Spacecraft VHF Radio Propagation Analysis in Ocean Environments Including Atmospheric Effects

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The Communication Systems Simulation Laboratory (CSSL) at the National Aeronautics and Space Administration (NASA)/Johnson Space Center (JSC) is tasked to perform spacecraft and ground network communication system simulations. The CSSL has developed simulation tools that model spacecraft communication systems and the space/ground environment in which they operate. This paper is to analyze a spacecraft's very high frequency (VHF) radio signal propagation and the impact to performance when landing in an ocean. Very little research work has been done for VHF radio systems in a maritime environment. Rigorous Radio Frequency (RF) modeling/simulation techniques were employed for various environmental effects. The simulation results illustrate the significance of the environmental effects on the VHF radio system performance.

I. Introduction

THE commercial off the shelf (COTS) wireless communication and sensor systems can be readily acquired and rapidly deployed, and the new commercial crew spacecraft could utilize COTS equipment to speed up system development. One of the key questions, however, is how the COTS systems would operate in a harsh Radio Frequency (RF) environment. The performance of wireless networks is greatly dependent on the operational environment - especially in the ocean environment. The standard and classic propagation models may not be suitable for the unique spacecraft ocean landing applications.

The ocean surface can introduce surface wave propagation to the very high frequency (VHF) signal at short range. The reflections off the ocean surface can cause destructive interference to the received signal at long range. Atmospheric impacts on propagation can include gaseous and particulate absorption of energy, or molecular refraction. These can change the signal propagation and cause convergence or divergence of RF energy. The atmosphere may extend the communication range beyond line-of-sight, but in other cases, the atmosphere can also shorten the reachable communication ranges. Thus it is necessary to analyze the radio performance impact due to the spacecraft landing environment, and it is essential to integrate the environmental impacts into mission planning.

Low altitude applications such as wireless radio and sensor systems on a post landing spacecraft (or buoys or small vessels) are analyzed in this paper. The VHF radio systems are deployed in complex operational ocean environments. Low altitude applications - where propagation is very close to the ocean surface and where the signals interact with the seawater and atmosphere - can significantly affect signal propagation. In these scenarios the direct and reflected waves tend to cancel each other at long distances. On the other hand, the surface wave component

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becomes the dominant mode of propagation at short range distances. This surface wave must be taken into account in order to correctly model propagation of radio waves in seawater.

Figure 1. Commercial Crew Spacecraft lands on ocean.

The achievable communication range between a post landing spacecraft and a surface ship (or a low elevation aircraft) may be limited due to the destructive interference from the seawater reflection. The anomalous atmospheric effects such as elevated ducts and surface ducts can further complicate the signal propagations and VHF system performance. The atmosphere can act like a leaky waveguide to the RF signals or the signals can be trapped in certain atmospheric boundary layers. This can significantly reduce the RF signal strength even at short range distances.

Due to the complexity of the ocean environment and of spacecraft modeling, the system design could either fall short or it could be over designed due to the uncertainty in modeling the propagation effects. A good understanding of this environment will allow designers to eliminate unnecessary design margin or improper requirements margin in the system. Due to the complicated propagation mechanism in the ocean environments, rigorous RF modeling techniques are employed in the radio communication system performance assessment. Various sea state and atmosphere conditions are analyzed in this study, and the simulation results illustrate that the environmental conditions can greatly impact COTS wireless system performance.

II. Computational Method

The Geometrical Theory of Diffractions (GTD) was used for sea wave reflection and blockage simulations.[1-4] The ocean wave are very large in terms of the VHF signal wavelengths. As the 1st order approximation, the sea wave is modeled by triangular wedges of dielectric material which resembles the sea water. The height and width of the wave are based on the Pierson-Moskowitz spectrum (see Table 1 for sea state detail). The sea wave is modeled as dielectric material with relative permittivity of 70 and conductivity of 4 mho/m. The sea wave causes blockage to the line of sight between the post landing spacecraft transmitter antenna and the rescue vessel receiver antenna.

The Geometrical Theory of Diffractions was used in the simulations to take into account the wave reflection and blockage effects on the signal propagation. This method is computationally efficient for reflection and diffractions off the electrically large objects.

At high frequencies the scattering fields depend on the electrical and geometrical properties of the scatterer in the immediate neighborhood of the point of reflection and diffraction. In the field computation, the incident, reflected, and diffracted fields are determined by the field incident on the reflection or diffraction point multiplied by a dyadic reflection or diffraction coefficient, a spreading factor, and a phase term. The reflected and diffracted field at a field point r', $E^{r,d}(r')$, in general has the following form:

$$\mathbf{E^{r,d}(r') = E^{i}(r)\, D^{r,d}\, A^{r,d}(s)\, e^{-jks}} . \qquad \mathbf{(1)}$$

where $E^i(r)$ is the field incident on the reflection or diffraction point r, $D^{r,d}$ is a dyadic reflection (D^r) or diffraction (D^d) coefficient, $A^{r,d}(s)$ is a spreading factor for reflection or diffraction, and s is the distance from the reflection or diffraction point r to the field point r'. $D^{r,d}$ and $A^{r,d}$ can be found from the geometry of the structure at reflection or diffraction point r and the properties of the incident wave there. Thus, the total fields ($\boldsymbol{E}^{tot}$) can be obtained by summing the individual contributions of the direct field ($\boldsymbol{E}^{dir}$), reflected field ($\boldsymbol{E}^{ref}$), and diffracted field ($\boldsymbol{E}^{dif}$) along the propagation paths as follows and also as shown in Figure 2:

$$\boldsymbol{E}^{tot} = \boldsymbol{E}^{dir} + \sum_{n=1}^{N} \boldsymbol{E}_n^{ref} + \sum_{m=1}^{M} \boldsymbol{E}_m^{dif} \ . \quad (2)$$

$\boldsymbol{E}^{tot}$ = Total field at the observation point
$\boldsymbol{E}^{dir}$ = Direct fields from antennas
$\boldsymbol{E}^{ref}$ = Reflected fields from flat plates and curved surfaces
$\boldsymbol{E}^{dif}$ = Diffracted fields from flat plates and curved surfaces

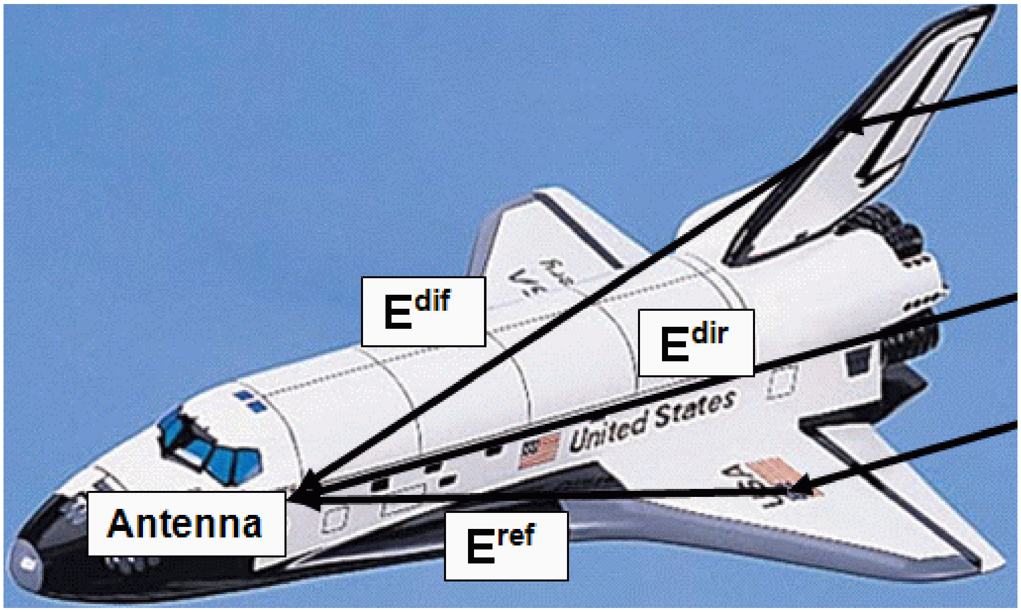

Figure 2. The total fields ($\boldsymbol{E}^{tot}$) including the direct field ($\boldsymbol{E}^{dir}$), reflected field ($\boldsymbol{E}^{ref}$), and diffracted field ($\boldsymbol{E}^{dif}$).

III. Seawater Reflection Effects

The seawater reflections can significantly reduce the signal power for low altitude near surface communications. Figure 3 shows the computed results for a VHF radio with a dipole antenna on a post landing spacecraft in an ocean environment, and the impact on VHF signal propagation is illustrated. The antenna is on a small platform 2 m above the ocean surface. The plots show the antenna gain levels from the zenith (θ=0 degree) to the ocean surface (θ=90 degrees). The pink line is for the dipole antenna in free space. As expected, the maximum gain is at the horizon (θ=90 degrees). The brown line is for the same antenna above a smooth sea surface which is modeled by a perfect conducting plane. The maximum gain is also at the horizon (θ=90 degrees). The blue line is for the antenna above a smooth ocean surface which is modeled by lossy dielectric material with relative permittivity of 70 and conductivity of 4 mho/m. There is a deep null at horizon.

The antenna in free space gives 2 dB gain at horizon (θ=90 degrees). The antenna above a conducting plane gives 8 dB at horizon due to a constructive interference from the perfect plane reflection. The antenna above a realistic lossy ocean surface has a deep null at horizon. The seawater reflection causes more than 20 dB signal loss near horizon. The deep null is due to a destructive interference from the lossy seawater surface reflection. The reflected signal phase is reverse 180 degrees from the direct signal.

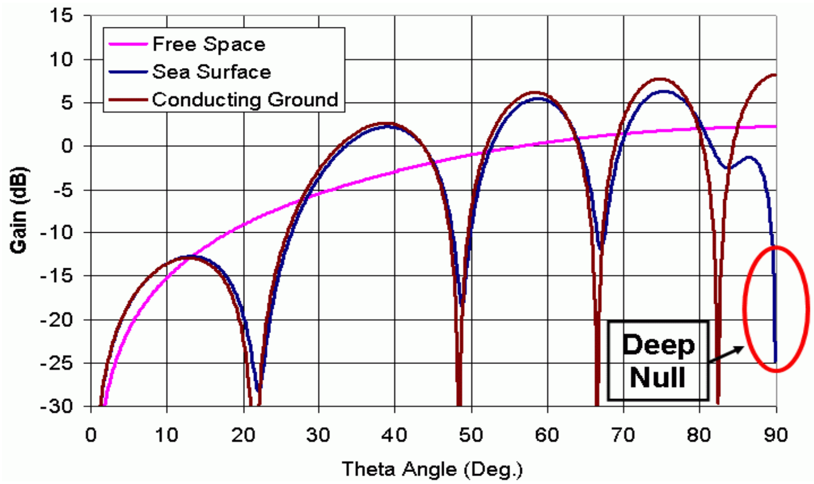

Figure 3. Seawater reflection causes a deep null in signal level near the horizon.

IV. Ocean Wave Blockage Effects

In many post landing environments, the sea wave height can be higher than the crew capsule. At a sea state 5, the average wave height is 4 m. The Line-of-Sight (LOS) between the crew capsule transmitter and the rescue ship receiver may not exist due to the sea wave blockage, as shown in Figure 4. The diffracted field components are not shown in Figures 4 and 5, but they are included in the signal propagation simulations and computed results. The sea wave blockage effects on the signal propagation loss have to be accounted for in computing achievable radio coverage in the ocean environment.

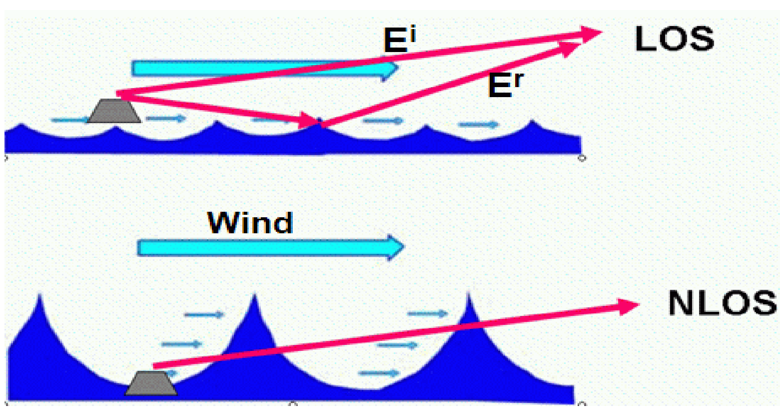

Figure 4. Seawater reflection and blockage could affect signal propagation.

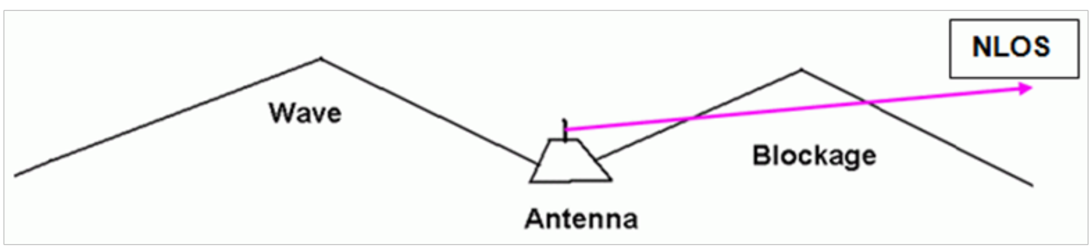

Figure 5. Sea wave blocks the Line-of-Sight (LOS) between crew capsule and rescue ship.

The Navy's code Advanced Refractive Effects Prediction System (AREPS) may not be suitable to simulate the wave blockage with an antenna in the Non-Line-of-Sight (NLOS) environment.[5-7] The AREPS rough surface formulation is based on the Miller-Brown model. The Miller-Brown model modified the smooth surface reflection coefficiency with perturbation theory to account for the surface roughness. This approach causes a modeling limitation. The sea wave height cannot be higher than the transmitting or receiving antenna on small vessels.

As an alternative, the GTD modeling technique is used to compute the sea wave blockage effects on the signal propagation near the horizon. Figure 6 shows the computed results for a VHF radio with a dipole antenna operated in a post landing environment with different sea states. As a comparison, the dashed line is for the antenna in free space. The blue line is for the crew capsule on an ideal smooth sea surface at sea state 0. The pink line is for the rough ocean surface at sea state 5. The sea wave height is 4 m. The antenna on the crew capsule is 2 m above the sea surface. As a result, the communications suffer signal degradation due to sea wave blockage. The GTD computed results indicate that the sea state 5 wave can cause up to 8 dB shadowing/blockage loss (vs. smooth sea surface) for low elevation angles (θ> 85 deg.) near horizon operations.

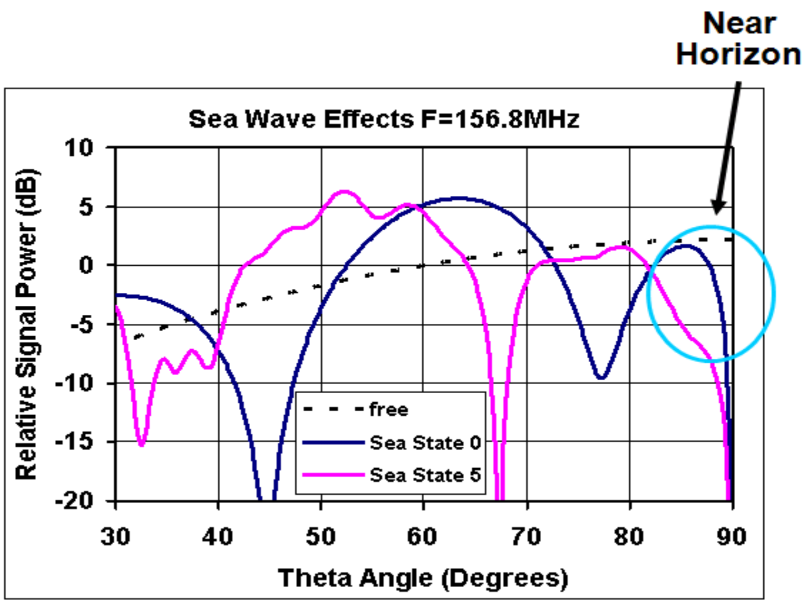

Figure 6. Sea wave blockage causes signal degradation for low elevation near horizon operations.

Table 1 shows the wave height and wave length for various sea states. The wind speed is also shown for the corresponding sea states. Table 2 shows the shadowing/blockage loss (at the worst case vs. smooth sea surface) for various sea states at low elevation angles (θ> 85 deg.) near horizon.

Table 1. The wave height and wave length for various sea states.

Wind Speed (Kts)	Sea State	Wave Height (m)	Average Length of Waves (m)
4	0	0.0	0.6
8	1	0.1	4.9
13	2	0.5	12.0
17	3	1.3	20.0
20	4	2.5	30.2
25	5	4.0	48.0

Table 2. The shadowing/blockage loss for various sea states at low elevation angles (θ> 85 deg.) near horizon.

Sea State	0	1	2	3	4	5
Max. Shadowing Loss (dB)	0	0	-2	-4	-5	-8

V. Surface Wave Effects

The surface wave effects can be significant at short range distances for small platforms on near-surface communications. At VHF frequencies over distances of a few hundred meters, the surface wave components of near-surface radio and sensor systems can be significant. They cannot be ignored in realistic system design and performance evaluations. The GTD ray method is not suitable for the surface wave computations. The full wave modeling based on the Method of Moments (MoM) in conjunction with the Norton-Sommerfeld green's function implementation is the favored technique for surface wave propagation over the ocean surface. This method can accurately account for the near-surface effects and eliminate the need to make approximations on boundary conditions.[8,9]

The signal power levels near the ocean surface were computed and compared for various range distances to demonstrate the significance of the surface wave in the near-surface propagation. Figure 7 shows the computed relative signal level variations for VHF signals near horizon at range distances between 200 and 5,000 m. The surface wave contributions are observed as the signal level increases near the horizon (0 degree) for distances less than 500 m. On the other hand, the signal level decreases sharply near the horizon for range distances greater than 1,000 m. This is an indication that the surface wave component is vanishing when the signal travels along the lossy seawater at distances over 1,000 m.

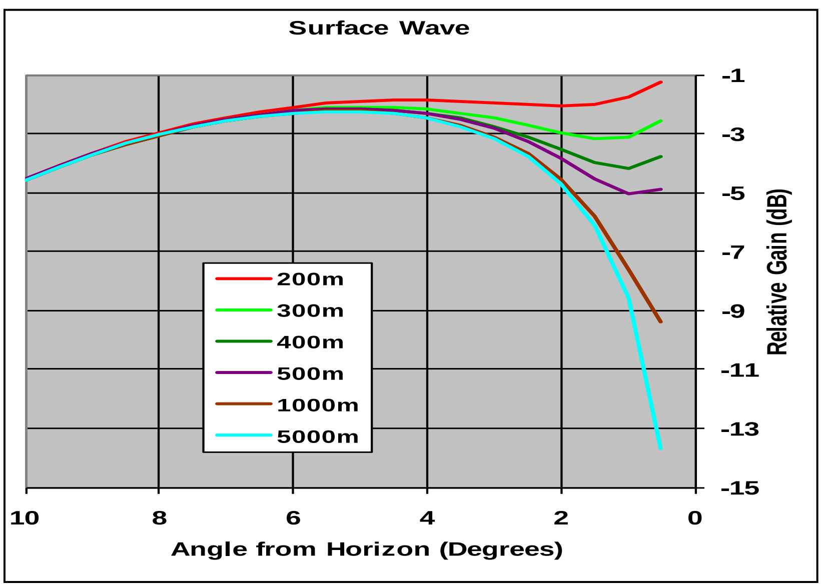

Figure 7. Surface wave contribution for near surface communications at various range distances.

VI. Atmosphere Effects

The atmosphere can change the VHF signal propagation and alter the RF energy field distributions. There are no analytical closed form solutions for the atmosphere effects. Computer simulations can take into account the non-uniform atmosphere modeling and the effects on the signal propagation in the ocean environment.

The computational methods for solving the atmosphere problems can be either the integral equation methods or differential equation methods. Integral equation methods result in large and full matrices in order to determine the field distributions. The modeling of an inhomogeneous troposphere by an integral equation method is quite complex.[10] Thus, the integral equation method is not the choice for long-range communication coverage applications. The differential equation method models the atmospheric effects in a simpler way and results in sparse matrix systems that can be efficiently solved numerically.[11,12] The Navy's code AREPS is a powerful tool to model the atmospheric effects by solving the exact vector differential wave equation with the vector Parabolic Equation (VPE) method.[13,14]

Figure 8 illustrates a typical surface ducting atmospheric effect on VHF signal propagation near an ocean surface. A blackout region is formed in an area between 18 and 28 nautical miles (nmi) from the transmitter. The VHF signals are trapped in certain atmospheric boundary layers. The radio signals will be attenuated significantly and not be able to reach to the target receiver within the blackout region. The communications may be recovered once outside the blackout region. The communication range may be extended far beyond the expected distance due to the waveguide effects introduced by the certain atmosphere layers. As shown in Figure 8, the signal strength at a range of 40 nmi could be much higher than that at a range of 20 nmi. The blackout region is determined by the radio signal frequency and the atmosphere conditions.

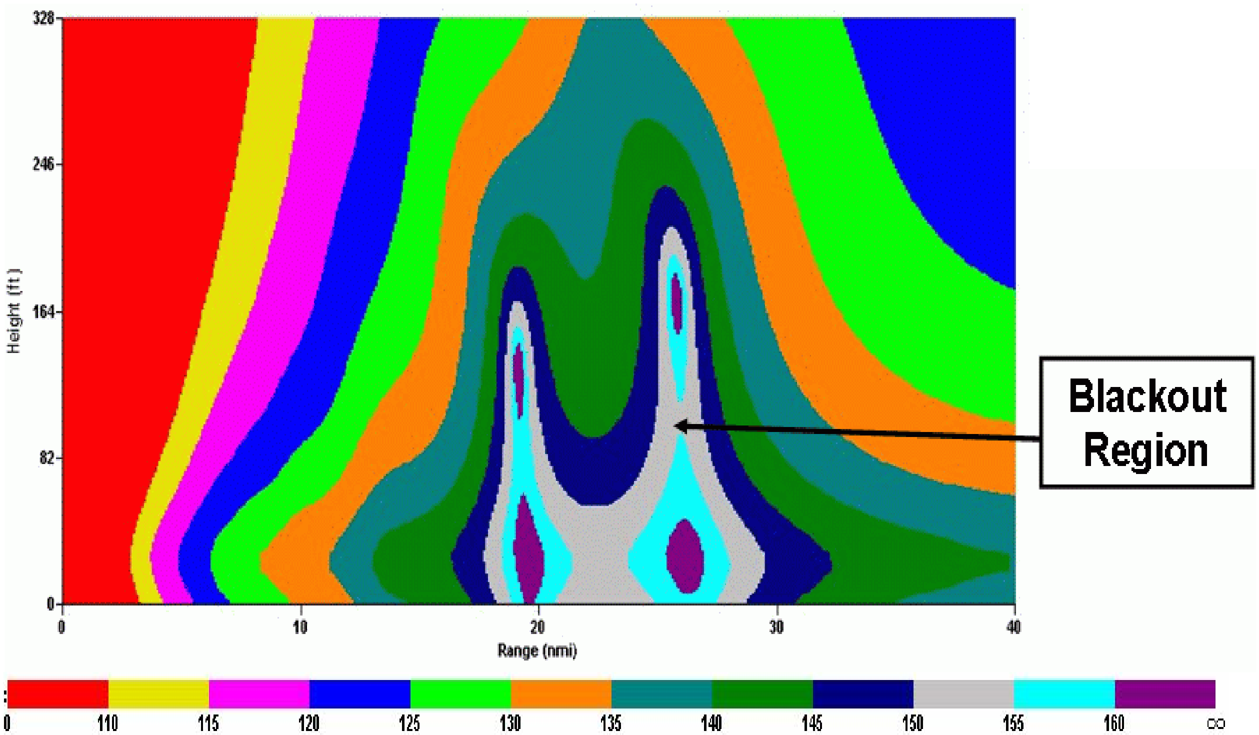

Figure 8. The atmospheric effects can drastically alter the signal propagation at VHF. The color map shows the signal propagation loss versus range and height.

VII. Conclusion

This paper analyzes the environmental effects on the spacecraft VHF radio when operated in a complex post landing ocean environment. The ocean surface reflection and destructive interference on the signal propagation in long range were investigated. The ocean surface cannot be replaced by a conducting surface to simplify the simulation, because the seawater reflection effects on the signal propagations near horizon are different from a conducting ground plane.

As the 1st order approximation, the sea wave blockage effects on the VHF communication links were modeled and analyzed. The propagation loss due to sea wave blockage at various sea state levels was computed by the GTD simulations. The computed results indicate that the sea state 5 wave can cause an 8 dB propagation loss in low elevation communications. The achievable communication range distance will be reduced depending on the sea state levels. The higher the sea state results in the shorter the achievable communication range distances due to the sea wave blockage.

The atmosphere effects on the VHF propagation were modeled and analyzed. The VHF radio communication blackout region may exist at certain distances from the post landing spacecraft. Since the atmosphere ducting is a frequency dependent phenomenon, a radio system with multiple frequency band switching capability may mitigate or reduce the problems.

The communication system performance could be a challenge in post landing operations when the spacecraft lands on a complex ocean environment. All the environmental effects should be analyzed rigorously by appropriate methods and combined to determine the overall propagation degradation of VHF signals in such an environment

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