Obscured Ship Signals Over Ninety Kilometers at Arecibo

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Abstract

This paper will discuss the coherent interference which has been determined to be ships on the ocean, and review the ship signal phenomenon that has been detected numerous times with the incoherent scatter radar at the Arecibo Observatory in Puerto Rico. V-shaped coherent structures have been observed when the magnitude of raw power bounced back to the receiver is plotted against time and altitude. These structures have been determined to be ships due to the slow velocity of the objects, the high amount of power reflected back to the receiver and the relatively short range. While the radar apparatus at Arecibo is the world's most sensitive and is able to monitor electron density changes in the different regions of the ionosphere it is unable to detect large cruise ships beyond a distance of 90 kilometers. The main reason for this is that the radar at Arecibo was never intended to monitor ships as the dish and antenna are aimed directly towards the sky. However, we will investigate the reason why ship signals observed at Arecibo are not able to be detected beyond a range of 90 kilometers and demonstrate that the causation for the inability of the radar to detect ships beyond this range is due to the line of sight of the radar at this specific location and the curvature of the Earth.

Introduction

The world's largest radar dish, located at the Arecibo Observatory, was built on a sinkhole in the middle of Puerto Rico through the vision of Dr. Bill Gordon. Gordon began designing the large radar dish in the late 1950s, construction began in1960 with funding from ARPA (Advanced Research Projects Agency) and the facility was completed in 1963 *Mathews* [2013]. Puerto Rico was a strategic location because of its proximity to the equator which was thought to be advantageous for observing phenomenon in space. Back when the facility was being built there were some concerns about the radar being too close to large populated areas which would cause interference when research was being conducted. Therefore the site of the radar dish is very remote and is surrounded by small mountains at the interior of the island. The radio telescope at Arecibo is quite an impressive feat of engineering. It is reported to be the largest and also the most sensitive in the world. The radar dish itself is a fixed entity with an antenna apparatus that has a restricted range of motion of 20 degrees from zenith. While this may be somewhat of a disadvantage for some forms of radar monitoring, there are several applications for which the Arecibo Observatory is advantageous.

One of the core concepts behind the construction of the Arecibo Observatory was incoherent scatter radar theory which was proposed by Dr. Gordon in 1958. Incoherent scatter radar (ISR) has been used at Arecibo to conduct various experiments which led to the first radar detection of Venus and the first incoherent scatter measurements of the ionosphere in 1964.

Arecibo uses this technology to monitor, observe, and conduct experiments in the different regions of the ionosphere. Within the overall structure of the ionosphere there are several different regions where the density of electrons has been measured to be different. The change in electron density can be explained by the different levels of solar radiation that penetrate the earth's atmosphere. The upper most layer gets the greatest exposure to this radiation, but due to its distance from the surface of the earth there is not a significant electron density and consequently there is not a great amount of excited electrons in this region. As we move down through the ionosphere we find a greater density of electrons, while there is less intense radiation at these levels, the density of excited electrons increases as the quantity of electrons increases.

The discovery of the different layers of the ionosphere, and the subsequent changes in electron density, was made at Arecibo observatory. Being permanently aimed towards the sky gives this observatory a few advantages over a dish with a boundless range of motion, and allows for uncommon experiments that require a more precise and sensitive radar to pick up on minor variations in the ionosphere. However, there is an interesting side effect when these signals are sent from the transmitter. The signal was meant to go straight up into the atmosphere and into space. While the majority of the signal is directed upward some of the radar waves escape or "leak" and are not directed upwards but instead travel along a horizontal path.

Radio waves can travel extremely far distances at the speed of light (c) once the signal has been transmitted. Radar receives signals when the transmitted radio waves collide with an object that are then sent back to the receiver which allows us to detect objects. When the horizontal signals are sent from Arecibo they sometimes detect bodies which have been determined to be ships out on the ocean. The curious aspect of this phenomenon is that even though the radio waves transmitted from Arecibo can travel distances greater than several hundred kilometers large ships cannot be detected from a range greater than 90 kilometers out. Radar signals have no problem travelling this distance and many observations are made on bodies which are infinitesimally smaller than a large ship sailing upon the ocean. So why is it that the ship signal cannot be detected at a range greater than 90 kilometers with the giant radar at Arecibo?

We offer the hypothesis that this phenomenon is occurring due to the curvature of the Earth, which is inhibiting the radar signal at Arecibo Observatory from being able to detect a ship. The curvature of the Earth actually disrupts the line of sight for the radar. We will show mathematically that the reason the ship signal disappears after a range of 90 kilometers is because this is the maximum range for line of sight from the elevation of the transmitter in Arecibo to a tangential point on the surface of the Earth. A simple model was constructed to show what kind of dimensions would be required for the curvature of the Earth to become a factor. To prove that this is legitimate reason we will research the elevation of the antennae, observations of ship signals collected at Arecibo, and anything else that can be used to construct an accurate model. The observations we have made will then be compared and contrasted with a mathematical model we have constructed to try and prove the validity of our hypothesis.

Ship signals detected at Arecibo Observatory

First, how can we determine that there is a ship being detected at Arecibo Observatory? After analyzing data gathered with ISR several V-shaped bodies at low altitudes are visible when the data is plotted showing the received power signatures. This phenomenon has been observed several times now and it has repeatedly been determined that these bodies are ships on the ocean. These traces of ships return a very high amount of power to the receiver and the velocity is very slow due to their size, especially when compared to a small meteor. The greater the cross sectional area of the radar target and greater the electron density of the target, the more visible the object becomes when the data is analyzed. The radar at Arecibo is able to detect changes in electron density at a range of hundreds of kilometers so it is of no surprise that it can detect larger bodies.

Ship signals can be seen in the power return graphs of ISR and they are denoted by a distinct V shaped pattern, which was first discovered and documented by *Zhou and Mathews* [1994]. Signals were never detected over ninety kilometers with that signature, but that was not logical because there are definitely ships beyond ninety kilometers that should be detected. The disappearance of any ship signal became an odd phenomenon that remained consistent throughout many observations using the radar at Arecibo. Due to the fact that power profiles in the D-region of the ionosphere are so sensitive to any form of interference it is vital that interference signals are identified and removed, this was stressed by *Mathews* [1986]. Consequently, it is important to understand how and why these ship signals disappear over ninety kilometers so that we can justify eliminating them from our data and not treating them as some other occurrence that has yet to be considered.

Data acquisition

Through the supervision of Dr. Sulzer of the NAIC (National Astronomy and Ionosphere Center) and Dr. Zhou of the Miami University we were able to use the ISR at the Arecibo Observatory to conduct our observations of physical parameter of the ionosphere such as electron density, composition, and temperature. During our workshop at Arecibo each radar pulse transmitted was encoded with a 13 baud barker code. The simplest way to analyze Barker-coded ISR measurements is to decode the data in the amplitude domain. This is possible through use of a matched filter *Damtie*, *Lehtinen and Nygren* [2002]. We specifically scanned through all the data that was acquired on January 2nd through January 5th 2015 in hopes of finding and isolating ship signals. We implemented a simple algorithm to find the Barker code from the massive amount of data we collected, similar to the algorithm used by *Pateti, Kota, and Rao* [2011]. Our algorithm searched through the data for an RF length of 52 associated with the Barker code used. We were also able to document specific parameters such as altitude, time, and number of transmitter pulses.

A Barker code is a string of digits $a_i = \pm 1$ of length $l \geq 2$ such that

$$\left| \sum_{i=1}^{l-k} a_i \, a_{i+k} \right| \leq 1$$

for all $1 \leq k \leq l$. Barker codes are used for pulse compression of radar signals. There are Barker codes of lengths 2, 3, 4, 5, 7, 11, and 13 (wolfram.com). The Barker code is a short, finite number sequence used for radar signal applications and is very popular due to its efficiency.

The coherent structures which we have determined to be ships on the ocean are typically considered to be an interference when using ISR to conduct experiments, such as monitoring electron density, and are therefore usually filtered out using such procedures as the one reported by *Zhou and Mathews* [1994]. However, once the data was filtered with the program mentioned above we created an algorithm to generate the image shown in figure 1 which is showing the raw power returned for the entirety of the time period that data was collected. The return power was then plotted against the time and altitude for the entire observed time period of two and one half days that we collected data. Once the data is presented in this simple format we can visually confirm the presence of ship signals by the V-shaped bodies present at low altitude (distance).

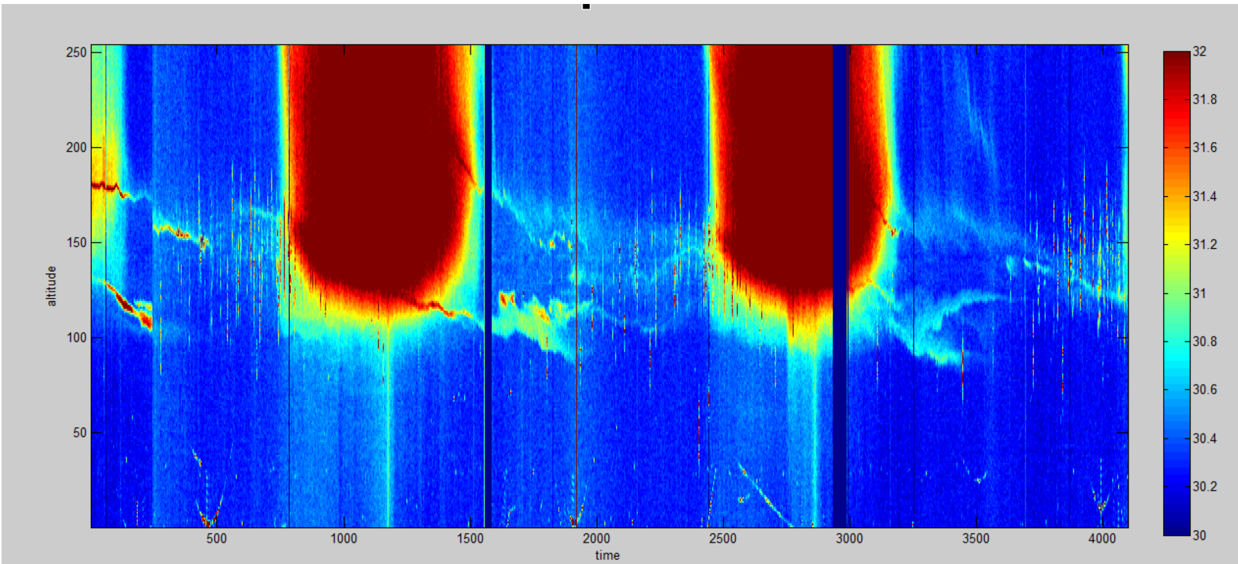

Figure 1: Returned raw power for the 2 ½ day period that data was collected at Arecibo Observatory in January 2015. The V-shaped coherent structures observed in the image have been determined to be ships that are bouncing the radio waves sent from the radio telescope back to Arecibo. We can also observe that they are all respectively close when we compare the distance to all of the other readings.

Research findings

We were fortunate to find that several ships were observed over the time period which we investigated. Even though there were not as many ship signals as we had hoped, there were enough to compare and contrast our observations with the hypothesis that no ships can be observed beyond a distance of 90 kilometers. The identification of ship signals in the radar data allowed us to observe the range for the ship signals. In fact, we did find that none of the ship signals could be found beyond the distance of 90 kilometers much like the observations of *Zhou and Mathews* [1994]. This was the first step for our team towards offering a simple explanation for why these ship signals can only be found in a small portion of the data collect at Arecibo.

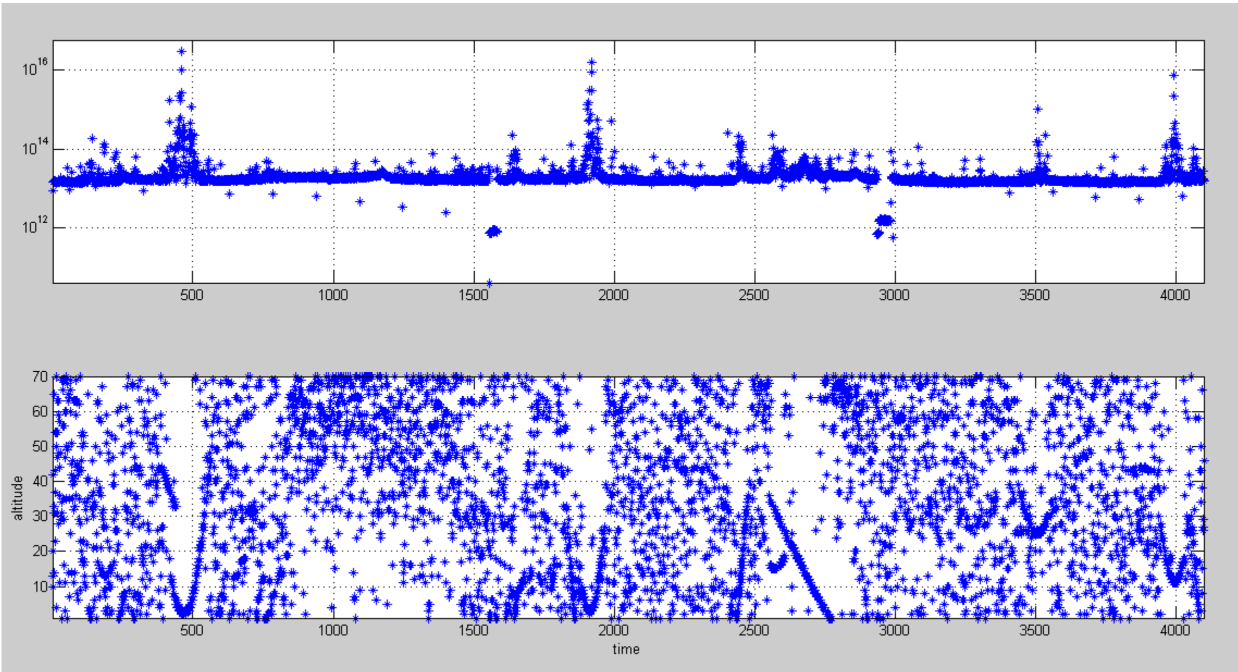

Figure 2: Log scale of power signature returned and returned power plotted against time and altitude. In the scatter we can see several V-shaped structures which we have determined to be ships on the ocean. When the graph of the returned power is observed along with the corresponding scatter plot we see that the power is being returned from a large reflective surface at the same locations of the V-shaped structure in the scatter.

As shown in figure 2 we can see there is a correlation between the magnitude of power returned and the altitude, or distance, of the body observed. In the case of ships being detected inadvertently at Arecibo it is observed that the power decrease is extremely sharp as the ship gets further away from the receiver. This observation agrees with the fundamentals of radar detection in which the target is able to be detected when there is a cross sectional area of the target that can bounce the radio waves back to the receiver, commonly known as the radar cross section. When a target gets closer it is easier for the radar to detect, given that the orientation and material of the target is conducive to returning radio wave. Coincidentally the further the target the harder it is to detect until the radar cross section of the target becomes so small that the target effectively disappears from the radar altogether.

Cruise ships on the ocean could be modeled as a basic rectangular shape in space that the radar shoots radio waves at. Depending on the orientation of the ship the way the radio waves bounce back to the receiver could be very complex. For a simple case an equation that allows the radar cross section to be determined if the radio waves are bouncing off a rectangular plate, such as the side of a cruise ship on the ocean, $\sigma = \frac{4\pi b^2 h^2}{\lambda^2}$ where σ = radar cross section in square meters, b = base in meters, h = height in meters and λ = wavelength in meters (radartutorial.eu).

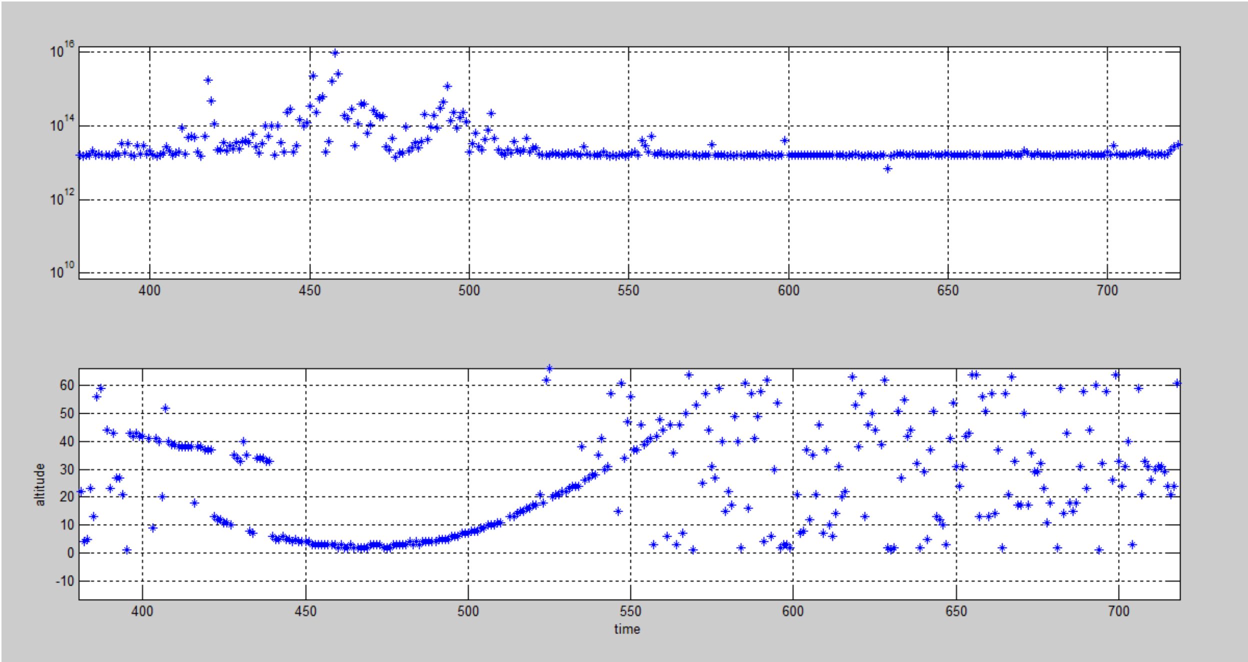

Figure 3: Close view of how the return power declines as the ship distance increases. This is a closer view for a portion of the image shown in figure 2.

As we zoom in on the plot of the data measured by the radar, shown in figure 3, we can observe the diminishing magnitude of power as the range of the ship increases. This we can plainly interpret as the ship moving to such a distance away from the antenna that the radar cross section of the target can no longer be seen. This observation supports our claim that as the ship signal is lost due to the reason that the ship is no longer in the line of sight of the antenna. This simple confirmation gives us an explanation for the ship signal interference observed several times. We are able to detect the ships when they are close due to the radar cross section that is enormously greater than the ionosphere that is being monitored. As the ship disappears from the line of sight from the radar, the radar cross section disappears and does not return any power. All of this can be verified by the data plot in figure 2 and again on figure 3.

Radar, curvature of the earth, and line of sight

One of the fundamental properties of a target that can be measured by a radar system is the distance of the target from the antenna, also known as range. The radar transmits signal pulses and the time between sending the pulse and receiving the echo of the pulse can be used to determine the range of the target. Radio waves travel at the speed of light ($c = 300{,}000 \frac{km}{sec} = 186{,}000 \frac{miles}{sec}$). The radar range equation is used to determine the range of the target from the antenna and we used the measured time that it takes the pulse to leave the transmitter and also the time it takes for the pulse to bounce back to the receiver, therefore $R = \frac{c * time}{2}$ (haystack.mit.edu).

However, radar does pose certain limitations in its ability to detect targets. For normal radar operating frequencies the radio waves travel in a straight line. Therefore the line of sight from the radar antenna will have an influence on the ability of the radar to detect a target or, in this case, explain why the radar cannot detect a target at a certain range. Depending on the elevation of the transmitter the radar may not be able to detect a target due to the radio waves traveling tangent to the Earth.   This phenomenon can be illustrated by figure 4 below.

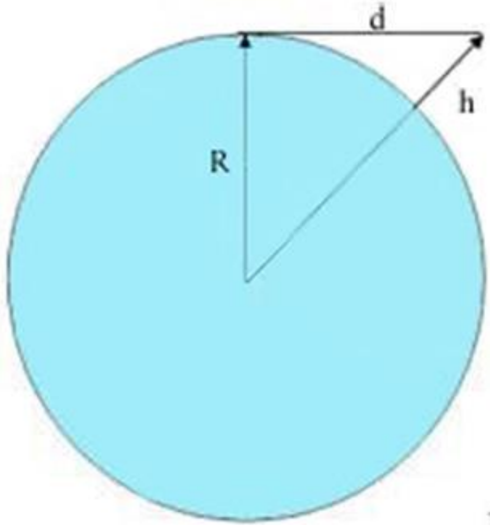

Figure 4: Line of sight from the observatory to a target **d** distance away from the antenna (Earthbulge.jpg)

Our simple mathematical model is basically calculating a right triangle with the parameters of the location to find the maximum distance for the line of sight at Arecibo. We will show that the line of sight from the transmitter at Arecibo Observatory has an approximate horizontal range of 90 kilometers. If the Earth is assumed to be spherical with minimal irregularities that has the radius **R**, we can calculate the line of sight distance **d** for any transmitter with a given height **h** above the Earth's surface. Performing the simple calculation we are able to figure what the line of sight for the transmitter at Arecibo should be.

The mean radius of Earth is 3,959 miles (6,371 kilometers). However, Earth is not quite a sphere and so there will be some considerable deviations. The planet's rotation causes it to bulge at the equator. Earth's equatorial diameter is 7,926 miles (12,756 kilometers), but from pole to pole, the diameter is 7,900 miles (12,720 kilometers) a difference of only 40 miles (64 kilometers). Due to the close nature of the Arecibo Observatory to this bulge area located at the equator we have approximated the radius at this point to be 3,963 miles (6,378 kilometers). The 6378 kilometers is the value that we shall use when we calculate the maximum distance from the transmitters elevation in Puerto Rico to a tangential point on the Earth's surface.

Conclusion

Our group was able to confirm that multiple ships were detected during our radar observations. After analyzing the data we determined the reason ship signals go undetected at a range greater than 90 kilometers at Arecibo while using incoherent scatter radar. We concluded that the curve in the power profile is produced as the ships travel along the gradual curvature of the earth and therefore the ships become unseen as they move out of Arecibo's line of sight. Radar detection depends on radar cross section of the target, or the area of the target and its ability to reflect radio waves back to the antenna.

The radar at Arecibo is able to inadvertently detect ships on the ocean up to a maximum range of ninety kilometers away. We were able to observe the effective disappearance of the radar cross section for several ships. The line of sight for radar detection is disrupted as a ship travels along the curvature of the Earth and then disappears from the radar. At Arecibo the line of sight for the radar antenna is simply calculated by basic trigonometry. We take the square of the height of the transmitter plus the square of the radius of the Earth and this magnitude is equal to the square of the line of sight distance from the transmitter to the tangential point on the Earth plus the square of the radius of the Earth. In effect we have $a^2 + b^2 = c^2$, while a is the radius, b is the line of sight distance and c is the transmitter height plus the radius. From here it is trivial but for our calculation we have the radius of the Earth is 6378 kilometers, the height of the transmitter is calculated as the elevation of the site at 497 meters plus 137 meters to the platform which gives (naic.edu).

$$a = 6378km$$
$$b = unkown\ range$$
$$c = 6378km\ + .497km + .137km = 6378.634km$$
$$a^2 + b^2 = c^2$$
$$b^2 = c^2 - a^2$$
$$b = \sqrt{8087.8}km$$
$$b = 89.9km$$

In conclusion we calculate that the line of sight distance from the elevation of the transmitter is equal to 89.9 kilometers. This result confirms our hypothesis for the reason ships are unable to be detected beyond a distance of 90 kilometers. Our explanation is that the ships being detected drop off the radar data after they have travelled too far along the curvature of the Earth and therefore are out of the line of sight at Arecibo. While this was a very simple project, it was especially interesting to our team to get the opportunity to investigate and try to determine the cause of the behavior of the ship signal interference. The research itself is admittedly of little consequence to the future of ISR research as it is common for scientists to employ a correction procedure such as the one discovered by *Zhou and Mathews* [1994]. However, we have explained why the ship signal interference does not occur past a certain range and now we posses a better understanding of what is being discarded when scientists make adjustments to exclude this type of interference.

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