Ionospheric focusing and defocusing effects in EME communication

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Abstract
In this paper we examine the Mid latitude ionospheric structure and models. localized ionospheric irregularities also act like convergent and divergent lens which focus and defocus the radio waves and can create caustics (please see the specific section in this paper). Such effects are commonly referred to as “scintillations” which affect amplitude, phase and angle-of-arrival of the trans - ionospheric signals in EME communication (1). EME propagation occurs within a rippled earth-ionosphere, so the electromagnetic field is subject to focusing and defocusing. We consider that the ionosphere causes significant propagation effects at frequencies up to at least 10 GHz.

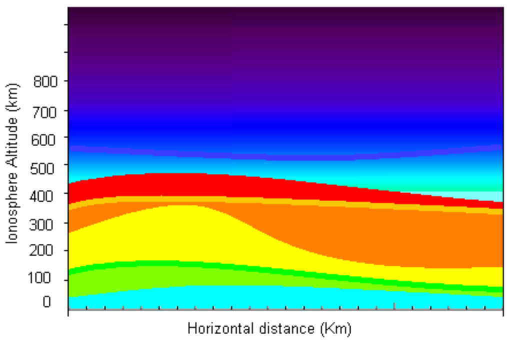

Fig.1 The illustration is a speculation of a curved model of the ionospheric layers, modelled by neutral winds and solar radiation. (Computer simulation)

The morphology and the physics of the ionosphere
The ionosphere and neutral atmosphere are strongly coupled, dynamically as well as chemically. There are important dynamic processes in the ionosphere depending greatly from solar radiation and strong thermospheric winds (2). These parameters are able to model the structure of the ionosphere and the result is a plasma in continuous motion, affected by turbulence and large instability and important undulations. The ionosphere is inhomogeneous plasma, its characteristics changing at different points as a consequence, the ionospheric refractive index varies significantly in the spatial domain.

Ionosphere sinusoidal model
We assume that the more realistic model of the ionosphere boundary is a sinusoidal model. Due to the complex nature of ionospheric physics, there are small-scale and large -scale irregularities. Turbulent neutral winds, and AGW Atmospheric Gravity Waves (4), are the cause of rippled layers and turbulences. A signal that passes through these corrugated sheets may be subject to random phenomena of focusing and defocusing. We have estimated that the ripples may have a wavelength of about 100 km and an amplitude of a few kilometers.

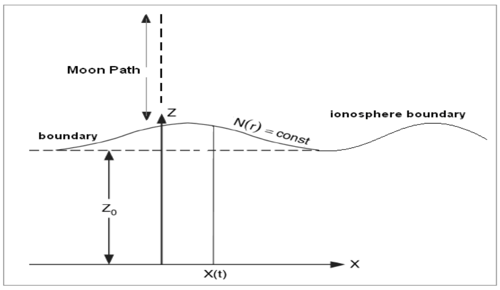

Fig.2 Sinusoidal model of the earth’s Ionosphere boundary

Ionospheric focusing and defocusing model
The mid latitude ionosphere (up to 400 Km altitude) can contain high ion concentrations in horizontal small and medium scale quasi cylindrical formations and probably aligned in a north-south direction, following the orientation of earth’s magnetic field. The signals beaming to the moon and also reflected back from the moon, could be focused/defocused as they pass through the ionosphere. (The interaction could occur in two ways) Fade and enhanced areas occur on the earth as a result of the focusing/defocusing effects. The ionospheric irregularities can be seen as a fading that affects the EME signals and on the other hand it is similar to the phenomenon of Ionospheric scintillation (3) in trans- ionospheric communication.

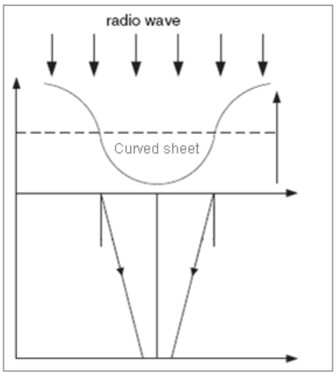

Fig.3 Model of penetration of radio waves trough a sinusoidal shape ionospheric layer. A ray passing trough a curved sheet changes the trajectory of his path.

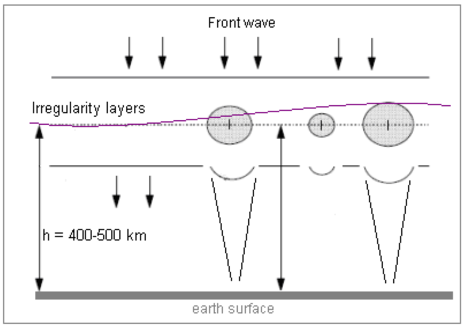

Fig.4 Illustration of penetration of radio waves trough the ionosphere within irregularities.

Sporadic focusing effects.
WSJT Echo test evidence some random focusing effects. These echoes have been made by Giorgio Marchi, IK1UWL, transmitting with circular polarization and receiving in H pol. They are therefore exempt from the Faraday effect, so the scintillation present is caused by attenuation and diffraction. They are not averaged (WSJT, Echo mode, Avg=0). In ideal conditions, without ionospheric absorption and without cosmic noise (degradation), for that station the echoes should have a -10 dB level. On the graph there is a red line at -14 dB corresponding to -10dB and - 4 dB of moon degradation during that day.

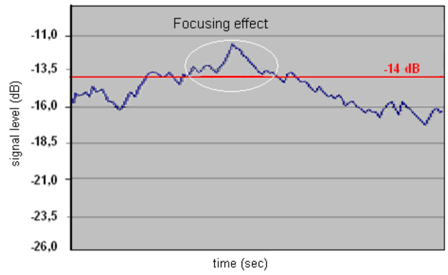

Fig.5 The diagram show a focusing event during an Echo mode test. The signal enhancement due to ionospheric focusing effect is estimated in about +3 dB (during this event). We repeated several echo tests detecting some other random signal focusing spikes.

Frequency dependency

The focusing and defocusing phenomena associated with intense scintillations are mostly confined to the VHF range. This means that intensity scintillations with periods much longer than a second, arise from focusing and defocusing in irregularities behaving as lenses. Such behaviour is facilitated by the dominance of large-scale structures in the ionosphere's spatial distribution. Fluctuations of the signals are caused by the irregular variations of the refractive index and it is well known that the index and consequently the variations are inversely proportional to the square of the signal frequency .As well as scintillation effects decreasing with increasing wave frequency, focusing and defocusing effect are most evident in VHF. More over it is very difficult to establish a precise calculation of the focal of such lenses due to the dispersive nature of the ionosphere.

Grazing incidence rays

We display the general principle involved in applying the grazing incidence concept connected to the problem of scintillation studies. As well as in the case of the diffraction screen model, the irregularity is aligned along the magnetic field line and has correlation surfaces of an ellipsoid of revolution. (The case may be easily extended to more general geometries such as the case of TID wave fronts.) A planar wave propagating from above the ionospheric region passes through the layer under consideration, and in instances where the aspect angle is very small, some component of the wave front may experience total internal reflection within the irregularity. The resulting change to the direction of propagation and the difference between the path lengths traversed by the affected and unaffected segments of the wave make it possible for wave fronts originating from the same source to interfere at a receiving location. As for a diffracted wave, amplitude scintillation records are observed on the ground.

Grey line focusing effects (Hypothesis)

A consequence of the pressure from the solar radiation is the non-concentricity of ionosphere and Earth. The shape of the ionosphere changes continuously as can be seen when the Sun sets on a meridian (terminator). In this phase the ionosphere is highly dynamic and its ionization changes drastically after the passage from day to night. The density of electrons in the E layer decreases by a factor 200 to 1, and the F layer by a factor 100 to 1. After sunset the D layer disappears. The signals that go through these layers for some hundreds of kilometres encounter curved surfaces that are oblique with respect to ground and that can generate focusing effects and can create attenuation and/or phase changes on the signal in transit. From the many tests we have conducted, it emerges clearly that an EME signal, going through a zone in transformation, is strongly influenced, undergoing attenuation and instability and probably sporadic focusing/defocusing effects, at least for a grazing incidence radio waves.

The role of TID (Traveling ionospheric disturbances)

The upper ionosphere is usually characterized by developed turbulent structure with scales of electron density irregularities from a few tens of meters to a few tens of Kilometres and a wide spectrum of quasi regular, large and medium scale inhomogeneity similar to TID traveling ionospheric disturbance of scales of tens to hundreds of Kilometres.
The local structure typically drifts from west to east.

<u>TID : a short summary</u>

- Large Scale TID (associated with AGW propagating in the thermosphere. Wavelenght >1000 Km, period 0.5 to 3 hours. Velocity 400 to 1000 m/s (sound velocity in the thermosphere)
- Medium Scale TID (associated with AGW propagating in the troposphere. Wavelenght 300-500 Km. period 15 to 60 minutes. Speed 100 to 250 m/s (< speed of sound in the troposphere)

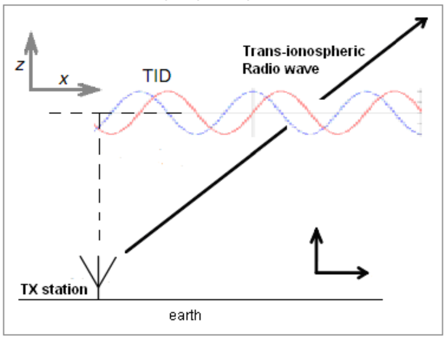

Fig.6 Another fading mechanism is caused by the movement of large and medium -scale irregularities in the ionosphere. Depending on the position of the irregularity, the ionosphere boundary will effectively becomes a concave or convex layer for radio-wave, which causes a focusing or defocusing effects on the trans-ionospheric signal.

Caustic surface

In optics, a caustic is the envelope of light rays reflected or refracted by a curved surface or object, or the projection of that envelope of rays on another surface. The caustic is a curve or surface to which each of the light rays is tangent, defining a boundary of an envelope of rays as a curve of concentrated light. Therefore in the image to the right, the caustics can be the patches of light or their bright edges.

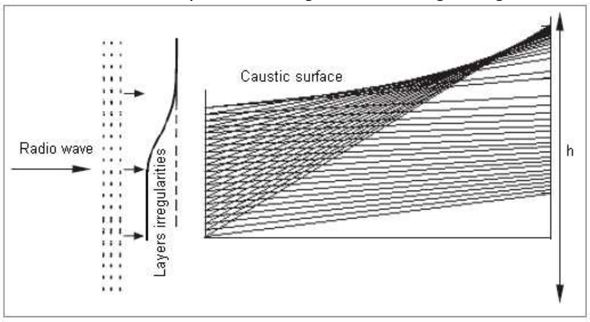

Fig.7 Caustic surfaces generated by irregularities in the ionosphere.

Lens effect of the earth's Ionosphere

(Extracted from a research by prof. Giovanni Silvestro: "High Resolution Methods in Radio Astronomy")
Istituto di Fisica Generale Universita' di Torino – Italy
Laboratorio di Cosmo-geofisica del CNR.

The earth's ionosphere can focus radio waves thanks to the grazing incidence refraction index with regular gradient N above the 400 km of altitude (Caustic surface). Radio waves from a distance source at grazing incidence on the earth's ionosphere, are focused at the moon. But this is not possible for radio waves that pass through the ionosphere and reach the ground, because it lacks the effect of "caustic surface". We deduce that only ionospheric disturbances and irregularities can induce focusing effects on trans-ionospheric signal.

APPENDIX

Reirradiation properties of the Lunar surface

Abstract

The surface of the moon may be considered as rough at radio wavelengths and a large number of scattering areas simultaneously contributing to the signal. The lunar surface is therefore a very poor reflector of radio waves. In this paper we focus to analyze the reflection coefficient and its possible variations. The effective scattering area of a moon reflecting in this manner has been calculated, and the theoretical and observed signal to noise ratios are now in good agreement, indicating that the power reflection coefficient of the lunar surface is about 0.1, with some possible small variations. The effect of this type of variations on a moon relay communications system is briefly discussed.

Reflection coefficient

The reflection coefficient, is the diffuse reflectivity or reflecting power of a surface. It is defined as the ratio of reflected radiation from the surface to incident radiation upon it. Being a dimensionless fraction, it may also be expressed as a percentage.and depends on the frequency of the radiation.

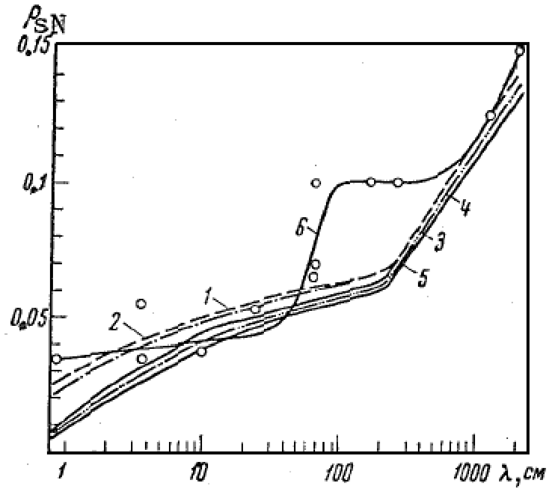

Fig.1 The graph display the normal incidence reflection coefficient. Circles show the findings of the different authors (see the table below).The incidence power reflection coefficient in terns of wavelength in this graphic shows that the reflection coefficient increases with wavelength. There is a smooth rise of from 3.2 to 4.5 percent between 0.8 and 30 cm, almost no change in the mean value of the reflection coefficient, which holds at 10 percent, between 1 and 5 - 7 meters, and an increase by a, factor of approximately 1.15 when the wavelength increases from 7 to 20 meters. There is an increase in the reflection coefficient by a factor of 2 between 30 cm and 1 meter, Bear in mind that the value in the decimeter and meter bands, calculated using the Evans and Pettengill method, will not be significantly larger than the psN values calculated including the reflections from large-scale irregularities. *(Graph source: "Radar Studies of the moon"- NASA)*

Wave-length, cm	$\rho_{s\,N}$	Author of Experiment	Author of Processing	Year of Measure-ment
0.86	0.035	Linn	Evans and Hagfors [108]	1961
3.2	< 0.1	Kobrin	Kobrin [31]	1957
3.6	0.035	Morrow	Girand [116]	
3.6	0.055	Evans and Pettengill	Evans and Hagfors [108]	1963
10	< 0.1	Kobrin	Kobrin [31]	1954
10	0.038	Hughes	Girand [116]	1961
68	0.065	Pettengill	Evans and Hagfors [108]	1960
68	0.057	Pettengill	Rea et al. [157]	1960
73	0.07	Fricker et al.	Fricker et al. [111]	1960
75	0.1	Leadbrand	Pettengill [154]	1959
150	0.1	Trexler	Trexler [70]	1958
250	0.1	Evans	Evans [80]	1957
300	0.1	Evans	Evans et al. [59]	1959
1130	0.125	Davis and Rohlfs	Davis and Rohlfs [103]	1964
1920	0.15	Davis and Rohlfs	Krupenio [40]	1964

Studies about radio wave scatter properties of the lunar surface at Jodrell Bank in 1956 revealed that most of the power in the reflected signal arose from scatterers lying near the center of the visible disk. The range extent of these returns was less than 1 ms. that is much less than the full radar depth of the moon (approximately 11 ms due to the curvature of the moon). Moreover, reflections observed from the moon by Trexler (1) employing a powerfull radar using 12 micro sec. pulses. The short range extent of the signal spectrum confirms that the reflections ae largely from the center of the visible disk.
(As show in the figure 2.)

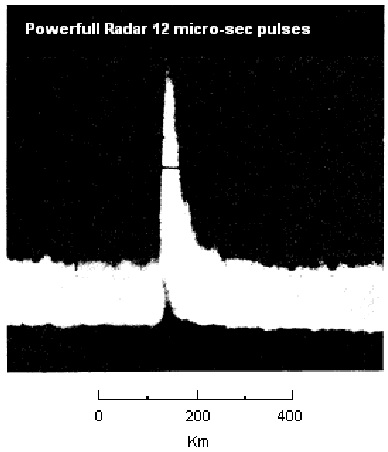

Fig.2 reflections observed from the moon employing a powerfull radar using 12 micro sec. pulses. The short range extent of the signal spectrum confirms that the reflections ae largely from the center of the visible disk. The Graph is taken from this document:
"Radio communication via the Moon" by J.V Evans (COMSAT Laboratories-United States)

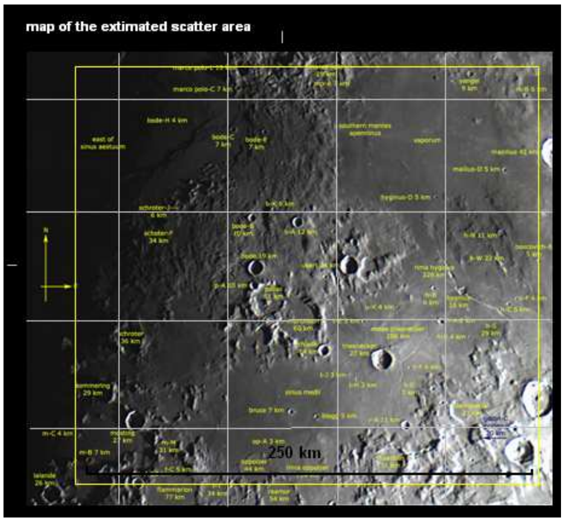

Fig.3 The map of the lunar surface on the center of the visible disk

Radar equation

Starting from the standard radar path link formula that is basis for EME path-loss calculations:

Loss-eme(dB) = 20Log(F) + 40LOG(d) - 17.49, F = MHz, d = km

I have obtained a graph that shows changes in path loss at the variation of the reflection coefficient. The variation in dB is not to exceed 3 dB in a range of 0,05 and 0,1 of the reflection coefficient.

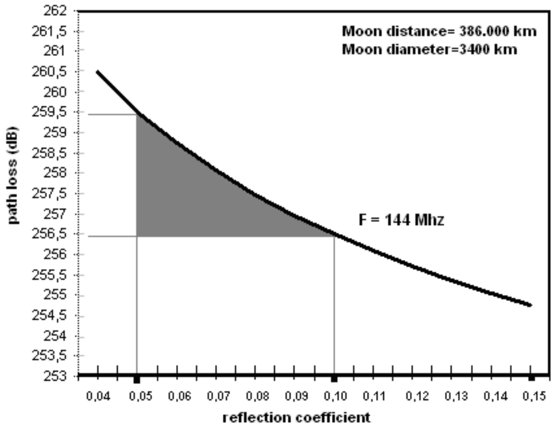

Fig.4 EME Path loss at the 144 Mhz versus reflection coefficient variations. The variation is about 3 dB in a range of 0,05 and 0,1 of the reflection coefficient. The calculation refers to a Moon distance of 386.000 Km (average distance from the earth).

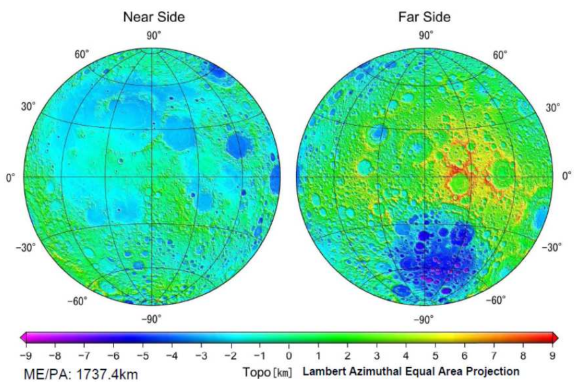

Fig.5 Lunar shaded topographic map (The Laser Altimeter (LALT) aboard KAGUYA captured data on the entire lunar surface height. The Lunar topographical map was produced by the Geographical Survey Institute (GSI) from the LALT product of the National Astronomical Observatory (NAOJ).

Acknowledgments

I thank Prof. Giovanni Silvestro for providing his valuable resources and information for use during the writing of this experimental work. Gratitude also goes to Giorgio Marchi, IK1UWL, for his unwavering support and guidance.

Remarks:

1- ITU recommendation "Ionospheric propagation data and prediction methods required for the design of satellite services and systems (Question ITU-R 218/3).
2- Thermospheric winds : A considerable temperature differences exist in the upper ionosphere between day and night side of the Earth. This creates a pressure difference that drives a horizontal wind in the upper atmosphere from the dayside toward the night side, called the neutral wind or thermospheric winds.
3- Ionospheric Scintillation occurs as a result of variations in refractive index of the medium through which waves are traveling and the variations in the index of refraction are caused by variations in the density of ionospheric plasma. Different indices of refraction result in phase changes between waves traveling through different locations, which results in interference. As the waves interfere, both the frequency of the wave and its angular size are broadened, and the intensity varies. (Please see the illustration below, Fig.8).

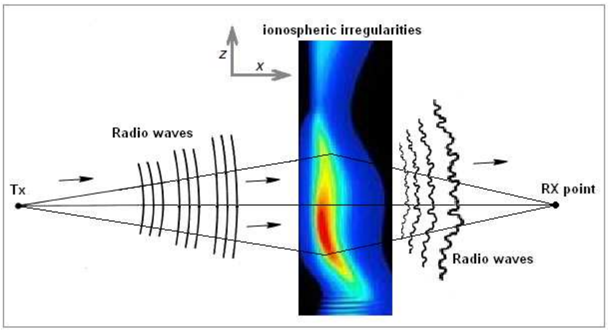

Fig.8 The mechanism of Ionospheric scintillation.

4- AGW Atmospheric Gravity waves: In the Earth's atmosphere, gravity waves are important for transferring momentum from the troposphere to the stratosphere. Gravity waves are generated in the troposphere by frontal systems or by airflow over mountains. At first waves propagate through the atmosphere without affecting its mean velocity. But as the waves reach more rarefied air at higher altitudes, their amplitude increases, and nonlinear effects cause the waves to break, transferring their momentum to the mean flow. This process plays a key role in controlling the dynamics of the middle atmosphere.

References:

-RECOMMENDATION ITU-R P.531-7 (Ionospheric propagation data and prediction methods required
for the design of satellite services and systems)
-Wikipedia
-High Resolution Methods in Radio Astronomy by G.Silvestro
-Lens effect of the earth's ionosphere on radio waves reaching the Moon by G.Silvestro and T.Gold
-JPL Jet Propulsion laboratory (various documents)
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-The synthesis of travelling ionospheric disturbance (TID) signatures in HF radar observations using ray tracing by A. J. Stocker, N. F. Arnold, T. B. Jones Department of Engineering, Leicester University, University Road, Leicester
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-Focusing of Radio waves reflected from a rough curved ionosphere By By J . D. Withehead Radio Research Board Laboratory, Universi ty of Sydney.

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Lunar science by Kaguya

Notes:

(1) Trexler, J.H. 1958, "Lunar Radio echoes," IRE,46, proc.286-292