-B explorer. In Figure 8 the interference levels at various frequencies during the occultation are shown. At 0.25, 0.36 and 0.48 MHz, and also in the upper plot, it can be seen that before the end of the occultation there is already RFI observed at these frequencies. This is the RFI due to the AKR. The interference produced at the Earth’s surface, for example at 3.93 MHz, cannot be observed until the occultation is over. The “straight line” of signal that can be observed during occultations is the Galactic Background Radio Noise, which contains interesting signals which will be observed by OLFAR [1].

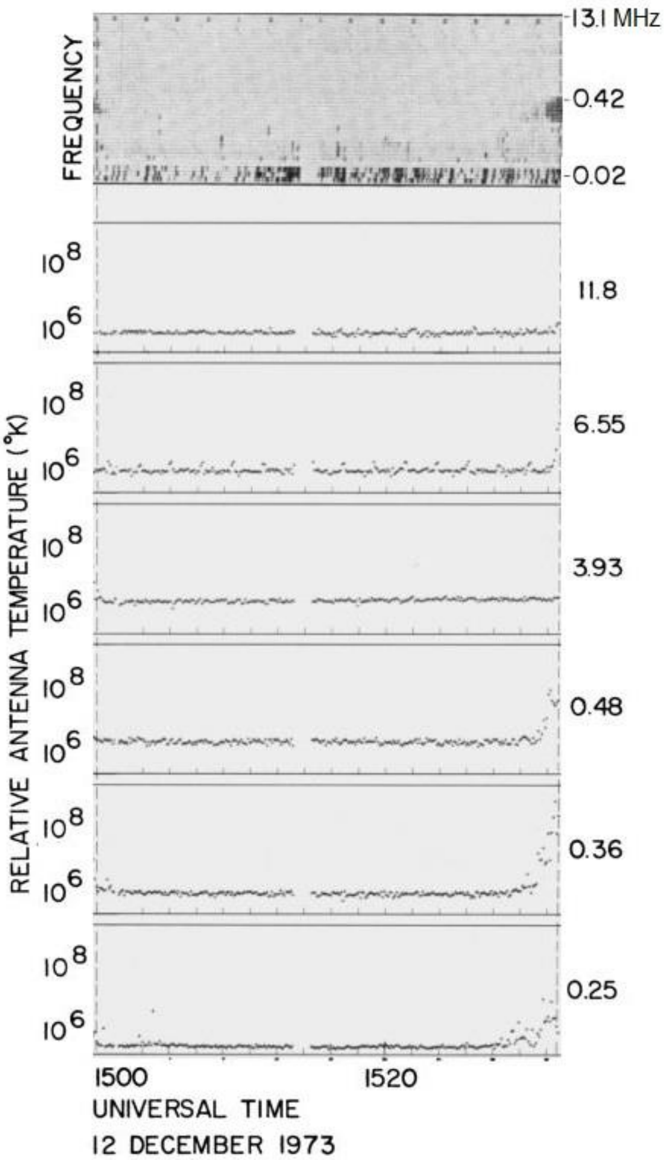


Figure 8: Relative antenna temperature measured by the RAE-B during occultations [10]

Under some conditions, which are estimated to occur around 10% of the time, the AKR is refracted at an altitude of 20-40 R_E [14]. When this happens, the altitude of the LOS-free zone above the Moon's surface will be at most 1674 km (appendix B). Satellites in orbit at an altitude higher than 1000 km will be in the LOS of the interference even when they are far behind the Moon. This also happened to the RAE-B Explorer, which was in orbit at an altitude of 1100 km above the Moon's surface. During the refractions, the satellite was in LOS during the entire occultation as shown in Figure 9. In this data of the RAE-B Explorer it can be seen that interference from other sources above 1 MHz is effectively blocked by the Moon during occultations, while the AKR interference at the lower frequencies is almost unaffected.

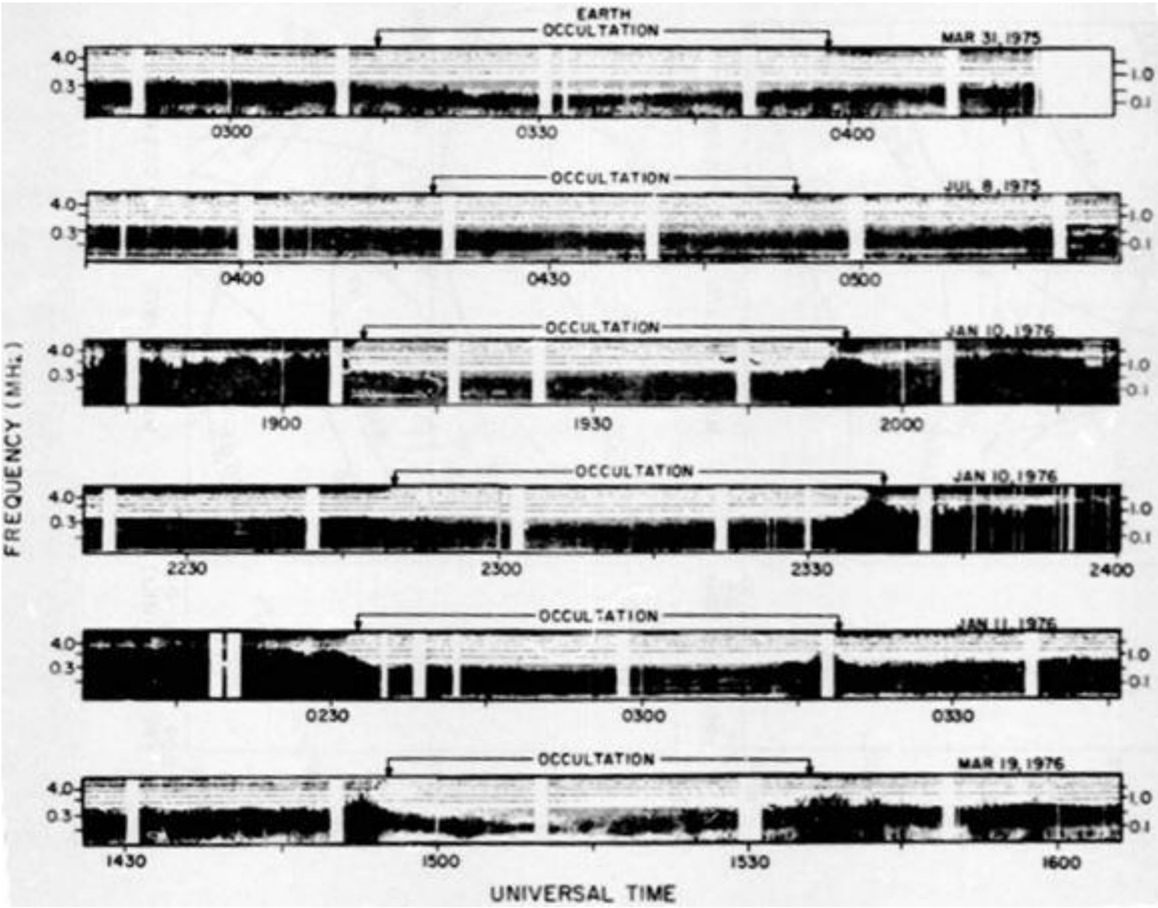


Figure 9: RFI measured by the RAE-B during refraction at 20 – 40 R_E [14]

When this happens, the interference at observing satellites will likely be too high to conduct observations, and saturation of the measurement equipment may occur. Therefore, data collected under these conditions will probably have to be discarded.

4. Ground wave propagation

Based on the preliminary research, the most important mechanism to let the RFI propagate around the Moon is the ground wave propagation (Section 2.2.3). When the RFI produced by the Earth reaches the Moon, it will propagate around the Moon due to ground wave propagation. Several factors determine the amount of attenuation during ground wave propagation, and therefore determine how much of the RFI will be observed behind the Moon. These factors will be examined to determine the effect of ground wave propagation on the amount of RFI behind the Moon.

The polarisation of the signals is important for ground wave propagation. Horizontally polarized waves suffer a lot from ground losses because the surface tends to short-circuit the E-field component, which is tangent to the surface. For vertically polarized waves however, this is not the case. With these waves, the E-field will induce currents in the surface. These currents will flow to adjacent wave fronts [15]. An illustration of this mechanism is shown in Figure 10. The ground constants of the surface determine how much current is returned, and therefore also how much energy is lost and how much the signal is attenuated.

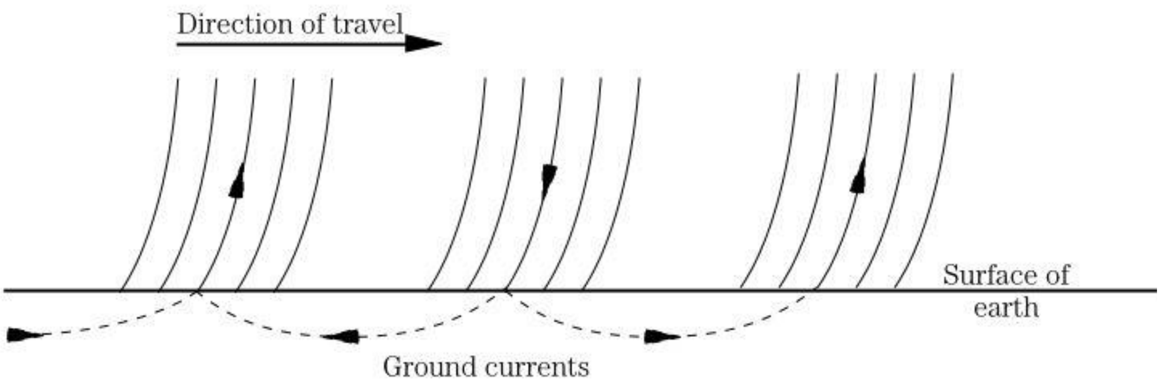


Figure 10: Ground currents in vertically polarized electric field [15]

The important properties of the ground for ground wave propagation are its conductivity (σ), which governs the loss of energy while the charge is moving, and its permittivity (ε), which influences the production of the charge. At frequencies below 1 MHz, the conductivity is the most important factor, while above 5 MHz the permittivity becomes more important. Since the AKR only goes up to 1 MHz, the conductivity will be the most important factor [7]. Terrains with a high conductivity give less attenuation than terrains with a low conductivity. The sea for example conducts very well, and gives less attenuation than a desert, which has a very low conductivity.

The conductivity of the Moon's surface appears to be very low, partly due to the lack of water. The conductivity of several samples collected by the Apollo 11 and 12 missions varies between 10^{-5} and 10^{-7} ohm^{-1} m^{-1} [16]. This low conductivity is several orders of magnitude lower than the conductivity of a sandy desert which is around $2 \cdot 10^{-3}$ ohm^{-1} m^{-1}.

Due to the low conductivity and the roughly shaped surface of the Moon, RFI produced by the Earth will be attenuated a lot during ground wave propagation. The attenuation is so strong that almost immediately after the occultation starts, the strength of the RFI produced at the surface of the Earth will be smaller than the strength of the Galactic Background Radio Noise at an observer behind the Moon. This is also visible in Figure 2 and Figure 8. During the occultation only the relatively constant Galactic Background Radio Noise is observed.

5. Conclusions

In this work, some of the most important sources of RFI and the propagation mechanisms that will get this RFI to interfere behind the Moon are looked into. This is done to estimate the influence of these sources and propagation mechanisms, and estimate whether or not it is possible for OLFAR to use the Moon as a shield against low frequency radio interference.

From the information collected about the different sources and propagation mechanisms it can be concluded that the Moon can act as a shield against RFI produced by the Earth.

Interference produced at the surface of the Earth, artificial radio transmissions and lighting, are effectively blocked by the Moon. Below 3 MHz, these signals are already attenuated a lot by the ionosphere of the Earth, and above 3 MHz the attenuation during ground wave propagation around the Moon is so high that the surface produced RFI won't be observed behind the Moon.

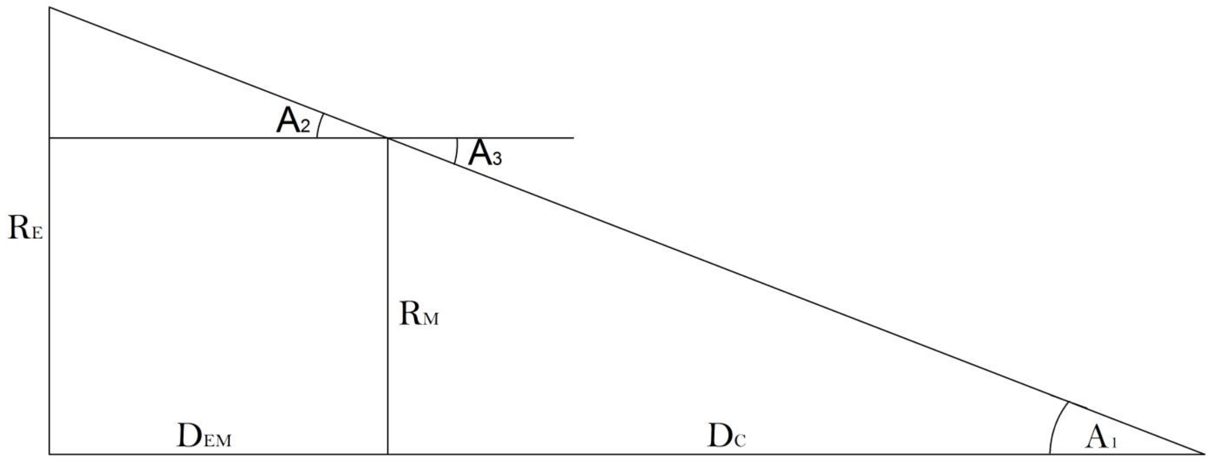
The Auroral Kilometric Radiation (AKR) is more troublesome because it is not produced at the surface, but at an altitude of 1-3 times the radius of the Earth. This means that it does not have to propagate through the ionosphere to reach the Moon. The AKR has a frequency range of 100 kHz – 1MHz. These low frequencies are less attenuated by ground wave propagation. However, due to the very low conductivity of the Moon's surface and the very rough terrain, the RFI produced by AKR will still be much weaker than the Galactic Background Radio Noise when there is no direct LOS.

However, due to the high altitude of the AKR, there will be a smaller area behind the Moon where there is no direct LOS to the source, which reduces the amount of time where observations can be executed during a Moon orbit. For a satellite at the Earth-Moon L2 point it is even worse. This point is located outside the LOS-free area, and therefore satellites located there will be directly exposed to RFI produced by the AKR. Because the interference will be very significant, this location is not suitable for OLFAR.

Another problem is the reflection of the AKR at an altitude of 20-40 times the radius of the Earth. During these reflections that occur approximately 10% of the time, RFI produced by AKR will directly travel to the backside of the Moon and OLFAR will not be able to do observations in orbits higher than approximately 1000 km. During the other 90% of the time, observations will be possible.

Appendices

Appendix A: Calculation on the LOS-free cone



A_1 and A_3 are alternate angles, and therefore equal
A_3 and A_2 are vertically opposite angles, and therefore equal.
So $A_1 = A_2 = A_3$
This means that A_1 can be calculated with the trigonometric tangent function for the upper left triangle:

$$A_1 = Tan^{-1}\left(\frac{opposite}{adjacent}\right) = Tan^{-1}\left(\frac{R_\mathrm{E} - R_\mathrm{M}}{D_\mathrm{EM}}\right)$$

The length of the cone (D_C) can be calculated with trigonometry over the entire triangle:

$$A_1 = Tan^{-1}\left(\frac{opposite}{adjacent}\right)$$

$$adjacent = \frac{opposite}{Tan(A_1)}$$

$$D_\mathrm{EM} + D_C = \frac{R_\mathrm{E}}{Tan(A_1)}$$

$$D_C = \frac{R_\mathrm{E}}{Tan(A_1)} - D_\mathrm{EM}$$

The following values are given:
$R_\mathrm{E} = 6.371 \cdot 10^6$ m
$R_\mathrm{M} = 1.7375 \cdot 10^6$ m
$D_\mathrm{EM} = 3.844 \cdot 10^8$ m
This results in the following values for A_1 and D_C:

$$A_1 = Tan^{-1}\left(\frac{6.371 \cdot 10^6 - 1.7375 * 10^6}{3.844 \cdot 10^8}\right) = 0.69°$$

$$D_C = \frac{R_\mathrm{E}}{Tan(A_1)} - D_\mathrm{EM} = \frac{6.371 \cdot 10^6}{Tan(0.69)} - 3.844 \cdot 10^8 = 1.441 \cdot 10^8 \text{ m}$$

Appendix B: Calculation on the LOS-free cone for AKR

The following values are given:
R_E = 6.371·10^6 m
R_M = 1.7375·10^6 m
D_{EM} = 3.844·10^8 m
Altitude AKR ≈ 2·R_E

$$R_{\mathrm{Source}} = R_{\mathrm{E}} + Altitude\ AKR = 1.911 \cdot 10^7\ \mathrm{m}$$

The angle and length can be calculated the same way as in appendix A, but with R_{Source} instead of R_A:

$$A_1 = Tan^{-1}\left(\frac{1.911 \cdot 10^7 - 1.7375 \cdot 10^6}{3.844 \cdot 10^8}\right) = 2.59°$$

$$D_C = \frac{R_{\mathrm{Source}}}{Tan(A_1)} - D_{\mathrm{EM}} = \frac{1.911 \cdot 10^7}{Tan(2.59)} - 3.844 \cdot 10^8 = 3.845 \cdot 10^7\ \mathrm{m}$$

When refraction at 20-40 R_E takes place:
Altitude AKR ≈ 30·R_E

$$R_{\mathrm{Source}} = R_{\mathrm{E}} + Altitude\ AKR = 1.975 \cdot 10^8\ \mathrm{m}$$

$$A_1 = Tan^{-1}\left(\frac{1.975 \cdot 10^8 - 1.7375 \cdot 10^6}{3.844 \cdot 10^8}\right) = 27°$$

$$D_C = \frac{R_{\mathrm{Source}}}{Tan(A_1)} - D_{\mathrm{EM}} = \frac{1.975 \cdot 10^8}{Tan(27)} - 3.844 \cdot 10^8 = 3.412 \cdot 10^6\ \mathrm{m}$$

When the radius of the Moon is extracted from this distance, the altitude above the Moon's surface is found:

$$3.412 \cdot 10^6 - 1.7375 \cdot 10^6 = 1.674 \cdot 10^6$$

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