Underwater Antenna Design Characterization for Tropical Shallow Water Oilfield Applications

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Abstract—**This paper presents a design characteristics of underwater antenna for oilfield applications. The design specification is focused on tropical shallow water type where most of oil platforms at Malaysia are located within this region (depth from seabed is less than 500 feet). Characteristics of sea water at this region were studied and related properties were taken into consideration in designing the desired underwater antenna. Circular Bow-Tie type was selected as the antenna design due to its good performance in underwater environment. The antenna then was subsequently modelled, simulated & optimized in CST software and the result are presented in this paper.**

***Index Terms*—Circular Bow-Tie; Oilfield; Tropical Shallow Water; Underwater Antenna.**

1. INTRODUCTION

Over the years, the demands in underwater communication technology have increased aggressively resulted from the growth in earth exploration where ocean covers 70% of the earth surface [1]. For oil and gas industry in Malaysia, exploration of underwater hydrocarbon has started since the 1960s [2]. Underwater communication technology is essential for oilfield applications especially in underwater wells drilling, subsea production system, operation of Remotely Operated Vehicles (ROV) [3], oil & gas pipeline monitoring and underwater structural maintenance. For countries which are located at tropical region just like Malaysia, most of the hydrocarbon reserves are still active in the shallow water clusters, where the depth from the seabed is less than 500 feets [4]. Since the depth is still within the limit of saturation diving [5], several underwater oilfield applications are still performed by human, where the needs of flexible communications are vital. Nevertheless, even at the deeper location where mostly utilizing robotic equipment, there is still demands from the industry to acquire advanced communication technology.

In the early years, nearly all of the activities involving underwater communication were utilizing conventional underwater cables [6] as the communication medium. However, this method acquired high installation and maintenance cost plus less flexibility due to the high dependency of the cable structure. Underwater wireless technology is the alternative solution for these issues where if properly planned, could bring to significant cost reduction compared to the conventional technology. The flexibility of underwater wireless technology also has attracted numerous industries to explore on its usability though it still can be considered as developing technology.

This paper will focus on EM wave as the communication signal since its characteristics are appropriate with the research title. Maxwell's equation will be used to estimate the propagation speed in seawater [8]. Mathematically, the EM propagation in water medium is merely about 9 times slower than in free space medium. This is a significant advantage for networking protocols and command latency in underwater communication where information has to be switched over different sensors. Furthermore, Doppler Effect is much smaller in EM wave since it is inversely relative with propagation velocity. Underwater wireless communication requires a highly efficient antenna to obtain smooth data transmission. Communication system via EM antenna is essential for oilfield underwater applications due to its higher data transmission rate up to 10 Mbps. Underwater activities at oilfield location such as wells drilling, subsea production and pipeline monitoring via ROV require high data rate for live video streaming and data transfer. For other tasks which are performed by divers i.e. riser inspection and underwater structural maintenance, it requires medium transmission speed for voice communication and equipment data logging. Thus, advanced antenna design plays a significant role in ensuring the efficiency of antenna performance for underwater oilfield applications.

2. LITERATURE REVIEW

The typical underwater wireless communications are established via acoustic wave system [7]. It is extensively used in the deep water environment due to its long distance propagation characteristic. However, for shallow water environment the system might be severely affected by regular human activities and ambient noises (e.g., breaking waves from vessel movement and congested surroundings just like jetty). The system also suffers excessive multipath effects that caused the inter symbol interference, resulted in low transmission data rate (less than 30 kbps). The other drawbacks including high propagation delay (1500 m/s), low frequency (30 – 300 Hz), high bit rate error (10^{-4}) and high transmission power (10 – 50 W). These issues caused various constraints in maintaining the high speed, long range and reliable underwater communication in acoustic system.

The other well-known underwater communication is by using optical wave system [7] where it can reach a very high propagation speed (3.33 x 10□ m/s). Optical wave offers higher data transmission than acoustic wave (1 – 10 Mbps), yet in shallow water environment it is still prone to scattering effect caused by water salinity and ambient light. For that reason, optical system is generally restricted to the extremely short distance, typically within a few meters only and therefore it is still not the best option for long distance communication. Even in some regions, the optical system is not applicable at all where the water visibility is close to zero due to high underwater suspended particles. The system has advantage from the wide bandwidths but require a good alignment between the emitter and receiver which is not recommended due to additional high installation cost.

Electromagnetic (EM) wave [7] has been disregarded from the underwater communication previously due to its high attenuation characteristic on water conductivity. However, the recent researches have proved that the EM wave offers the best solution for underwater communication system. EM wave attenuates rapidly and has higher data rates than acoustic and optical waves (up to 10Mbps), but in a very short distance (few meters). It is primarily depends on the conductivity (σ), permittivity (ε), permeability (μ), density (ρ) and volume charge parameters. These parameters vary with the types of waters so as the wave propagation speed and this attenuation boosts in proportion with the frequency

The development of underwater antenna for oilfield application at the tropical shallow water environment will provide many benefits to the Malaysia's oil and gas industry which operated in the tropical region. In underwater applications, some desirable features such as flexibility (wireless), high bandwidth, high speed and smaller size can be achieved due EM characteristics of fast propagation speed, in the wide usable frequency spectrum and in the small environment noise compared to acoustics, factors that all lead to high possible data rates. For oil and gas industry, it will benefits during wells drilling by the utilization of ROV to locate the exact drilling points through real-time video and on-site data transfer.

As mentioned above, antenna design plays an important role in underwater communication system to ensure for high efficiency of data transmission. However, only a few research studies have focused on the seawater properties and depth. Hence, these two significant elements will be explored further in this project research.

3. RESEARCH METHODOLOGY

Since the existing researches on underwater communication are quite limited, various aspects need to be considered during the execution of this project, which will be described in detailed at this chapter.

3.1 Selection of Suitable Communication Band

Ultra Wideband (UWB) technology is selected for this project. As defined by the Federal Communications Commission (FCC), UWB capable of transmitting and receiving information over a large bandwidth by modulating extremely short duration impulse [9]. It then generates waveform that carries several bandwidth at GHz capacity. There are two conditions of UWB technology:

1. Bandwidth ≥ 500 MHz, or
2. Bandwidth / Central Frequency ≥ 0.2

UWB is working at indoor communication of between 3.1 and 10.6 GHz at limited transmission powers. However for this project, the system will ideally works between 100 MHz to 1 GHz because of the propagation in liquid plus it is not affected by the interference with similar frequency range from in air

3.2 Underwater Signal Propagation

Acoustic wave is commonly used in underwater wireless communications but basically has limitation due to multipath propagation and low speed of sound in underwater environment resulted in poor communication channel and high latency. While the other alternative which is optical system is also a challenge since highly affected by the underwater suspended particles.

EM wave is useful for fast communication between few devices in short distances. Maxwell's equations mentioned about the speed of EM wave in a medium [10]. Propagation of EM wave works over 33:5 106 m/s, becoming more than 23 103 times faster than acoustic wave in sea water which is about 1440 m/s.

3.3 Seawater Properties

Sea water has distinct electrical properties that severely affect the signal propagation, hence the propagation of EM wave in sea water is differs significantly than in the air. Maxwell's equations [11] stated that:

$$\begin{aligned} \nabla \times \mathrm{H} &= J + (\sigma_e + j \bullet \omega \bullet \varepsilon') \bullet \mathrm{E} \\ &= J_i + j \bullet \omega \bullet \varepsilon'(1 - j \bullet \tan \delta_e) \bullet \mathrm{E} \end{aligned} \quad (1)$$

where:
- E = Electric field
- H = Magnetic field
- J_i = Impressed electric current density
- σ_e = Effective conductivity
- $tan\delta_e$ = Effective loss tangent

Relationship between those is given by:

$$\sigma_e = \sigma_s + \omega \bullet \varepsilon'' \quad (2)$$

$$\sigma_e = \sigma_s + \omega \bullet \varepsilon'' \quad (3)$$

where: σ_S = Static conductivity

$\omega \bullet \varepsilon''$ = Conductivity of alternating field

3.3.1. Conductivity

The conductivity, σ of specific medium affects the transmission of an EM wave through that medium. Generally, as the conductivity of medium is increasing, the transmitted signal will face more attenuation. As an example, pure water has a typical value ranges between 0.005 and 0.01 S/m while sea water has a high conductivity averaged value of around 4 S/m which changes with the salinity and physical properties of each sea water type. The conductivity of sea water with reference to temperature and salinity has been measured previously in a laboratory experiment [12]. For salinity range of 20 ppt < S < 40 ppt, the relation is:

$$\sigma = \sigma_0 \bullet S \bullet \frac{37.5 + 5.4 \bullet S + 0.015 \bullet S^2}{1004.8 + 182.3 \bullet S + S^2} \bullet \left(1 + \frac{\frac{6.9 + 3.3 \bullet S - 0.1 \bullet S^2}{84.6 + 69 \bullet S + S^2}}{49.8 - 0.23 \bullet S + 0.2 S^2 + T} \bullet (T - 15)\right) \quad (4)$$

where: S = Parts per thousand
T = Degree centrigrade
σ = Siemens per meter
σ_0 = Conductivity at S=35ppt and is dependence of temperature:

$$\sigma_0 = 2.9 + 8.6 \bullet 10^{-2} \bullet T + 4.7 \bullet 10^{-4} \bullet T^{-2} - 3 \bullet 10^{-6} \bullet T^3 + 4.3 \bullet 10^{-9} \bullet T^4 \quad (5)$$

3.3.2. Relative Permittivity

The relative permittivity, ε_ror also called as dieletric constant is the ability of medium to transit electric field. The relative permittivity of sea water commonly is 81. However, in general it depends on other factors such as sea water temperature, salinity and propagating frequency [13]. Below is the equation to determine the mean value of dielectic constant of sea water:

$$\varepsilon(\omega) = \varepsilon\_0 \bullet \varepsilon\_r(\omega) = \varepsilon' - j \bullet \varepsilon'' = \varepsilon\_0 \bullet (1 + X\_e) = \varepsilon' \bullet (1 - j \bullet \tan \delta\_e) \quad (6)$$

$$\varepsilon\_r(\omega) = (\varepsilon\_\infty + (\varepsilon\_S - \varepsilon\_\infty - \varepsilon\_salt)/(1 + (\omega \bullet \tau)^2) - j \bullet (\sigma/(\omega \bullet \varepsilon\_0) + (\omega \bullet \tau \bullet (\varepsilon\_S - \varepsilon\_\infty - \varepsilon\_salt))/(1 + (\omega \bullet \tau)^2) \quad (7)$$

The above equations are applicable to calculate some of the sea water properties [14]. However for this project, data from World Ocean Database (WOD) will be used for better precision and shorten the project phase.

4. PARAMETRIC STUDY

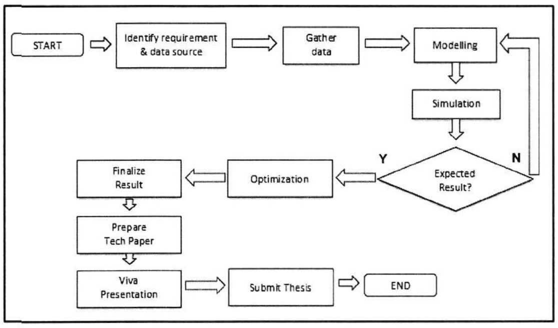

Figure 1: Project Process Flow

The early stage of the project started with data gathering activity. The project scope require knowledge & data related to *ocean & sea water properties* i.e. *salinity, conductivity,* temperature, depth and etc. Physical sampling check on sea water properties require a lot of efforts and time consuming. Alternatively, National Oceanic & Atmospheric Administration of the United States of America is also publishing World Ocean Database (WOD) on yearly basis as the open source references [15]. The main data with regards to sea water properties were downloaded from the website and subsequently used in this project

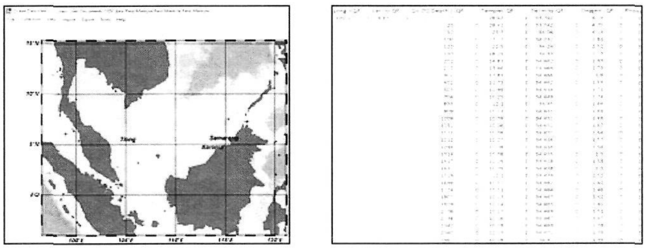

Figure 2: Sample of Downloaded Oceanic Data

Next, the required antenna was modelled according to the available sources and specific requirements to suit with oilfield applications i.e. wide band, small in size (few millimeters) and high data transfer rate. UWB antenna type was selected for this project because of its features that suitable with the project requirement. Furthermore, few recent researches had successfully experimented this type of antenna for underwater communication.

Initially three types of UWB antennas (half wave dipole, circular loop & bow-tie) were modelled & simulated in CST software to examine their operability in water environment. From this initial testing, two out of the three antenna showed an encouraging result (circular loop and bow-tie) when simulated in water environment in CST. The next stage was involving re-designing of the antenna. Bow-tie type antenna was modelled in circular form to imitate circular loop design. The simulation in air medium showed the characteristic of narrow band but surprisingly the characteristics was changed to wide band when tested in water medium (bandwidth over 1GHz). Based on this promising result, this antenna design was selected for further enhancement in this project.

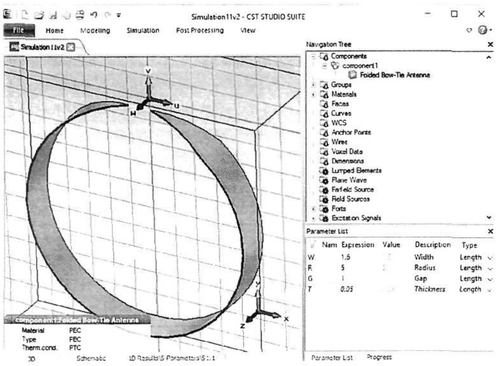

Figure 3: Folded Bow-Tie Antenna Design

5. SIMULATION RESULT

Since the Folded Bow-Tie design had shown good performance when simulated in underwater environment, the subsequent process (modelling, simulation & optimization) will also utilizing the same design. The simulation will be performed for each category as below representing different sea water properties at different depth.

Category	Water Depth (ft)	Temperature (°C)	Salinity (PSU)	Conductivity (S/m)	Permittivity (ε_r)	Density (kg/m³)
A	< 100	26.84	33.98	4.79	78	1029.32
B	100-300	20.55	34.40	3.81	80	1029.32
C	300-500	15.38	34.54	3.35	82	1029.32

Table 1: Tropical Shallow Water Properties by Group Category

5.1. Simulation by Category

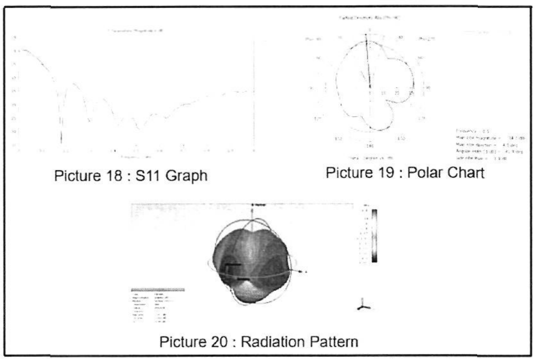

Figure 4: Category A

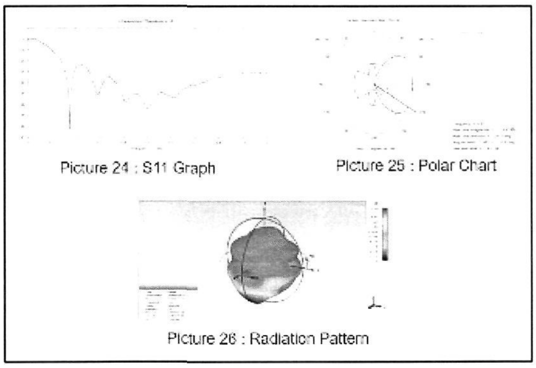

Figure 5: Category B

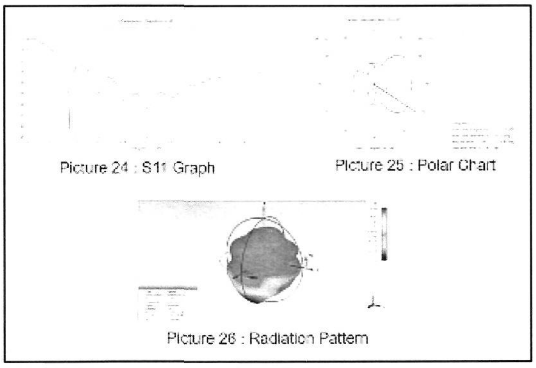

Figure 6: Category C

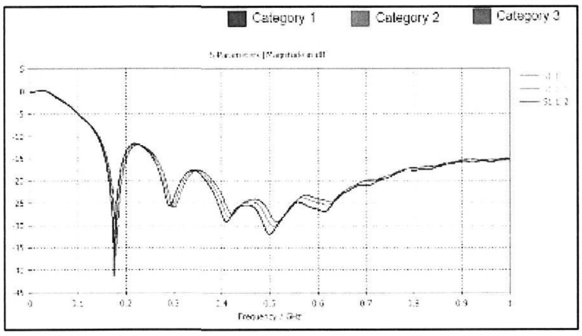

Figure 7: S11 Graph by All Categories

Based on antenna simulation according to category, the data showed quite the similar result. This is probably resulted from the small variances of sea water properties at each category. This is basically a good indicator that showing that the design antenna are applicable at each category. The process was further executed until optimization stage where the result shown slightly antenna dimensional change s for respectively category.

6. OPTIMIZATION

The designed antenna was further optimized in dimension to explore the opportunity for performance improvement. The optimization was conducted based on selection of antenna properties as below:

i. Radius
ii. Width
iii. Thickness

The challenges for this optimization stage was the processing time consumed by CST software to produce the output as a result of heavy mesh load from antenna simulation in water environment. In view of the issue, the optimization stage was conducted with minimum number of data sequence running in sweep mode (3 data only: original data, 1 lower data & 1 higher data). We assumed that the antenna performance can be improved further based on the result from optimization stage (by reducing or increasing the antenna dimension).

6.1. Optimization by Category

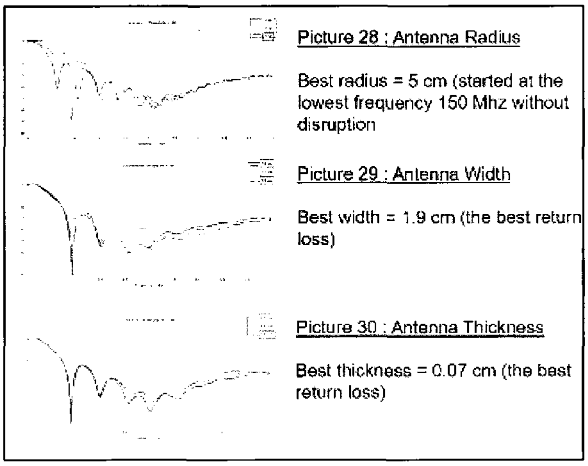

Figure 8: Optimization for Category A

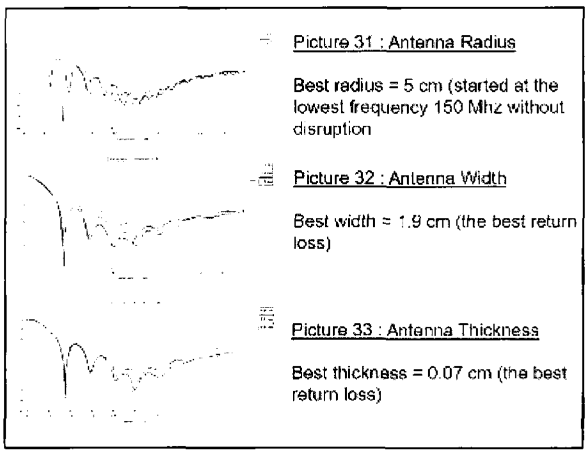

Figure 9: Optimization for Category B

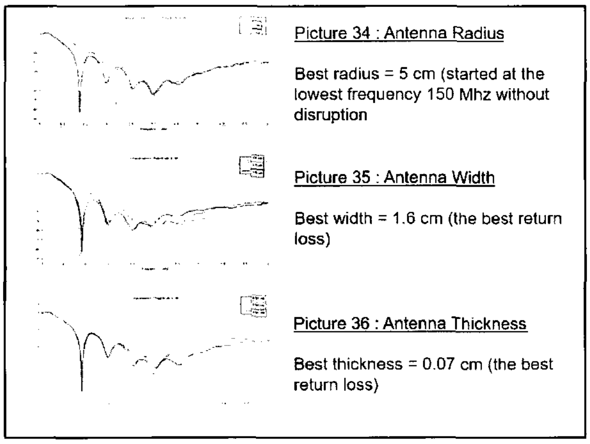

Figure 10: Optimization for Category

7. RESULT AND DISCUSSION

Based on the simulation result and optimization done, it shows that the antenna designed which was used in this project is suitable for underwater usage at different water depth & activities according to project requirement i.e. wide band, small in size (few millimeters) and high data transfer rate. However, to operationalize the antenna at this stage for real application is not suitable since a prototype not be tested first to proven the theoretical result. Another issue is due to the non-water proof feature for this antenna. Electrical & electronics parts are part of the antenna composition. To operationalize antenna in real water environment, this part shall be sealed or covered to prevent from being short-circuited. Furthermore, water may deteriorate the antenna structure if exposed too long especially sea water which contain various particles & high salinity

As a quick solution for this issue, we propose for the whole antenna structure to be isolated by waterproof casing. We re-simulated the antenna with considering this issue by isolating the whole antenna inside a sphere or an air ball. Theoretically, we assume that the casing is in ideal state (not influenced by external factor or affecting the antenna performance significantly). In CST simulation the casing will be assigned to contain common air to demonstrate isolation. The behaviour of the antenna is presented in the next part.

7.1. Proposed Recommendation: Antenna Isolation

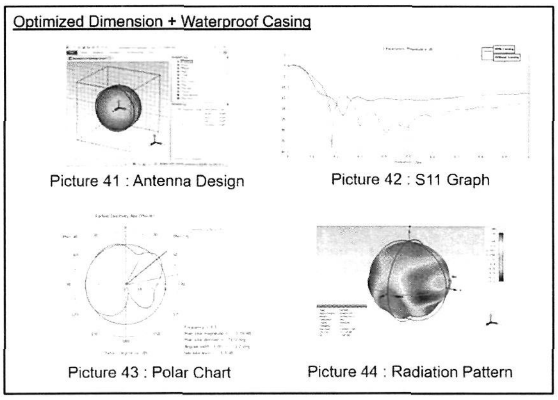

Figure 10: Proposal for Category A

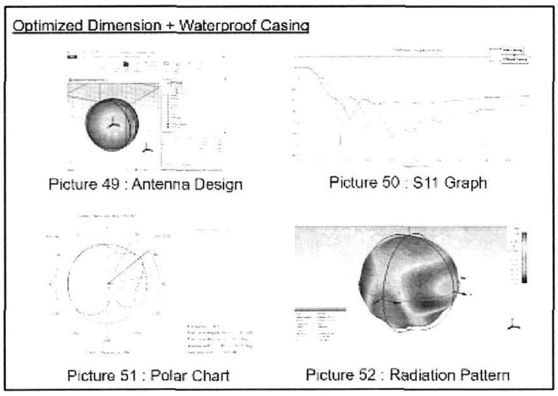

Figure 11: Proposal for Category B

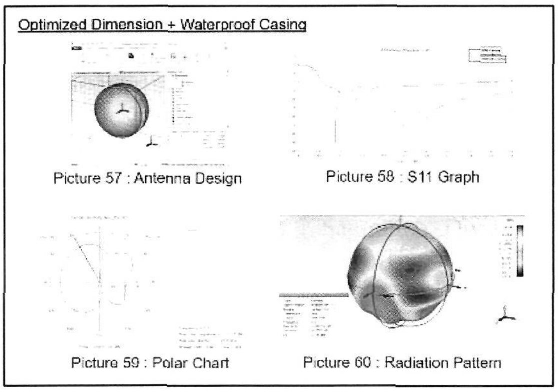

Figure 12: Proposal for Category C

8. CONCLUSION

Underwater antenna was designed, simulated and theoretically proven for oilfield underwater applications after examining tropical shallow sea water properties during antenna design & simulation stage. Below is the characteristics table for underwater antenna design for oilfield applications. The project meeting all of its objectives & expected outcomes.

Category	Water Depth (ft)	Oilfield Applications	Communication Type	Antenna Dimension (mm)	Operating Frequency
A	< 100	Structural welding	Voice Communication	Radius = 5 Width = 1.9 Thick = 0.07	
B	100-300	Pipeline maintenance	Voice Communication	Radius = 5 Width = 1.9 Thick = 0.07	150 Mhz – approx. 1 GHz
C	300-500	ROV (seabed analysis, subsea production, etc)	Video Streaming	Radius = 5 Width = 1.6 Thick = 0.07	

Figure 13: Underwater Antenna Design Characteristics for Tropical Shallow Water Oilfield Applications

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