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Article

Electromagnetic Characterization of EAC-1A and JSC-2A Lunar Regolith Simulants

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Abstract: The development of devices for In-Situ Resource Utilization (ISRU) of the lunar surface powder (regolith) by means of microwaves needs regolith simulants with electromagnetic properties similar to the lunar regolith. This document deals with the measurement of complex permittivity and dielectric loss tangent of the aforementioned simulants at ambient temperature from 400 MHz to 20 GHz. In addition, further studies are carried out taking into account humidity of the samples and their densities. The obtained results will be applicable for comparing the measured values of EAC-1A and JSC-2A among them and with other previously measured simulants and real samples. The measurements are carried out applying two different nonresonant techniques: Open-Ended Coaxial Probe (OECF) and Transmission Line. For this purpose, the DAK and EpsiMu commercial kits were respectively used.

Keywords: Regolith; electromagnetic properties; permittivity; permeability; tangent loss

1. Introduction

One of the reasons why it is important to know the electromagnetic properties of lunar regolith (lunar surface dust) is to be able to use this material as an in situ resource (ISR) [1–3]. The latter enables the permanent or temporary human presence on the Moon, which is of great importance for further human space exploration and colonization [4].

In response to this, it can be highlighted different uses of regolith or lunar dust. From it, it is possible to extract oxygen [5] and water [6,7] for habitability, as well as the use of water for protection against radiation for missions that extend in time outside the protection of the earth. Also hydrogen [8] and oxygen can be extracted from it for space propulsion and electricity generation [9].

Moreover, the lunar regolith can also be used as a construction material [10] once sintered. And it is at this point where this study has a greater interest.

To sinter the regolith it is necessary to heat it up, and an effective way to do it is through radiation in microwave wavelengths [11,12]. Therefore, to design and test an effective microwave device that processes regolith it is necessary to know the optimal frequency at which the regolith transforms the greater amount of electromagnetic energy into heat. The characterization of regolith will be based on knowing electromagnetic properties such as permittivity, permeability and loss tangent, and in the widest frequency range possible. Knowing the frequency at which the loss tangent is greater (or the shape of its variation) can allow establishing design criteria for lunar regolith processing devices using microwave radiation. On the other hand, there have not been many missions to the moon which means that there is a shortage of these materials and, hence, it is not possible to carry out extensive testing and measurements using lunar regolith. Nevertheless, the solution that NASA and other public and private companies have had is to simulate these lunar dusts through materials that we have on Earth [13], so that these dusts can be measured even with destructive tests. These new powders that simulate the lunar regolith are known as simulants and several of them have been developed [14], as well as Martian surface simulants [15], since, as it is known, the next step after settling on the Moon will be

the arrival of human beings on the martian surface. These lunar simulants differ on the composition, and this is because the lunar dust is not homogenous throughout the entire Moon, so is mandatory to have different simulants so that the entire surface of the Moon can be characterized. In this context, this work focuses on measuring the complex permittivity and permeability of simulants EAC-1A [16] (which is one of the first simulants developed by ESA European Astronaut Center) and JSC-2A [17] (developed by NASA at Johnson Space Center) (see Figure 1).

In addition, ESA is developing a facility called LUNA for prospective lunar missions payload and technology development and testing. Its ground has to be filled with a regolith simulant, and EAC-1A is a likely candidate for that propose [16]. The content of this article is structured as follows: section 2 describes the methods and techniques used in the measurements of the two simulants; in Section 3 the results are presented; in Section 3.1 the two regolith simulants are compared with other similar simulants obtained from the literature, Section 4, deals with simulant's dielectric properties variation as a function of the density and the ambient water content, and finally, in Section 5 conclusions are drawn.

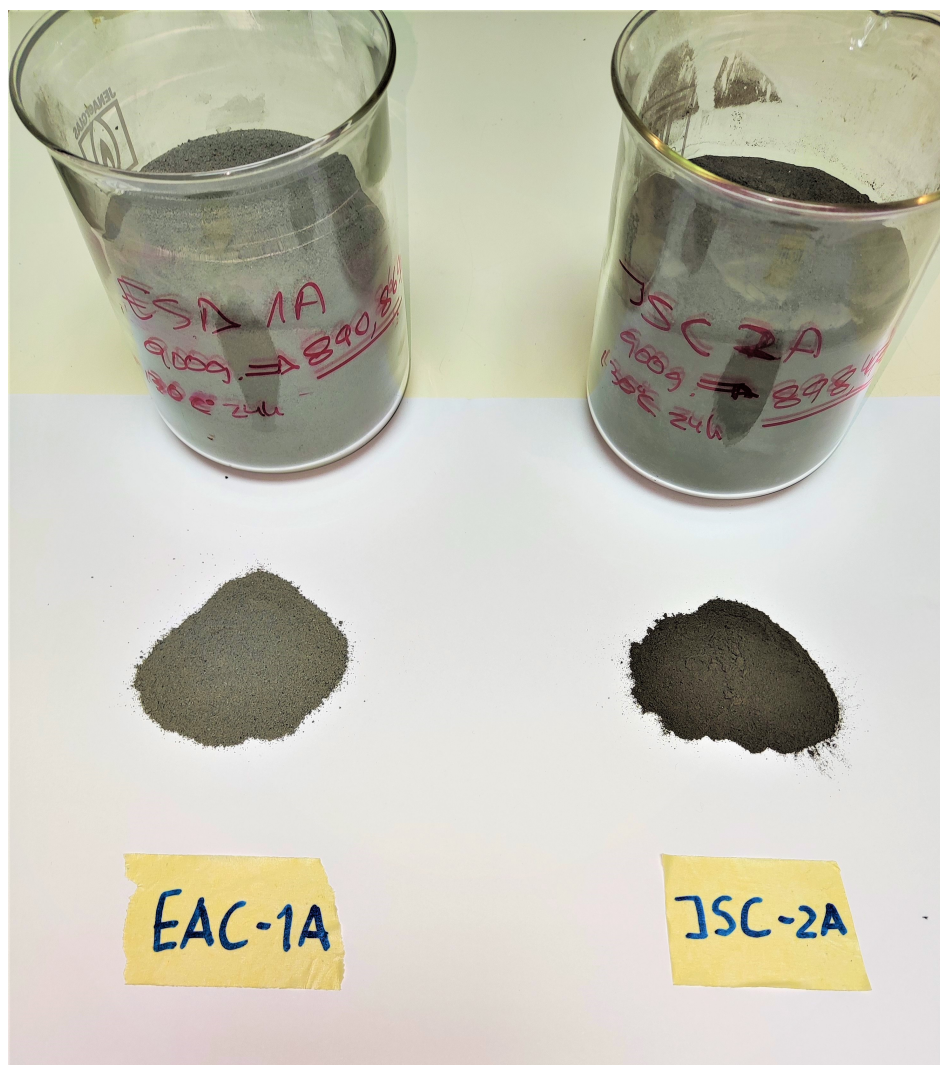


Figure 1. Sample of simulants EAC-1A (left) and JSC-2A (right)

2. Measurements Methods

Characterizing a material electromagnetically means knowing the interaction of that material with electromagnetic radiation. The way in which this interaction occurs can be known through two

parameters, which are the complex relative permittivity, shown in equation 1, and the complex relative permeability, shown in equation ??:

$$\varepsilon_r = \varepsilon'_r - i\varepsilon''_r \quad (1)$$

$$\mu_r = \mu'_r - i\mu''_r \quad (2)$$

Once the parameters, that are necessary to characterized a material, have been defined, it remains to be determined what method to use to obtain the values of these variables. The use of each of them will depend on various factors such as: the frequency at which the measurement is to be carried out, the required precision, the temperature, the nature of the material, the size of the sample to be tested or whether a destructive test can be carried out or in contact with the piece or not [18]. Taking into account the material to be characterized (in powder form) and wanting to know its behavior against electromagnetic fields in the widest frequency range, it has been decided to use two types of non-resonant measurement techniques [19]. These two methods are the OECF method (Open-Ended Coaxial Probe) and the coaxial transmission line method.

2.1. OECF and Transmission Line Methods

The OECF method [20,21] allows to extract the dielectric parameters of the non-magnetic material to be characterized, since it is only possible to obtain reflection parameters. Therefore, measurements of permittivity and loss tangent (see equation 3) have been obtained with this method.

$$\tan\delta_e = \frac{\varepsilon''}{\varepsilon'} \quad (3)$$

To carry it out, the DAK-3.5 measurement kit (Dielectric Assessment Kit) from the company SPEAG [22] has been used. This kit includes a commercial software for automatic estimation of permittivity and loss tangent, allowing measurements up to 20 GHz.

For the case of the Transmission line Method, the EpsiMu 13 mm measurement kit [23] has been utilized, which can be used to obtain transmission and reflection parameters [24]. To carry out the measurements using EpsiMu, the simulant must occupy the entire sample holder (30.10 mm) to avoid material movement during measurement as it is shown in Figure 2. Using this method, both permittivity and permeability can be obtained. Depending on the characteristics of the material to be analyzed, the maximum operating frequency of the method can be estimated as follows [23]:

$$\frac{\lambda}{2} = \frac{c}{2f} \frac{1}{\sqrt{\varepsilon\mu}} \quad (4)$$

Where c is the speed of light in vacuum and λ the wavelength. Solving for the frequency of equation 4, we have a value of $f = 2.5$ GHz. That is, for this sample size, the maximum frequency up to which it can be measured. On the other hand, if the material to be measured is non-magnetic ($\mu = 1$), this range may be extended to 6 GHz.

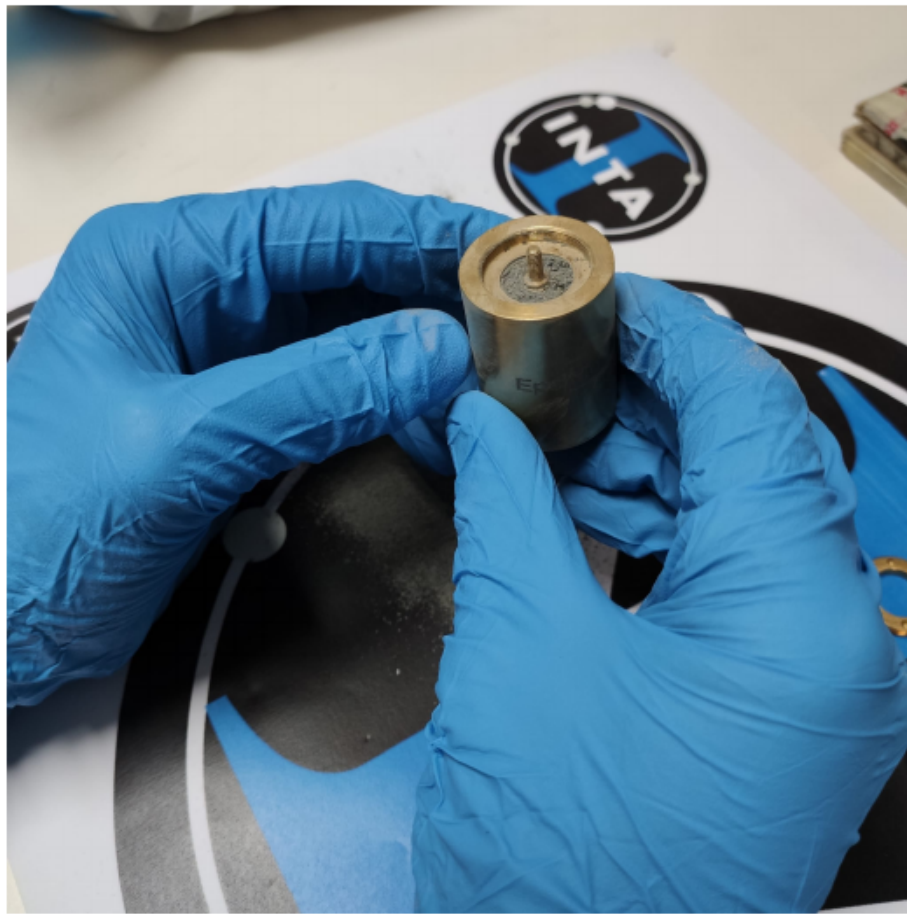


Figure 2. EpsiMu PE13mm sample holder with lunar regolith simulant inside

A more detailed description of the named kits, the calibration performed and how the measurements were made are detailed in [25].

3. Results and Discussion

The obtained values of permittivity and dielectric loss tangent for the studied JSC-2A and EAC-1A simulants are shown in addition to other lunar regolith and simulants obtained from bibliography. All the measurements of the JSC-2A and EAC-1A simulants have been carried out at room temperature and range between 400 MHz and 20 GHz, since it has been seen that unstable values are obtained for lower frequencies. Before carrying out the measurements, the density of the materials has also been estimated, obtaining a density at atmospheric pressure of 1.72 g/cm^3 for the EAC-1A powder and a value of 1.73 for the JSC-2A.

The results of magnetic permeability and tangent of magnetic losses have been previously published in [25], therefore, the graphs corresponding to these values are not shown in this study. From these graphs it was possible to conclude that the simulants JSC-2A and EAC-1A were non-magnetic, with a permeability of one and a value in the tangent of magnetic losses close to zero.

In addition, in [25], the results of permittivity and tangent of dielectric losses were also shown. In this case, a linear approximation of these results has been made. The values obtained can be seen in Table 1 and Table 2. In general, adequate values have been obtained according to the two simulants studied, both in the real part of the permittivity and in the loss tangent. A greater variation at low frequencies was observed by means of the DAK-3.5 Kit (at low frequencies, there is a longer wavelength, and the size of the sample to be measured was not large enough so the electromagnetic field had areas outside the material and the dielectric properties obtained were not adequate).

Table 1. Equations for trend lines generated from linear approximation for EAC-1A simulant.

Frequency (GHz)	EAC-1A
(0-6] EpsiMu	$\epsilon' = -0.0432f + 4.0397$ $\tan \delta_e = -0.0015f + 0.0659$
[6-20] DAK-3.5	$\epsilon' = -0.0432f + 4.0397$ $\tan \delta_e = -0.0039f + 0.1429$

Table 2. Equations for trend lines generated from linear approximation for JSC-2A simulant.

Frequency (GHz)	JSC-2A
(0-6] EpsiMu	$\epsilon' = -0.0172f + 3.8299$ $\tan \delta_e = 0.0005f + 0.0364$
[6-20] DAK-3.5	$\epsilon' = 0.0136f + 3.4003$ $\tan \delta_e = -0.0058f + 0.1550$

3.1. Comparison of Dielectric Properties

The approximation made is divided into two parts. In the case of measurements with the DAK-3.5 Kit, trend lines have been generated from 6 GHz to 20 GHz and in the case of measurements using the EpsiMu kit, the lines generated range from 500 MHz to 6 GHz. The error that is being introduced when linearly approximating the measurements has also been estimated. For the case of the adjustment from 0 to 6 GHz there is a maximum dispersion of ± 0.1 in permittivity and ± 0.015 for the dielectric losses. From 6 to 20 GHz there is a dispersion of ± 0.2 in permittivity and ± 0.07 for the loss tangent.

The results of the EAC-1A and JSC-2A simulants have been compared with the real part of the relative permittivity and the dielectric loss tangent values of other simulants analyzed in different studies. Additionally, the simulants measured in this study have also been compared to actual lunar regoliths. In a first instance, our simulants have been compared with those listed in Table 3. As can be seen, there are a total of five different lunar simulants and a sample of lunar regolith corresponding to the Apollo 17 mission. The simulants in this comparison are, on the one hand, the JLU-1 [26], which is a lunar highland simulant developed at Jilin University, China, and, on the other hand, the JSC-1 simulant and its variants JSC-1A, JSC-1A (1%CIP) and JSC- 1A (AGGL) [14], [27]. Simulants JSCs are no longer manufactured and have been replaced by JSC-2A, as it represents a more advanced simulant, with properties closer to that of real lunar regolith according to [28].

Table 3. List of lunar samples used for the first comparison.

Type of sample	Acronym	Type	Place
Lunar simulants	JLU	1	Jilin University
	JSC	1	John Space Center
		1A	
		1A (1% CIP)	
		1A (AGGL)	
Lunar regolith	70051	20	Apollo mission 17

This first comparison has already been published at the 2022 EuCAP (European Conference on Antennas and Propagation) in Madrid [25], where the properties of each of the named samples are detailed. However, in order to extend this comparison, new simulants and samples of real lunar

regolith have been added in this study. For this new comparison, three new types of simulants and two other types of lunar regolith have been added. The new measured samples can be seen in Table 4.

Table 4. List of lunar samples used for the second comparison.

Type of sample	Acronym	Type	Place
Lunar simulants	LHS	1	Lunar Highlands Simulant
	LMS	1	Lunar Mare Simulant
	CAS	1	Chinese Academy Science
Lunar regolith	14163	164	Apollo mission 14
	CE	5	Cheng'E mission

In order to differentiate the samples used in this study from those shown in [25], the real permittivity and loss tangent values of the newly added samples are represented by triangles, while the others appear by squares. The results of the set of samples corresponding to Tables 3 and 4 are presented in Figures 3, 4, 5 and 6.

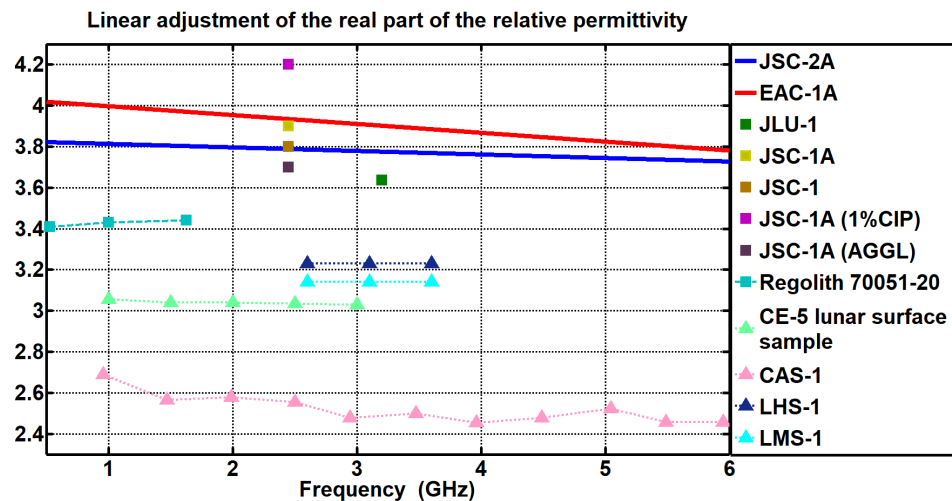


Figure 3. Linear fit of the measurements of the real part of the relative permittivity of the EAC-1A and JSC-2A simulants (EpsiMu kit)

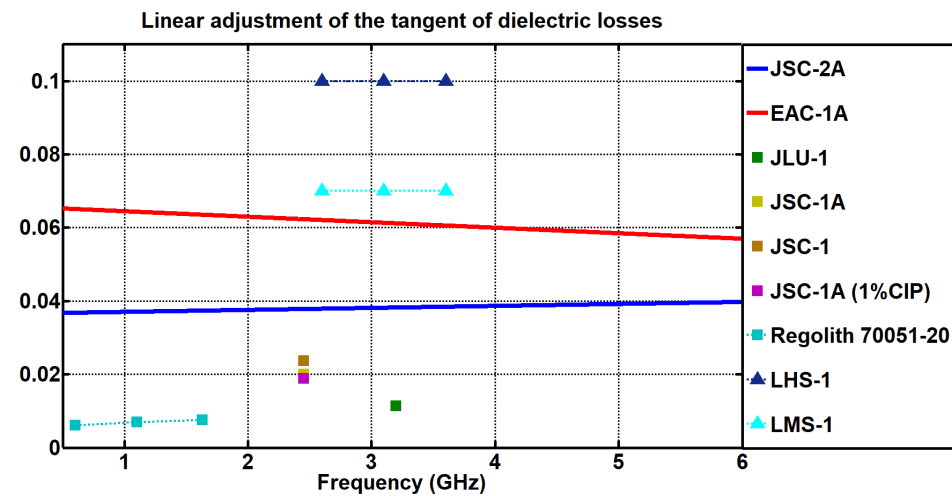


Figure 4. Linear fit of the measurements of the dielectric loss tangent of the EAC-1A and JSC-2A simulants (EpsiMu kit)

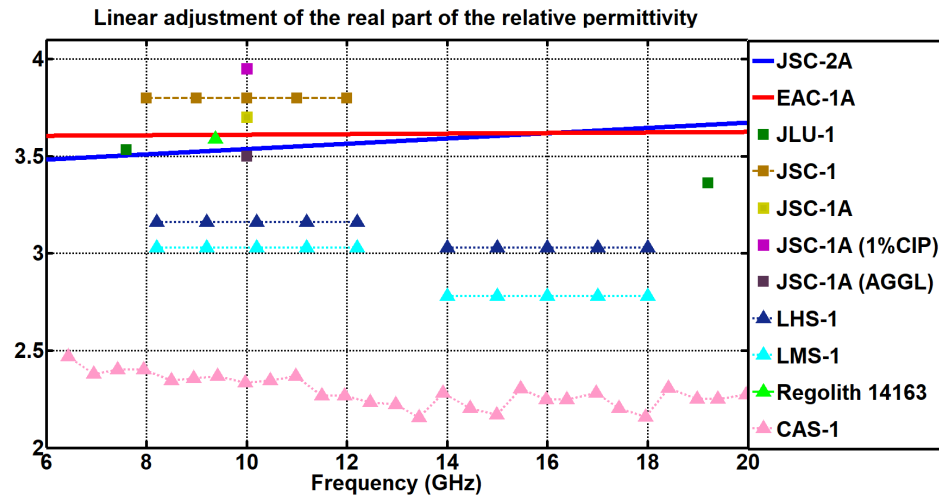


Figure 5. Linear fit of the measurements of the real part of the relative permittivity of the EAC-1A and JSC-2A simulants (DAK-3.5 kit)

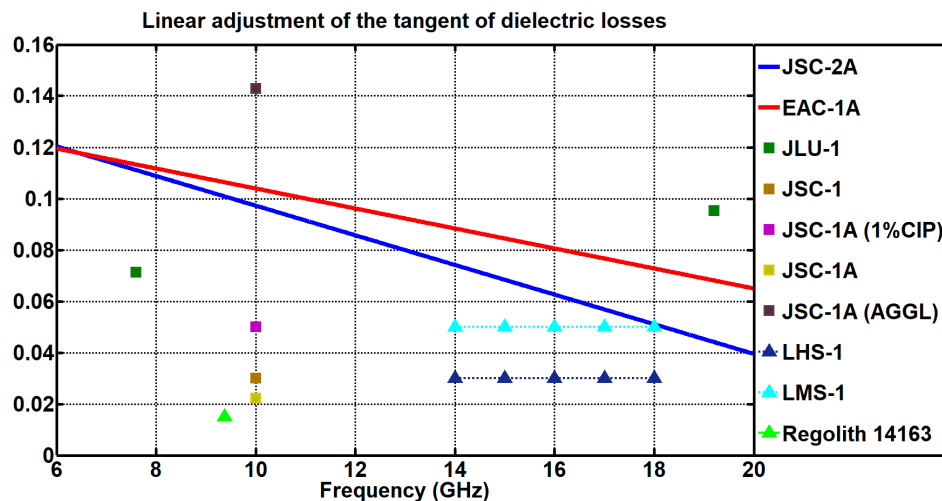


Figure 6. Linear fit of the dielectric loss tangent measurements of the EAC-1A and JSC-2A simulants (DAK-3.5 kit)

One of the comparisons carried out is based on the LHS-1 simulant [29] and the LMS-1 simulant [30], both manufactured at the Exolith Lab; which is a not-profit organization largely funded by CLASS, the Center for Lunar & Asteroid Surface Science. The measurements of these two simulants have been carried out in three frequency bands, S-band (2.6-3.95 GHz), X-band (8.2-12.4 GHz), and Ku-band (12.4-18 GHz), using the waveguide method [15]. The relative permittivity and dielectric loss tangent values of the LHS-1 and LMS-1 correspond to measurements at room temperature and for different concentration values of the samples. Therefore, in the present study, the values chosen for the comparison are those corresponding to the mean concentration values of the material, which appear in Table 4 of [15].

Other simulant with which the studied powders were compared is CAS-1. This lunar soil simulant was prepared by the Chinese Academy of Sciences, to support lunar orbiter, softlanding mission and sample return missions of China's Lunar Exploration Program [31]. Source material for this simulant was a low-Ti basaltic scoria from the volcanic area in the Changbai Mountains of northeast China. Consistent with [31], the scoria was analyzed by XRF (Xray fluorescence) and found to be chemically similar to lunar sample 14163 from Apollo 14 and at low frequencies (less than 1 GHz), it appears to have a similar permittivity value. Nevertheless, as can be seen in Figure 5, at 9 GHz the real

permittivity value of CAS-1 is well below the value corresponding to the Regolith 14163 sample. It can be seen that the Lunar regolith from Apollo 14, considering the complex permittivity, has a behavior closer to the studied simulants JSC-2A and EAC-1A in the X-band.

Once the simulants provided in the comparison have been described, the lunar regoliths remain to be defined. First, there is the lunar regolith corresponding to the Apollo 14 mission. The sample of this regolith is 14163-164 and the measurements shown in Figures 5 and 6 correspond to the complex relative permittivity at 9.375 GHz. These values have been obtained from the short-circuit wave guide technique, where the sample has been compressed until reaching a bulk density of 1.71 g/cm^3 [32], a value similar to the case of the simulants JSC-2A and EAC-1A analyzed (1.73 g/cm^3 and 1.72 g/cm^3 respectively). Considering the latter, it can be seen that at 9.375 GHz there are very similar values in the real part of the relative permittivity of the simulants JSC-2A ($\epsilon' = 3.53$) and EAC-1A ($\epsilon' = 3.61$) relative to the Apollo 14 regolith sample ($\epsilon' = 3.59$).

Furthermore, there are also data on the complex permittivity values of sample 14163 with higher bulk density values. According to [32] with a bulk density of 1.9 the value of the real part of the permittivity becomes 4.1. This increase in permittivity with increasing compaction in the powders is expected and the variation of this parameter is similar to the variation that has also been obtained in this study with the EAC-1A and JSC-2A powders, see Figure 11.

The other type of lunar surface sample is CE-5. This material corresponds to the regolith brought to earth from the third phase (Chang'E-5) of the China Lunar Exploration Program (CLEP). The displayed measures of the real part of the permittivity and tangent of dielectric losses of CE-5 are found in a frequency range from 1 to 3 GHz, and have been measured at a stable temperature of 26°C [33]. In addition, the measurements have been made with the transmission line technique and the bulk density value that corresponds to these measurements is 1.58 g/cm^3 , so according to Figure 11, at this density, the real part permittivity value of 3.04 appears to be in agreement with the simulants JSC-2A and EAC-1A.

From the results obtained, it can be proved that the measurements carried out for both, the EAC-1A and JSC-2A powders, are similar to the other types of simulants (Figures 3, 4, 5 and 6) which allows validating the results.

In the case of the real part of the permittivity (Figure 3), it can be seen that the values are quite close to other simulants, where the EAC seems to have a higher permittivity value than the JSC, and in the case of the loss tangent (Figure 4), the values obtained are slightly above those expected.

For the case of the range from 6 to 20 GHz it is again observed that, in the case of the real part of the permittivity, the values are close to the other simulants (Figure 5) and for the loss tangent (Figure 6), a greater dispersion can be observed.

The differences found in the measurement of the loss tangent discussed above are due to an accuracy problem, since the measurement methods used (non-resonant) have less accuracy for the measurement of the imaginary part of the permittivity than the resonant ones used in the bibliography; so the loss tangent, which relates the real part to the imaginary part takes this measurement uncertainty. However, the frequency range measured is larger in our case.

4. Other Studies

In order to continue advancing in the characterization of these materials, the study has been expanded, adding two new sections, which provide relevant information on their behavior in the face of changes in compaction and in the amount of water content.

On the one hand, variations in compaction imply variations in bulk density and this means obtaining higher permittivities by reducing the amount of air in the measured sample.

Variations in the amount of water will have the opposite effect. Measurements of lower permittivities will be obtained, since once the previous measurements have been made, it is known that the water has a much higher permittivity than the simulants (at room temperature the water has a relative permittivity value close to 80).

4.1. Drying Lunar Simulants

For the following case, 900 grams of both powders have been heated in an industrial oven for 24 hours at 130°C. Once heated, they have been let them stand long enough to return to room temperature and have been reweighed, in order to measure the percentage of water lost.

After heating, 890.70 g of EAC-1A and 898.24 g of JSC-2A remained. This represents a loss of approximately 1% for the EAC-1A simulant (9.3 g) and a loss of 0.2% for the JSC-2A (1.76 g).

The variations obtained will now be displayed, so that the values of the undried powder will be compared with the values of the dried powder (Figures 7, 8). All measurements in this section have been carried out using the DAK-3.5 kit already discussed throughout this study, in addition to having been made in a single day in order to avoid variations in the amount of water lost.

As can be seen in Figure 7 the expected result is obtained. The real part of the relative permittivity decreases for the dried simulants compared to the non-dried simulants.

On the other hand, it can be observed how the simulant with the greatest loss in the percentage of water (EAC-1A), had a greater decrease in the value of the real permittivity (red dashed line), which gives more validity to the hypotheses made on the relationship between the amount of water in the powders with the loss of dielectric permittivity.

As it happened in the measurements of the loss tangent in the previous sections, there is a frequency range where there is a large measurement dispersion and up to 6 GHz, at higher frequencies, it can be seen that these measurements stabilize. Taking this range into account, it is not possible to appreciate (Figure 8) variation in the dielectric loss tangent between the dried and non-dried simulants.

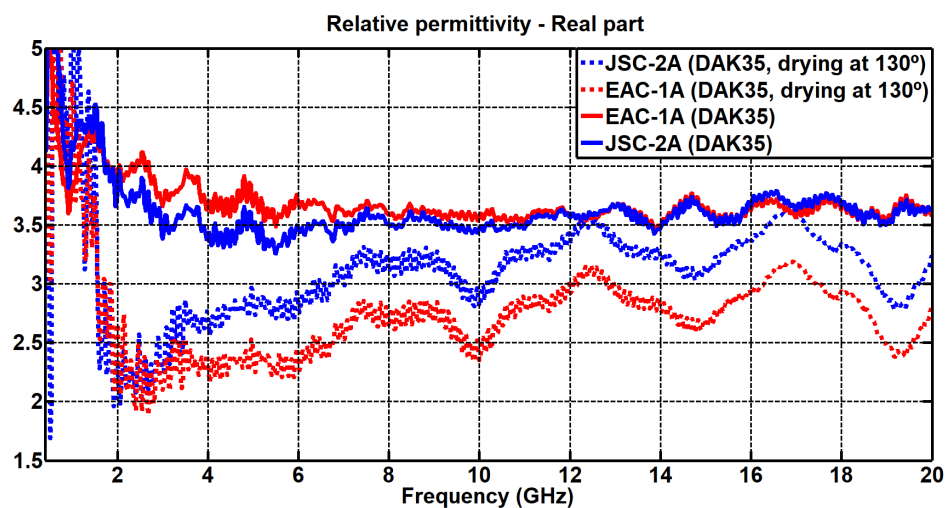


Figure 7. Comparison of the real relative permittivity measurements between the dried and the undried simulants. (DAK-3.5 kit)

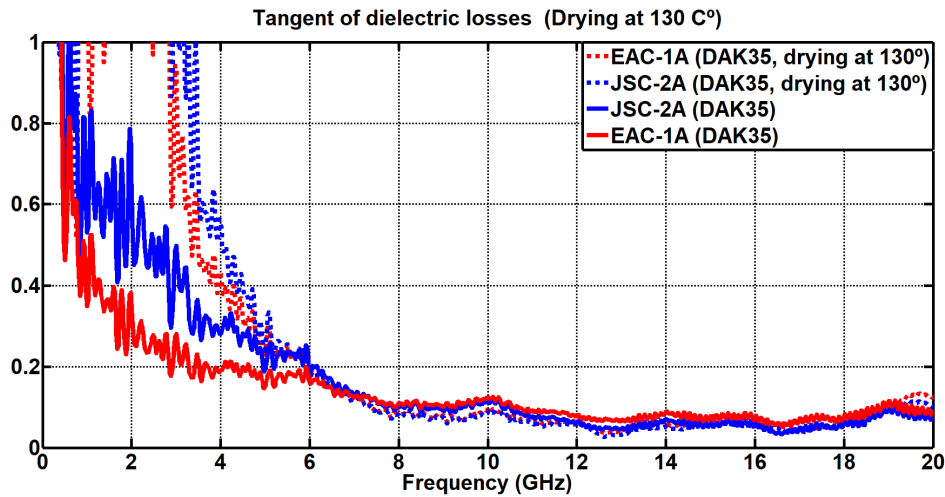


Figure 8. Comparison of the tangent of dielectric losses measurements between the dried and the undried simulants. (DAK-3.5 kit)

4.2. Study on Variations in Density

To carry out the measurements of this section, only the EpsiMu kit were used, since it is the only one that allows measuring different relative densities of the powder, depending on the amount that is incorporated inside the sample holder (Figure 2).

Therefore, for the calculation of the density, different amounts of powder have been added in the sample holder to be weighted, so that by obtaining the difference with respect to the weight of the sample holder alone, the weight of simulant that has been introduced can be determined. Later, the density is calculated dividing those weights by the volume of the sample holder.

The values obtained from the real part of the relative permittivity for each density and for each simulant can be seen in Figures 9 and 10.

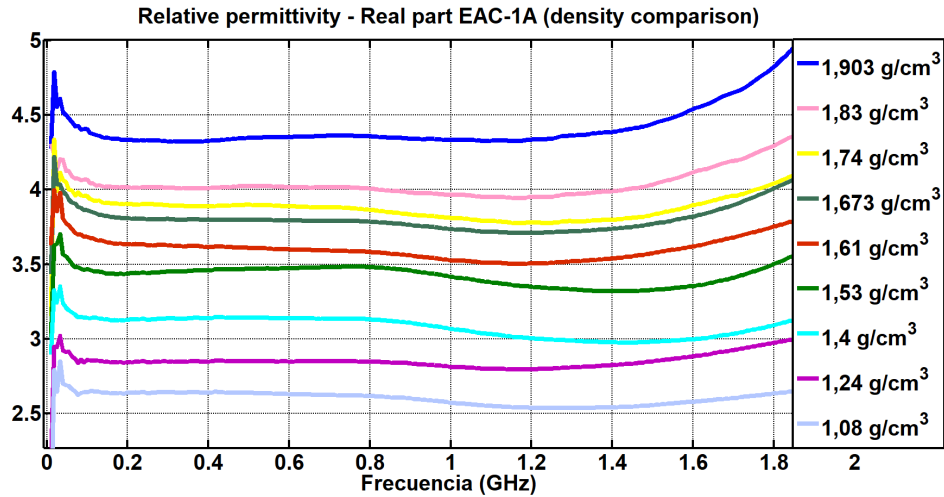


Figure 9. Comparison of the real part of the relative permittivity obtained varying the density of the simulant EAC-1A (EpsiMu kit)

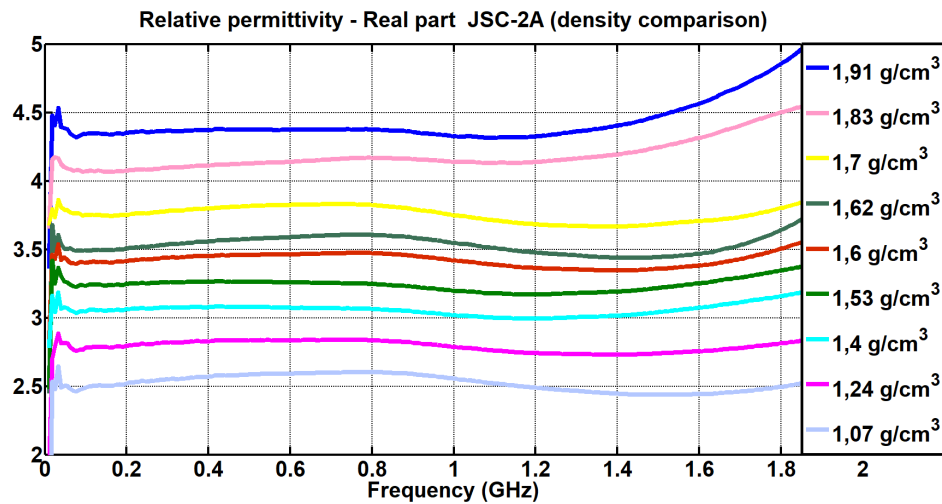


Figure 10. Comparison of the real relative permittivity measurements varying the density of the simulant JSC-2A (EpsiMu kit)

In Figure 9 it is observed that, as the density decreases there is a lower value of the real permittivity. It can be seen that from frequencies close to the cut-off frequency (2.5 GHz) mentioned in Section 2.1 of this study, the measurements diverge, although throughout the entire range between 400 MHz and 1.6 GHz the measurements are linear.

Finally, the results obtained have been compared with other studies carried out on the variation of density in the simulants. In [14] a large number of measurements are made with different simulant densities and an approximation curve of these measurements is reached, which relates the density variations as a function of the real part of the permittivity as follows:

$$\varepsilon' = 2.15^{\rho} \quad (5)$$

Where ρ is the density. This theoretical equation does not vary with frequency, since, as seen previously, the variation in density (in the case of the real part of the permittivity) is linear with respect to different frequencies. In this way, two frequencies have been chosen (0.6 MHz and 1.2 GHz) and the results obtained for the real part of the permittivity and density variation have been compared with the approximation extracted from [14] (Figure 11). As can be seen, the data obtained in our measurements are approximated with the aforementioned fitting curve.

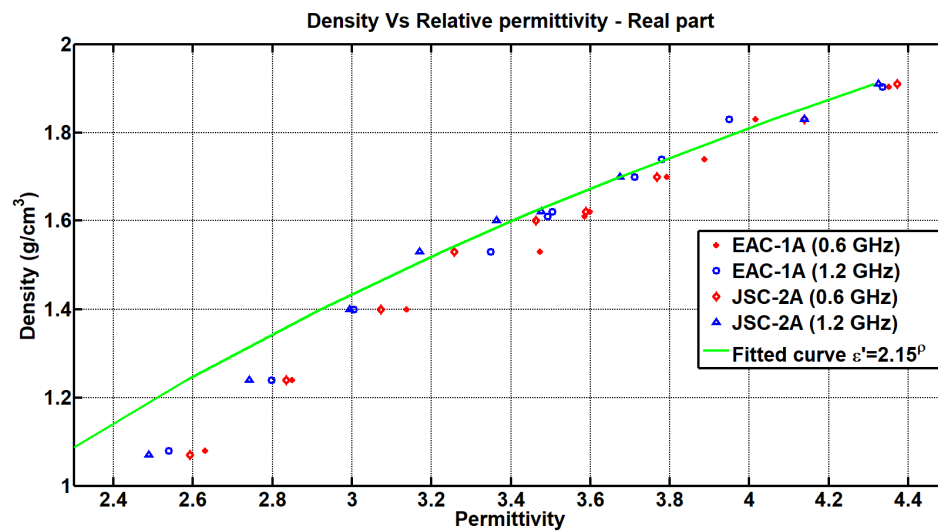


Figure 11. Comparison of the real part of the permittivity measurements of the EAC-1A and JSC-2A simulants varying the densities (EpsiMu Kit [0.6 and 1.2 GHz]), with respect to the fitting curve from [14]

5. Conclusions

This study tries to address the growing interest from the space industry in knowing the behavior of lunar dust against electromagnetic radiation, since it can be observed worldwide how the number of space programs to return to the moon have grown considerably.

Two types of lunar simulants (EAC-1A and JSC-2A) have been electromagnetically characterized and both of them present a similar mineralogy to other simulants and real regoliths extracted from the moon. Two independent measurement methods have been used (OECP and transmission line), from the DAK and EpsiMu measurement kits respectively. Using them, it has been possible to characterize the JSC-2A and EAC-1A simulants in a frequency range between 400 MHz to 20 GHz. This frequency range is especially wide taking into account the characterization seen for other simulants in the bibliography. To validate the results obtained from our measurements, a comparative study has been carried out. In it, the differences between the permittivity values obtained from our simulants with respect to others present in the bibliography have been seen and, in general, it has been possible to conclude that the measurements made are consistent.

Based on these results, it can be observed in the case of the real part of the relative permittivity how the simulants studied are similar to the JLU, JSC and their variants, and that the simulant CAS-1 is far from these values.

On the other hand, considering the LHS-1 and LMS-1 simulants, a greater difference in the permittivity value is also observed. However, this difference can be attributed to compaction when measuring the powders. In this sense, it can be observed in the data extracted from [15] how, in higher compactions, permittivity values close to those seen in the case of JSC-2A and EAC-1A are reached.

In the case of real lunar regoliths, it can be concluded that the sample corresponding to Apollo 14 and 17 have a greater resemblance to the simulants studied, while in the case of the Chinese CE-5 regolith, the resemblance is more consistent with the simulants LHS-1 and LMS-1.

Regarding possible future lines of research to continue improving the measurements of the characterization of powders, it can be highlighted the study based on temperature, the study based on the percentage of water inside them or the use of resonant measurement systems in order to obtain greater precision in the calculation of the loss tangent at specific frequencies, since it is a decisive variable for the in-situ processing of the lunar regolith [11].

Another possible study could be to increase the measurement range up to 110 GHz, since the Computational and Applied Electromagnetism Laboratory (CAEM-Lab) has a measurement bench for the free space technique, capable of measuring in the V and W bands (from 50 GHz to 110 GHz).

The study on the density variation could also be extended according to the range of frequencies measured, in this way it could be interesting to see if at higher frequencies, the relative density variations of the powders continues to be linear, as observed in the measurements made between 400 MHz and 2.5 GHz (Figures 9, 10).

Finally, in the case discussed in Section 4.1 about dried and undried simulants and water content in the simulant, it would be interesting to obtain measurements for water percentages greater than the measurements made, since water on the moon is an important resource. For the search of this resource on the moon, microwave synthetic aperture radar (SAR) imaging technique could be used [15], and therefore, obtaining the electromagnetic characterization of the material (with presence of water inside it) seems to be essential.

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Abbreviations

The following abbreviations are used in this manuscript:

ISRU	In-Situ Resource Utilization
OECP	Open-Ended Coaxial Probe
ISR	In-Situ Resource
ESA	European Space Agency
JSC	Johnson Space Center
DAK	Dielectric Assessment Kit
EuCAP	European Conference on Antennas and Propagation
CLEP	China Lunar Exploration Program
CAEM-Lab	Computational and Applied Electromagnetism Laboratory
SAR	Synthetic Aperture Radar

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