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14. ABSTRACT

This report results from a contract tasking University of Algarve as follows: The Grantee will 1) apply Maxwell's equations with vector radiation processing to determine how virtual antennas can be developed using the Huygens principle; 2) study the propagation medium to determine which physical parameters are important for radiation parameters of the spatial distributions of radiating sources and to establish the relationships among them. The aspects of the propagation medium that are to be studied depends on the GPS propagation error estimation and correction, after optimization of the model parameters; 3) simulate point to point links using the new procedures developed as a result of tasks 1 and 2 above; and 4) use classical point to point propagation links models to verify the newly developed propagation models of the virtual antennas procedure to provide a reference for, and to quantify the accuracy of, the newly developed models.

15. SUBJECT TERMS

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PROJECT

FA8655-05-1-3032

FINAL REPORT

OF THE RESEARCH WORK ENDED ON

MARCH, 15, 2006

A. INTRODUCTION

This is the final report concerning the contract FA8655-05-1-3032, "Space Weather Effects on RF Propagation" according the item "E" of the project . The objectives and description of the research work are copy of the project text. At the item "D" it is presented a summary of the results related with the proposed objectives, and at item "G", the details of the scientific aspect are presented.

The research work done in this project year (March 15, 2005 to March 15, 2006) made possible to deal with propagation problems in a way different from that it is usual, using spatial distributions of radiating sources as "virtual antennas", and processing this "virtual antennas" with the tools developed for antennas radiation problems. This was the first step in this new procedure that can be used to deal with propagation aspects, namely the Space Weather Effects on RF Propagation.

B. OBJECTIVES OF THE RESEARCH WORK

The objectives of this one-year project are:

1- to adapt the Huygens principle to spatial distributions of radiating sources as virtual antennas. (This has nothing to do with phased-array antennas, which is well-known existing technology for discrete arrays of equi-spaced phase-controlled elements. The procedure that is intended to be developed deals with continuous distributions of radiating sources dependent upon the propagation medium.)

2- to study which physical parameters of the propagation medium are important for changing the radiation characteristics of these antennas in the far field, and what approximations are acceptable in the simplest models. The model will assume that we are far from the antenna the sufficient wavelength distance to consider that is enough to deal with the far field, independently of the "distributed antenna" size.

3- for a single reception point and a single excitation point equivalent to a continuous virtual antenna, to study how the point-to-point propagation depends on this spatial distribution of radiating sources and their propagation parameters. The reception point is just one point. The emission point will become the point that makes the excitation of the continuous "virtual antenna".

4- to develop propagation models of these procedures and to test them with computational simulation.

C. DESCRIPTION OF THE RESEARCH WORK

To achieve the above objectives it will be necessary:

1- to apply Maxwell's equations and with radiation vectorial processing to determine how virtual antennas can be developed with Huygens principle, as presented in B1.

2- to study the propagation medium to determine which physical parameters are important for the radiation parameters of the spatial distributions of radiating sources and to establish the relationships among them. The aspects of the propagation medium that are to be studied depends on the presented at B1, namely those aspects that will be seen that are related with the Maxwell's equation application, and so with the radiation characteristics of the "virtual antenna".

3- To simulate some point-to-point links using the new procedure developed in B1 and B2 and to analyze how the received signal depends on the variation of the propagation parameters. The capabilities of this procedure only can be known at the end of the proposed work.

4- To use classical point-to-point propagation links models and to compare them with the propagation models of the "virtual antennas" procedure, using the signal in the reception point. This step will provide a reference for and to quantify the accuracy of the new developed models. So the classic models need to include the classic modeling of the propagation medium, namely the Fresnel propagation link models.

D. THE RESEARCH WORK DONE AND THE RESULTS OBTAINNED

Here it is presented a summary of the results related with the proposed objectives. The technical aspects are presented in the proper topic at G.

Objective 1

The Huygens principle was adapted, to a new propagation model that uses spatial distributions of radiating sources as "virtual antennas" that have the feed intensity and phase en each point dependent of the relation between the propagation wave at that point, and the propagation wave at another point that is considered as reference.

<u>So, the objective 1 was accomplished.</u>

Objective 2

Using the Fourier Relation [1][3][6][7] to deal with the "radiation pattern" of the "virtual antennas" it was found that, as well as in the "real antennas" the phase of the continuous element feed controls the radiation direction. The wavelength in each propagation medium is the parameter that is related with the change of the ray direction. So, all the physical parameters that, in each particular propagation medium, change the wavelength are important parameters for the changes of the radiation characteristics. On the other hand, the relative intensity feed of the "virtual antenna" controls the shape of the radiation pattern.

The approximations made for the simplest models were to consider that the propagation wave has just one frequency (monochromatic wave), or that the frequency dispersion is so small that the wave can be considered to have just one frequency; to consider that the length of the "virtual antenna" was much grater than the wavelength; and it was also considered, for this models, that each propagation media involved in each ray path slot, is linear, homogeneous, isotropic and without loss.

That is acceptable for the models used in this project, that are the first step in this new procedure because it was possible to compare with the well known classic models namely those involved with the well known Snell's law, that have the characteristics of the approximations made.

In general, is necessary to consider all the frequencies of the electromagnetic wave, if they have a wide dispersion in relation to the central frequency. This dispersion is a characteristic of the electromagnetic wave, not a physical parameter of the propagation medium, but, nevertheless, it will necessary to be considered, in a more complex model, because it also changes the wavelength if the velocity is different for different frequencies.

So, the objective 2 was accomplished.

Objective 3 and objective 4

Using the new procedure several propagation models were developed to study how the propagation direction changes for point to point links in different situations, namely: a) reflection with a mirror; b) the propagation with the incident ray having 90 degrees with the boundary of two different propagation media; c) the reflection of the incident ray if the incidence is not 90 degrees; d) the angle of the refracted ray in the previous case; e) the total reflection if a wave is incident at an angle exceeding the critical angle at the boundary when the ray comes from a medium where it has smaller wavelength to a medium where it has larger wavelength.

These models using the new procedure were tested by comparison with the results of the well-known classic models that include the Fresnel propagation link models, and the results agree completely, validating therefore the new procedure. In this way the computational simulation was not necessary for testing them.

So, the objectives 3 and 4 were accomplished.

E. PUBLICATIONS

The results were submitted as an abstract of a paper (a copy is enclosed in this report), with the title " An Antenna Array Approach for Propagation of Electromagnetic Waves in Different Media" for presentation in the "Progress in Electromagnetics Research Symposium" (PIERS 2006) the world-wide Symposium that will be held at the Chuo University, Tokyo, Japan, on 2-5 August 2006, and it was accepted with the n° 060127053116. The paper will be presented in the special session "Wave Scattering, Random Media and Wireless Communications"
After the presentation and discussion at PIERS, a paper with the new procedure will be submitted to the Journal of Electromagnetic Waves and Applications that is related with PIERS.
As it is necessary, the publications will contain:

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and a copy will be send to EOARD as soon as the paper is ready.

F. DISCLOSURE OF INVENTIONS

I certify that there were no subject inventions to declare during the performance of this grant.

G. DETAILS OF THE SCIENTIFIC ASPECTS

Here it is presented a more detailed view of the principal scientific aspects that are related with the new procedure. It is made a brief description of the different concepts that are used to avoid to the reader the need to go to look for them.

For result comparison it will be used the light point-to-point typical propagation models, because they are the most studied and well-known cases of electromagnetic wave propagation in typical situations, and so they give a very accurate validation results.

The Huygens principle

Cristian Huygens wrote this well-known principle in a treatise about the wave theory of light. He states that the wave front of a propagations wave conforms to the envelope of spherical wavelets coming from every point of the wave front at the same speed as the wave front [2]. As he was adept of the corpuscular theory of light he thought that the wavelets were a series of pulses and that the secondary waves were effective only in the point of tangency (fig 1).

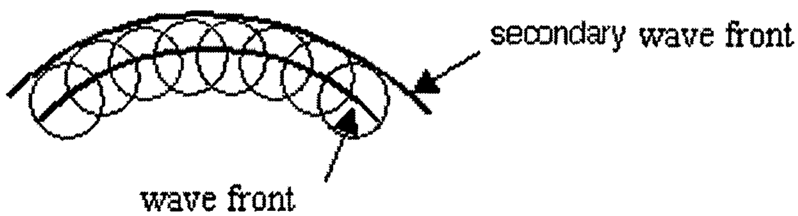


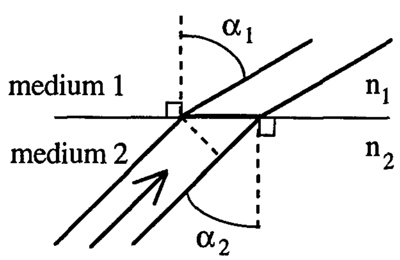
Fig.1 Huygens secondary wave front

The Fresnel correction

The Huygens principle was not able to explain some wave aspects, and the reason why the wave come not backward. One century later, Augustin Fresnel, that was adept of the wave theory of light, stated that the wavelets were waves, not corpuscles, and that the amplitude of the wave in any point was the superposition of the amplitudes of all the wavelets at that point. Although it does not resolve the backward problem, his approach gives results that are more accurate that only the Huygens approach. So it is necessary to take in account this approach as was refereed in the point C-4 of the research work description.

The Snell's law

The relation between the angles of incidence α_1 and α_2(direction change), for a point-to-point link, when a wave reaches the boundary between two media with different refractive indices must satisfy the well-known Snell's law (fig.2).



$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$$

Fig.2 The Snell's law

The Fourier Relation

It was shown in antenna processing [1][3][6][7], that, if appropriate variables are choose, whenever a source distribution translation produces in the fields a phase change related with the translation, the antenna radiation pattern is related with the source distribution by an window that depends of the wavelength, in the Fourier Transform of the distribution (fig.3). That situation is the "The Fourier Relation".

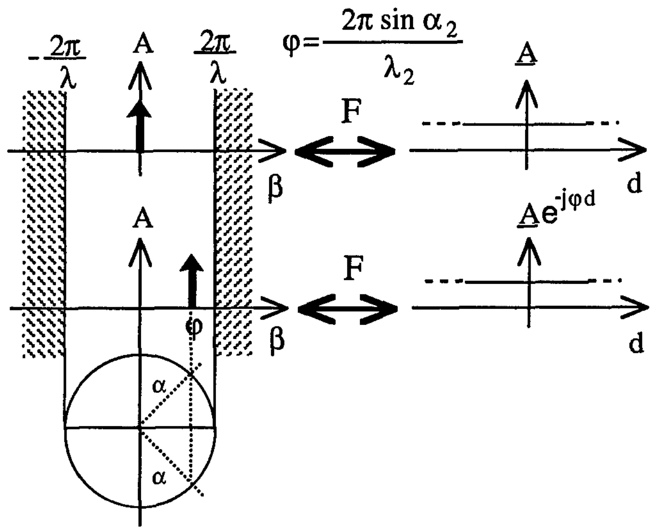


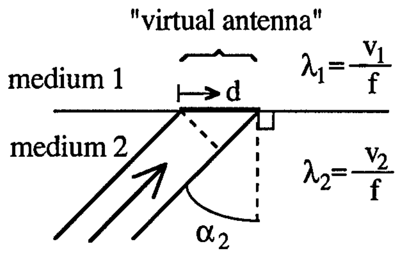
Fig.3 The use of the Fourier Relation

The "Virtual Antennas"

For this research work it will be considered typical propagation problems as "virtual antennas" radiation problems, using the Huygens principle and the Fresnel correction in spatial distributions of radiating sources as those "virtual antennas", as a first step in this new procedure.

For the validation of this new procedure, as we are dealing with electromagnetic waves, it was chosen situations that deals with classic and very well studied propagation problems of an electromagnetic wave that is propagating from one propagation medium to another propagation medium with different propagation characteristics, through a straight boundary, namely the so called the Snell's Law, that usually is applied for studies with light. The path that the wave takes to propagate in this situation, is, usually, explained by the Fermat principle of least time, but this principle do not explain how the photons "knows", how to follow the quickest way, as Fermat states.

A new approach is proposed in this research work. It is considered that there is a "virtual antenna" in the separation line between the two media (fig 4), formed by the incident ray. This "virtual antenna" is considered as a continuous linear array with the amplitude feed of the elements of this "antenna", and the phase of it elements depending on the distance "d" from a reference point. For instance, in the case of figure 4, if the incident ray is uniform, and we consider as the reference point that point were the ray first touches the boundary of the media, the amplitude of the elements feed is constant in "d" and the phase of those elements $\varphi(d)$ has the expression in the figure.



$$\varphi(d)=\varphi_2 d=-\frac{2\pi\, d \sin\alpha_2}{\lambda_2}$$

Fig.4 A "virtual antenna"

The application of the new procedure to the situation of point to point links within the Snell's law

In the Fourier Transform, a shift in one domain corresponds a progressive phase in the other (fig. 5)

$$A(\beta) \quad \overset{F}{<\text{--------}>} \quad \underline{A}(d)$$

$$A(\beta-\varphi_2) \quad \overset{F}{<\text{--------}>} \quad \underline{A}(d)e^{-\varphi_2 d}$$

Fig.5 The shift in the Fourier Transform

If we consider a "virtual antenna" as in figure 4, using the shift in the Fourier Transform with the Fourier Relation the array pattern is shifted when the wave propagates from the medium 2 to the medium 1 with a value that depends of the wavelength (it corresponds to what is usually called the refracted ray), and there is a re-radiation to medium 2 (it corresponds to what is usually called the reflect ray) (figs. 6).

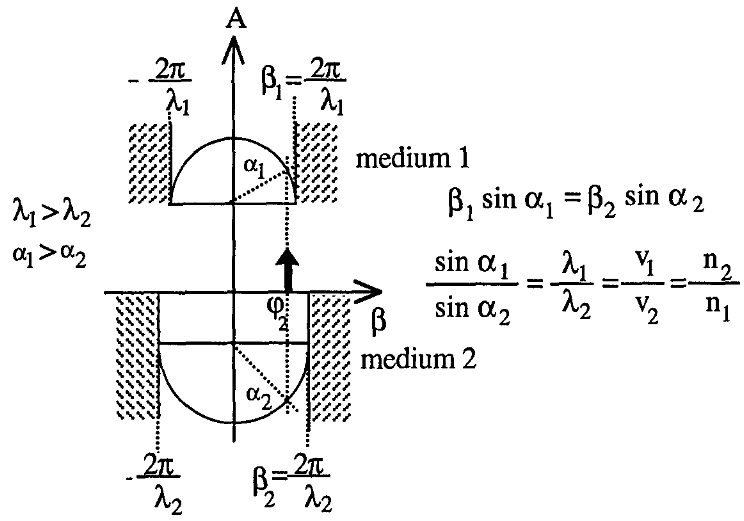


Fig. 6 The shift in the "antenna" pattern, and the Snell's law

In medium 1 the refracted ray has now an angle α_1 that is related to the incidence angle α_2 by the expression at figure 6, that is equal to the well known Snell's law: the validity of this new procedure is, therefore, confirmed in this case.

The application of the new procedure to point to point links in other situations

Next, the new procedure was applied to several other typical and well-studied point-to-point propagation situations.

First, it is possible to see a situation that is not cover by the Snell's law: besides the refracted ray that has an angle α_1 , there is yet a ray that is re-radiated to the medium 2 with an angle α_2 as can be seen in the lower part of figure 6. It is the well-known reflected ray. So the new approach is a better model than the Snell's law.

Another situation happens if the boundary is a mirror. The refracted ray does not exist and the ray is reflected with an angle that is also α_2 . The new procedure also agrees with the well-known classic results of these situations: the validity of the new procedure is confirmed also in those cases.

So, the new procedure presents not only a new approach for the refraction, but also for the reflection phenomenon.

If the boundary is perpendicular to the ray direction, the angle α_2 is equal to zero, and the angle α_1 is also equal to zero, as it is known, and this situation also can be treated using the new procedure as can be seen using figure 6: this situation also agrees with the Malus Theorem: "A bundle of rays is perpendicular to a plane and hence also to all parallel planes, it retains this property also after arbitrarily many refractions and reflections".

At last, if the incidence angle α_2 is increased, the angle α_1 approaches $\pi/2$ (the refracted direction approaches the limit of the window, in the upper part of figure 6). The angle α_2 were, the angle α_1 is $\pi/2$, is called the critical angle. If a wave is incident at an angle exceeding the critical angle, the radiation direction is out of the useful window and there is only reflection in the boundary (all the energy of the "virtual antenna" is sent to α_2 direction, as in the classic approach).

H. CONCLUSIONS

This research year was the first step into a new procedure to deal with the propagation of electromagnetic waves as radiation of "virtual antennas". This new procedure is based in the Huygens principle, with Fresnel development.

Using the Fourier Relation developed for antenna studies, it was found that the wave length is the physical parameter that is related to the changes of the radiation direction of these "antennas", and therefore all the physical parameters that in real situation can change the wave length, namely the refractive indice, will change the radiation characteristics of the "virtual antennas".

The new procedure gives results that are equal to the well-known typical link model of electromagnetic wave propagation, in the situation ruled by the Snell's law and therefore it is validated for this situation.

It was studied how the point-to-point propagation depends on this spatial distribution of radiating sources and their propagation parameters. Several point-to-point links were simulated, in different circumstances, using models with the new procedure, and tested by comparison with known results. All agree, so it was not necessary to make computational simulation for result confirmation.

In short, it was developed a new procedure that allows using the tools developed for antennas, to solve propagation problems, namely those related with Space Weather Effects on RF Propagation. The application advantages of the new procedure instead of the classic procedures, in practical cases of propagations problems must be seen in each case, and it can be foreseen that new applications will arise with further research. And the new procedure, at this research stage, already allows a unified view of several propagation situations usually studied with different methods.

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ABSTRACT ACCEPTED FOR PIERS 2006

An Antenna Array Approach for Propagation of Electromagnetic Waves in Different Media

The Huygen's Principle together with the Fourier Relation [1] can give a new insight to the reflection and refraction phenomena and the laws related with them. First we deal with the reflection and refraction of an electromagnetic wave when it crosses from one propagation media to a different one with a plane surface between the two media, and the result will be compared, for validation, with the Snells's Law.

In the classic framework it is usual to consider, the Fermat's Principle or the Malus Theorem [2] to deduce the Snell's Law. In the presented approach those principles are not necessary: the Snell's Law is a consequence of the "radiation and propagation proprieties" of the two media.

After, this procedure will be applied to atmospheric propagation where the "radiation and propagation proprieties" of the media are changed by the Space Weather conditions.

Let's consider the interface separating two transparent media and the line (virtual antenna) that an incident ray makes in that plane interface (fig.1). The ray comes from the media 2 to media 1. If we assume, using the Huygen's Principle, that the line is a virtual continuous radiating antenna array, the antenna elements will have different phases φ(d) due to the delay that different part of the ray has because of the incidence angle. The array pattern can be seen as an window in the Inverse Fourier Transform of the Source distribution [1], and, in this case, is shifted with a value that depends of the delay. In the Polar representation this shift gives an angle that depends of the wavelength, as in the right side of fig. 2.

So in the same media of the incident ray, the angle is the same. On the other side the angle of refraction has the same sine function value as the angle of incidence, with multiplication by a constant related with the wavelength (fig 2), because the window is now different (beta 2 is different from beta 1).

The final result agrees with the Snell's Law, and with the reflection law, and it is therefore validated. So the presented procedure, following a complete different way from the classic procedures, by using the concepts related with radiating array antenna [1][3], opens new possibilities of propagations studies using already developed antenna tools [4].

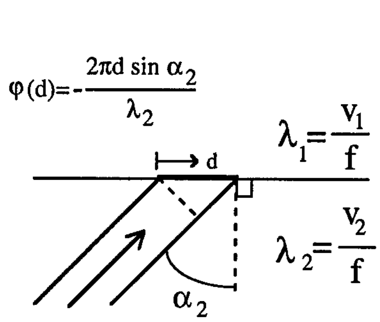

Fig. 1

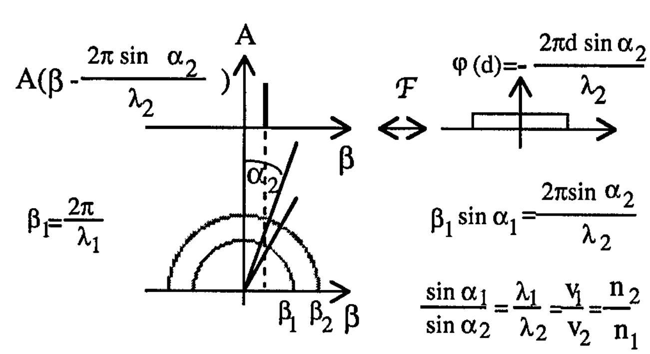

Fig. 2

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