[EN-027] Aeronautical satellite propagation channel characteristics using multiple antennas

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Abstract In this work we have investigated the use of multiple antennas for satellite-aircraft communications. In particular, we have looked at how signals received by antennas attached to the aircraft are correlated as a function of their separation distance. The signal correlation is an important factor when determining how effective a multiple antenna scheme will be. We have limited ourselves to reflections from sea surfaces due to the relatively simple analytical properties as opposed to land surfaces. The aeronautical channel is well described in the literature and analytical results exist for communications parameters like delay and Doppler spreads. There does not however, seem to be a simple analytical model to describe the correlation between signals as observed at different points in space. We therefore used Monte Carlo methods combined with electromagnetic scattering theory to obtain numerical estimates of the correlations. Due to the computational complexity we reduced the problem to a two-dimensional representation. That is, the sea surface is a one dimensional function, and the aircraft is positioned at an altitude *h* above the surface. Although this is a simplification, we still believe that the insights we gain with respect to changes aircraft altitude, elevation angles and sea surface roughness, are valid.

Keywords ATM, CNS, CARATS

1 INTRODUCTION

Systems providing communications between aircraft and ground play a vital role for the security, safety and efficiency of air traffic. As most of the earth surface is covered by water or ice, flights over these areas will often be out of reach of terrestrial communication systems and must therefore rely on satellite communication.

Several satellite communication systems, such as Inmarsat, provide aeronautical services in the so-called ORP (ocean, remote, polar) domain. A drawback related to geostationary satellite systems such as Inmarsat is that the polar coverage is poor, as the satellite will be located below the horizon for latitudes above 82°. Moreover, reliable communication is often difficult above 65° - 70° due to low satellite elevation angles. For polar routes, and some intercontinental routes, this implies long time spans without reliable communication means.

A propagation channel with low satellite elevation angle will generally be affected by multipath propagation, as the receiver antenna will receive signals reflected by the earth surface and the fuselage, as well as the direct signal. An efficient strategy to combat multipath propagation is to use multiple antennas. By implementing diversity schemes such as maximum ratio combining (MRC), the inherent diversity in multipath propagation channels can be exploited to obtain significant performance gains. A condition for obtaining diversity gain is however that the signals received by the different antenna elements are uncorrelated. If the correlation coefficient is close to one, the signals are close to correlated and no diversity gain is obtained. If however the correlation coefficient is close to zero, the signals are close to uncorrelated and diversity gains can be obtained.

In this publication, the correlation coefficient of the signal reflected by the earth surface is explored for low elevation angles and for flights over sea. Due to the waves of the sea surface, the receiver antennas will receive signals reflected by not only one point but from a surface area. The size of the area depends among others on the sea state and the flight altitude.

2. SCATTERING THEORY

This section describes the use of Monte Carlo simulations of scattering from a one dimensional (1D) rough sea surface. The goal of the simulations is to investigate the correlation between points in the diffuse component of the scattered electro-magnetic field. The first subsection will give a brief overview of the underlying theory and the approximations that need to be made to facilitate the numerical simulations. Later subsections will present the simulation results as well as interpretations and discussions.

2.1. The theory of scattering of electromagnetic waves from rough surfaces

Research into the effect of scattering from rough surfaces, be it e.g. acoustic or electro magnetic waves, has been conducted for more than a century. Our work will be based on [1] and [2].

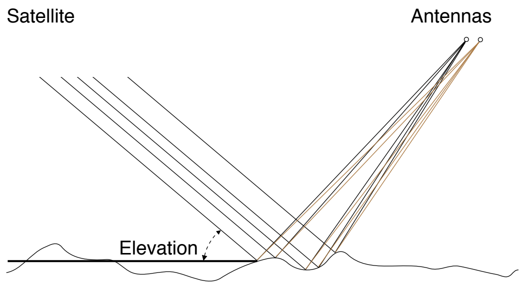


Figure 1: Geometry of satellite-aircraft communications. The elevation angle is measured between the satellite and the horizon.

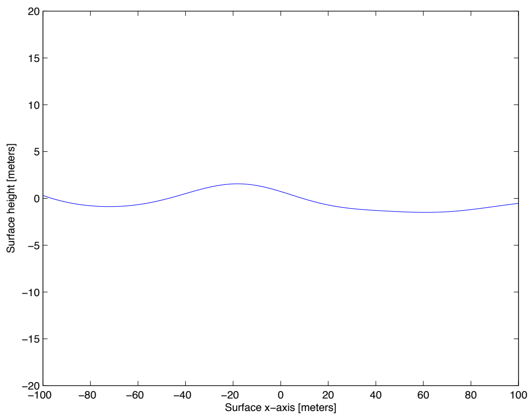


Figure 2: Random surface example. Rms height is 1.25 m, rms slope 0.07 and the resulting correlation length is 25 meters.

2.1.1. *Modeling the sea surface*

Before we can get into the scattering theory, we need a model for a rough sea surface. Although there is a rich theory of models for spectra of sea waves, it has been shown that a simple Gaussian process described by the root-mean-square (rms) height σ and the spatial correlation distance L is a sufficient model for many applications. There is a third parameter, α, that describes the rms slope of the waves. When the waves have a Gaussian spectrum it can be shown that:

$$\alpha = \sqrt{2}\frac{\sigma}{L} \tag{1}$$

This relation is useful when one wants to chose reasonable values for σ and L, as α has been determined empirically for various weather conditions.

2.1.2. *Approximations and conditions*

The Kirchhoff approximation states that the field existing on a point of a surface is the same as if the surface was a plane coinciding with the tangent plane. This approximation is stated to be valid whenever

$$\kappa \gg \frac{\lambda}{4\pi \sin\gamma} \tag{2}$$

where κ is the radius of curvature of the surface, λ is the carrier wavelength and γ is the elevation angle, that is, the angle between the horizon and the direction of observation. Clearly, care must be taken at low elevation angles as not to violate this assumption.

2.1.3. *The scattered field E(p)*

The scattered field off a surface S as seen from a point p in free space, is given by the Helmholtz integral:

$$E(p) = \iint_S \left(E\frac{\partial\psi}{\partial n} - \psi\frac{\partial E}{\partial n} \right) dS \tag{3}$$

where the constituents are as follows in the one-dimensional case:

- Under the Kirchhoff approximation the electric field is equal to $E = (1+\Gamma)E_1$. Here $E_1 = \exp i\mathbf{k_1}\cdot\mathbf{r}$ where $\mathbf{k_1}$ is the wave-number and $\mathbf{r}$ is a directional vector from the origin to the point $(x, \zeta(x))$, $\zeta(x)$ being a realization of the Gaussian surface. Γ is the reflection coefficient of a smooth plane-wave on a flat surface.

- $\psi = \frac{\exp(ikR)}{R}$ is the reflected wave. R is the distance from the point of observation, p, and the point of reflection $(x, \zeta(x))$. The scalar k is equal to the wave number, $k = \frac{2\pi}{\lambda}$.

- $\frac{\partial E}{\partial n}$ is shorthand for $\nabla E\cdot\mathbf{n}$, $\mathbf{n}$ being the surface normal. Under the Kirchhoff approximation it can be shown that $\frac{\partial E}{\partial n} = i(1-\Gamma)E_1\mathbf{k_1}\cdot\mathbf{r}$.

- The same goes for $\frac{\partial\psi}{\partial n}$. Computing the derivative yields $\frac{\partial\psi}{\partial n} = \phi\frac{(ik_2R-1)\nabla R}{R}$

- dS is the infinitesimal length of a surface segment at some point x.

2.2. Numerical simulations

This section describes the Monte Carlo simulations. The geometry of the simulations is given in the Figure 1.

Here the assumption is that the satellite is at infinity while the airplane antennas are at a much closer distance. The non-flatness of the earth is not considered, as it will only be an issue at very low angles at which the Kirchhoff approximation is invalid anyway.

The Monte Carlo simulation is performed as follows:

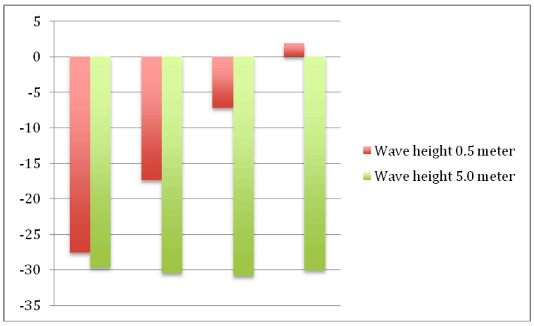


Figure 3: Specular-to-diffuse power ration [dB]. From left to right the bars represent the elevation angles 20, 15, 10 and 5 degrees.

1. Filtering white Gaussian noise using a spatial correlation filter having a Gaussian shape and correlation length L creates a series of surfaces. An example of a surface is shown in Figure 2 for rms height 1.25 meters, and rms slope 0.07 – which corresponds to a wave correlation distance of 25 meters.
2. For each surface the Helmholtz integral is evaluated. We use a mesh size of $dx = \frac{\lambda}{10}$, and assume that the aircraft is at height h and x-position zero. The antennas are placed at 0, a, $2a$, $3a$, and so on, where a typically is some multiple of a wavelength.
3. For each antenna position a series of complex channel gains are now available, and we can compute their correlation.

3. EXPERIMENTAL RESULTS

3.1. Prelimenary simulations

The experiments are performed for a carrier frequency of 1.5 GHz, which corresponds to a wavelength of 0.2 meter. This means that the integration resolution is 2 cm, or 50 points per meter. Clearly, integration domains in the order of tens of kilometers make for very intensive simulations, motivating the use of smaller domains. On the other hand, using too small domains result in a less rich scattering environment and consequently more correlation between antennas.

As an initial experiment we will focus on a low altitude aircraft scenario with h=1000 meter and a domain of integration equal to -30000 to 5000 meters. Here x-coordinate equal to zero corresponds to the point right below the aircraft. The satellite is assumed to be at minus infinity. We then compute the average power of the specular and diffuse components per surface area for several elevation angles. The results are shown in Figure 4a through Figure 4h for elevation angles 20, 15, 10 and 5 degrees above the horizon, as well as wave heights of 0.5 and 5.0 meters[1]. The immediate interpretation of these results is as follows:

- The effective surface area contributing to the reflected power increases with decreasing elevation angles.
- The ratio between specular and diffuse power increases with decreasing elevation angles.
- The main contribution to the specular reflection comes from the area around the glistening point – the surface point where the elevation angle is equal to the observation angle to the aircraft.
- For an elevation angle equal to five degrees and wave height 0.5 meters, the surface seems to be effectively flat and the specular component dominates.

All of the above observations are consistent with theory. Based on the above observations we can adjust our domain of integration. The parameters used are summarized in Table 1.

Finally, the specular-to-diffuse power ratio is shown in Figure 3. Clearly, for the 0.5 meter wave height scenario, the specular component becomes relatively stronger when the elevation angle decreases. For the 5.0 meter wave height scenario this effect is not seen, which indicates that the surface roughness is sufficient to completely annihilate the specular component for elevations at least down to 5 degrees.

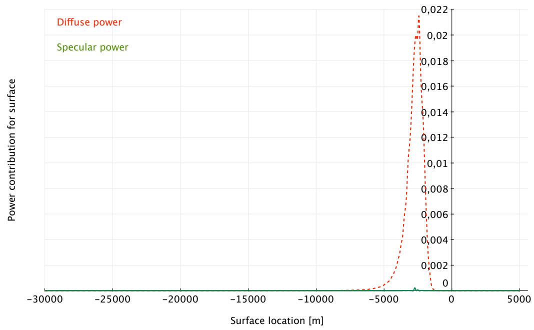
3.2. Antenna correlations

The correlation between antennas on an aircraft traveling at an altitude of 1000 meters is estimated for several elevation angles: 5, 10, 15 and 20 degrees. The wave heights are 0.5 and 5.0 meters. For each combination of elevation angle and wave height, 1000 random surfaces were generated and the electric field at each of the antennas was computed.

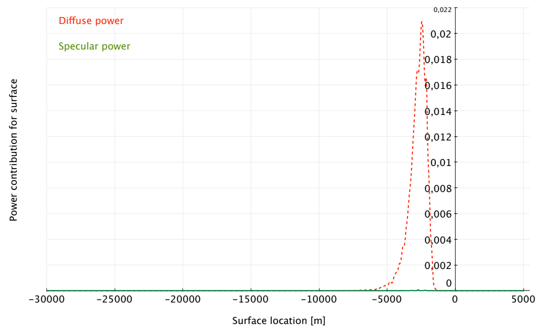
All simulations are summarized in the graphical representations in Figure 5 and 6. We make the following conclusions from these figures:

- The correlation between antennas increases as the elevation angle decreases.
- Larger wave heights results in less correlation between antennas for all elevations.
- The correlation is more dependent on the elevation angle than the wave height.

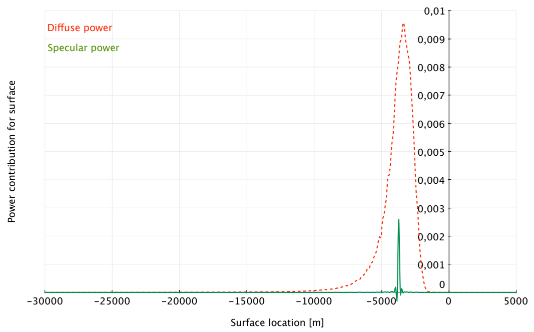
[1] When wave heights are specified without the explicit use of the term rms, it is assumed that the wave height corresponds to four standard deviations. This means that there is a 95% likelihood of any wave to be below the wave height when measured from trough to crest.



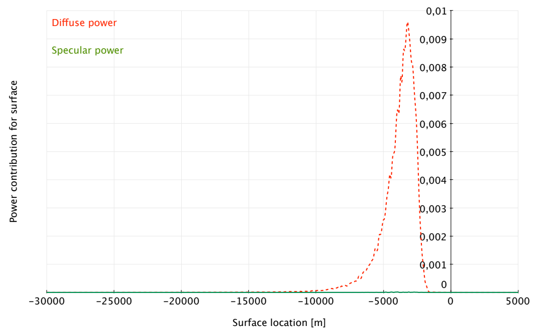
(a) Elevation 5 degrees, wave height 0.5 m



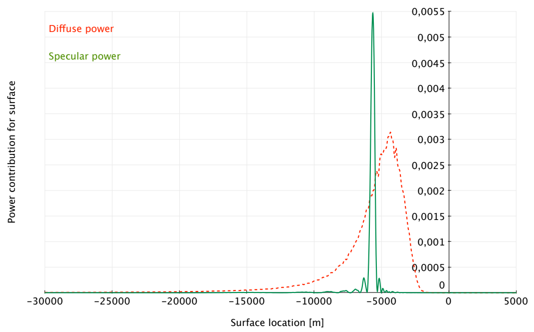
(b) Elevation 5 degrees, wave height 0.5 m



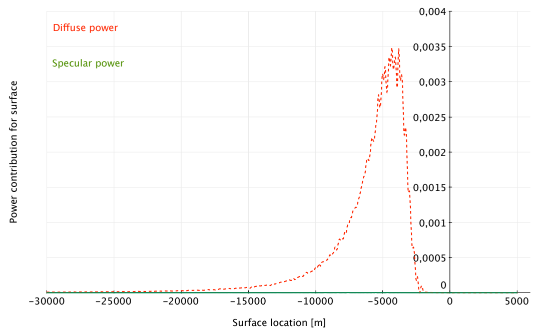
(c) Elevation 5 degrees, wave height 0.5 m



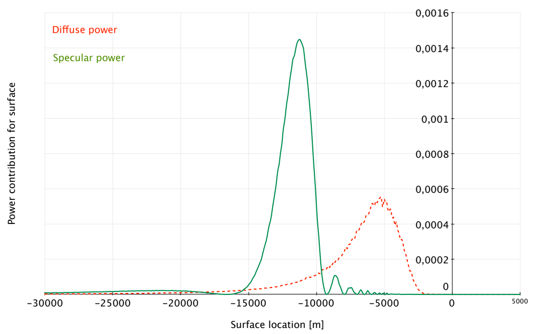
(d) Elevation 5 degrees, wave height 0.5 m



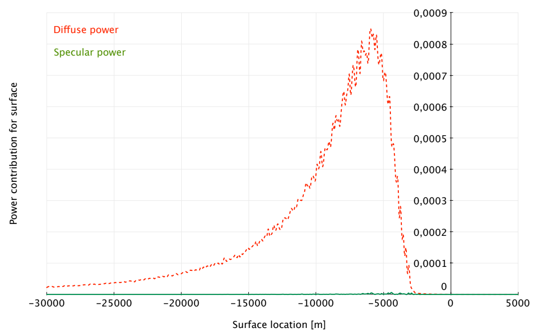
(e) Elevation 5 degrees, wave height 0.5 m



(f) Elevation 5 degrees, wave height 0.5 m



(g) Elevation 5 degrees, wave height 0.5 m



(h) Elevation 5 degrees, wave height 0.5 m

Figure 4: Specular (solid green) and diffuse (dashed red) power contributions from surface.

Table 1: Simulation parameters for the various scenarios

Physical parameters			Integration range	
Elevation	Waveheight	RMSSlope	Lower bound	Upper bound
5	0.5	0.07	-30000	0
5	5.0	0.07	-30000	0
10	0.5	0.07	-15000	0
10	5.0	0.07	-15000	0
15	0.5	0.07	-10000	0
15	5.0	0.07	-10000	0
20	0.5	0.07	-7500	0
20	5.0	0.07	-7500	0

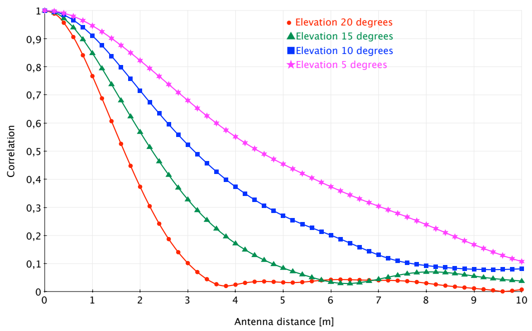


Figure 5: Correlation between antennas as a function of distance. Wave height 0.5 meters.

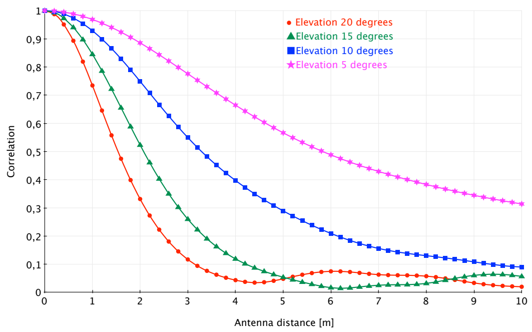


Figure 6: Correlation between antennas as a function of distance. Wave height 5.0 meters.

It may seem counter-intuitive that the correlation increases with the surface area contributing to the reflection. A larger surface implies a richer scattering environment, which should result in less, not more correlation. The explanation for this observation may be found by considering the effective wavelength of the incoming signal at low elevations (see Figure 7). For a wave height of 0.5 meters and a wavelength of 0.2 meters, the effective wavelength will be larger than the wave height when the elevation angle is less that $\arcsin(0.2/0.5) = 23.6$ degrees. For low angles the phase variations will no longer be uniformly random over 0 to 2π, but rather narrowly distributed.

Why the larger wave height is showing more correlation than the small wave height is less clear. Since both scenarios use the same rms slope, the correlation lengths are different and makes them difficult to compare. Using the same rms slope as in the 0.5 meter model will lead to very choppy waves, which in turn leads to blocking at low elevations.

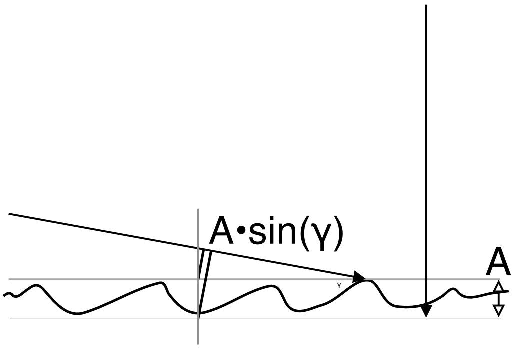


Figure 7: The effective wavelength of an incoming EM wave. Given a surface with a total variation A, the observed variation at an angle γ is $A \sin \gamma$. Equivalently, the effective wave length of the EM wave is $\frac{\lambda}{\sin \gamma}$.

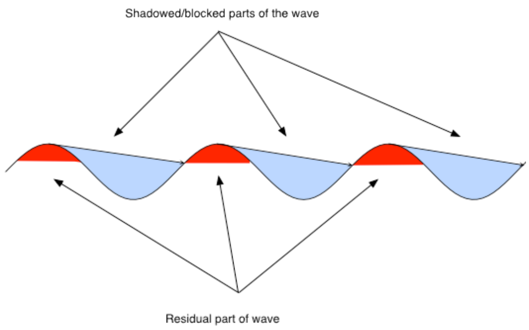


Figure 8: Shadowing/blocking of EM wave by sea surface. The figure shows the blocking of incoming waves from the satellite.

4. CONCLUSIONS

Using a simple one-dimensional representation of a rough sea surface we have investigated the antenna diversity corresponding to the signal reflected from the surface. Depending on the elevation angle and surface roughness, the channel gain correlation is less than 0.2 when the antennas are 3-10 meters apart. Finally, we want to discuss some of the shortcomings of this model and how they may impact the results:

1D vs. 2D: A 2D model will on one hand have a richer scattering environment, but on the other hand, the scattered field will attenuate as r^{-2} as opposed to r^{-1}. As the fastest decorrelation occurs for high elevation angles with smaller effective reflective surface areas, the attenuation may not be very important given that a "sufficiently" large area of the surface contributes. In that respect, the richer scattering environment should imply that the 1D simulations are an upper bound on the decorrelation.

Backscattering and shadowing: These effects have not been considered in this work. The backscattering effect is believed to be of little importance as it mostly affects the overall attenuation of the reflected signal. The shadowing or blocking effect may impact our results in theory, at least for large wave heights and low elevation angles. See Figure 9 where part of the surface is blocked by waves. The figure indicates that the effective surface wave height may be reduced, which in turn could increase correlation.

Polarization: Polarization has only been considered in the sense that a horizontally polarized EM wave is reflected perfectly from the surface. This is according to theory when considering plane waves and surfaces. A vertically polarized wave would see an elevation angle dependent attenuation. For a 1D surface this is sufficiently accurate, but for a 2D surface the full modeling of polarization effects should be undergone.

5. COPYRIGHT

6. REFERENCES

[1] P. Beckmann and A. Spizzichino, *The scattering of electromagnetic waves from rough surfaces*. Norwood, Mass.: Artech House, c1987.

[2] P. Bello, "Aeronautical channel characterization," *Communications, IEEE Transactions on*, vol. 21, no. 5, pp. 548–563, 1973.