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SKYWAVE:

HOW RADIO COMMUNICATION REQUIRES BREAKING THE SPEED OF LIGHT

BY MICHAEL XIONG

ACROSS THE ATLANTIC

The date is December 12, 1901, a blustering day in St. Johns, Newfoundland, and Guglielmo Marconi is wrangling kites. After his first kite is ripped away by a strong gust, Marconi defiantly releases a second kite into the winds. Trailing behind the kite is a length of copper wire, linked to a receiver to which he listens intensely. But he's not trying to get struck by lightning; he's waiting for a signal.

dit dit dit

Three short clicks are morse code for the letter S, the radio signal that Marconi's collaborators broadcasted from Poldhu, Cornwall. Marconi (using a kite as an antenna) has just received it from over 2000 miles away, marking the first transatlantic radio transmission.[1] But it should not have been possible.

Radio waves are a form of electromagnetic radiation, also called light (Figure 1). Light is a type of wave, an oscillation through space, and the various forms of light are characterized by their wavelength. The light we can see has wavelengths between 400 and 800 nanometers, while radio waves have wavelengths exceeding a millimeter—well outside the visible range. Most of the time, light travels in straight lines. Draw a straight line between St. Johns and Poldhu, and due to the Earth's curvature, you'll find it passes through the Atlantic Ocean, a hundred-mile tall wall of water smothering any hope of successful transmission. If you want to send a signal across this vast distance, you'll need the light to bend.

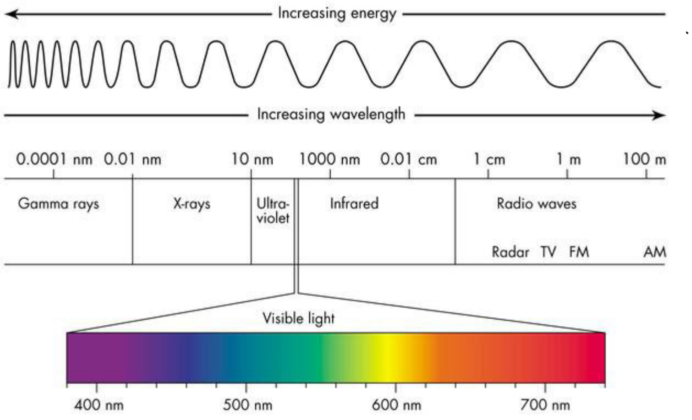

Figure 1: The electromagnetic spectrum of light. *As the wavelength of light increases, the rate of oscillation (frequncy) decreases, as does the energy it contains. Radio waves are the longest wavelength, lowest energy form of light.*

HOW TO BEND LIGHT

Einstein famously discovered that the speed of light through empty space, also known as a vacuum, is a constant and absolute speed limit of our universe: 300 million meters per second, or 670 million miles per hour.[2] This fundamental value is denoted as c. However, the light around us usually isn't traveling in a vacuum. When light passes through a medium such as air, water, or glass, it slows down as it interacts with the particles there. The ratio of the speed of light in a vacuum to the speed of light through a particular medium defines the refractive index of that medium, denoted as n. For example, light travels through water at about ¾ of the speed of light in a vacuum, so it has n = 1.33.[3] This value describes how light will behave when it enters water.

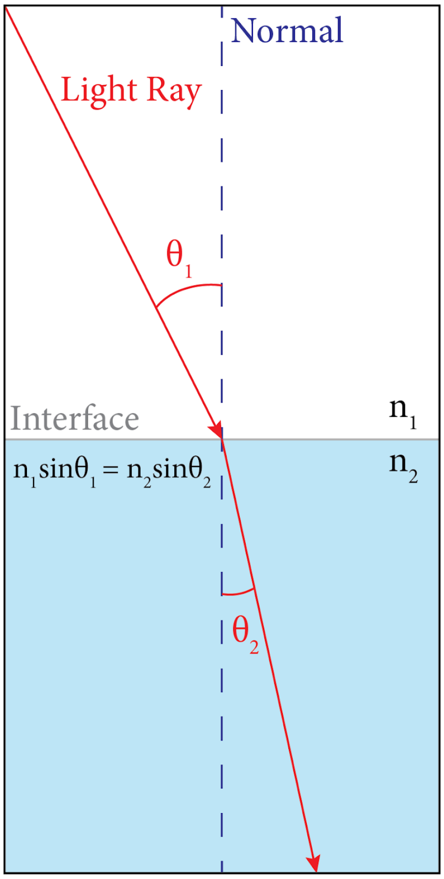

Figure 2: Light crossing an interface is refracted. *When a light ray crosses from a lower refractive index to a higher refractive index, ($n_2 > n_1$), it is bent towards normal. The reverse is true when the light ray passes into a lower refractive index. The angle of refraction can be calculated by the Snell-Descartes Law, as written in the figure.*

When a ray of light crosses the boundary, or interface, between two substances with different refractive indices, it will bend. Look through your drinking glass, and you'll see that the objects on the other side will appear distorted as the light passes from a medium with a lower refractive index—air—to a higher refractive index—water. At this interface, the light ray bends "towards normal," moving closer to a line perpendicular to the surface of the water. The reverse happens as the light exits on the other side.

Can this be used to bend radio signals around the Earth? The only interfaces which the light could encounter in this circumstance are between layers of the atmosphere. Since these interfaces are parallel to the Earth's surface, simply bending the light will still direct it out towards space. In order to send light back towards the Earth's surface, it must be reflected.

HOW TO REFLECT LIGHT

Picture a summer day at the pool. Pinch your nose and dive into the crystal-clear water, then look up once the bubbles disappear. Hopefully you didn't forget your goggles. Directly above you, the water's surface is transparent, but around you it adopts a silvery, mirror-like sheen. You can see the reflections of your fellow swimmers, and even of the lane markers on the floor. What is going on?

When a ray of light, or radio signal, exits a dense medium (like water) and enters a less dense medium (such as air), it is bent towards the water's surface. Tilt the ray too much, and the exiting light travels perfectly along the surface of the water. Increase the angle of incidence past this critical angle, and the light will be reflected back. This is the phenomenon called total internal reflection.

Total internal reflection isn't restricted to pool parties. Light reflecting within gemstones gives them their sparkle, and layers of hot—and, therefore, less dense—air close to the ground reflecting light are responsible for mirages.[4]

Climbing up from the Earth's surface, the atmosphere thins and eventually fades into the near-vacuum of space. In theory, this provides a transition where total internal reflection can occur. Unfortunately, the speed of light through air is very close to the speed of light in a vacuum, and the critical angle for reflection is near 90º. In order to bounce, a radio signal would have to be nearly parallel to the boundary of space. Marconi's signal from Poldhu should have been bound for the stars instead of Canada.

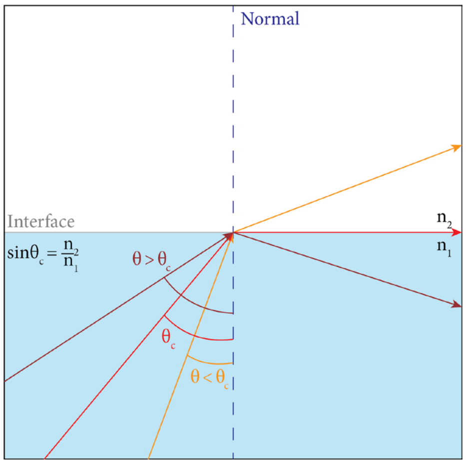

Figure 3: When light exits a dense medium past a certain angle, it is reflected. *Because the light ray is bent away from normal, it is possible to bend more than 90º, in which case the ray is reflected. This total internal reflection occurs past the critical angle, θ_c.*

THE IONOSPHERE

The true physics of Marconi's accomplishment wasn't understood until 1926, when H. K. Lassen—and later, physicists Edward Victor Appleton and Douglas Hartree—calculated the refractive index of light through a magnetized plasma.[5] Under these conditions, the electric field of the plasma interacts with the wave properties of light in a strange way.

Waves are characterized by their oscillation. When they travel through space, the rate of this oscillation can differ from the speed of the wave itself. The speed with which these oscillations move is called the phase speed. The overall speed of a wave is its group speed. In the case of light, its group speed in a vacuum is what is described by the aforementioned constant c. However, the refractive index of light within a medium depends on its phase speed, not its group speed. What Lassen, Appleton, and Hartree discovered was that, within an energized gas—a plasma—the phase speed of

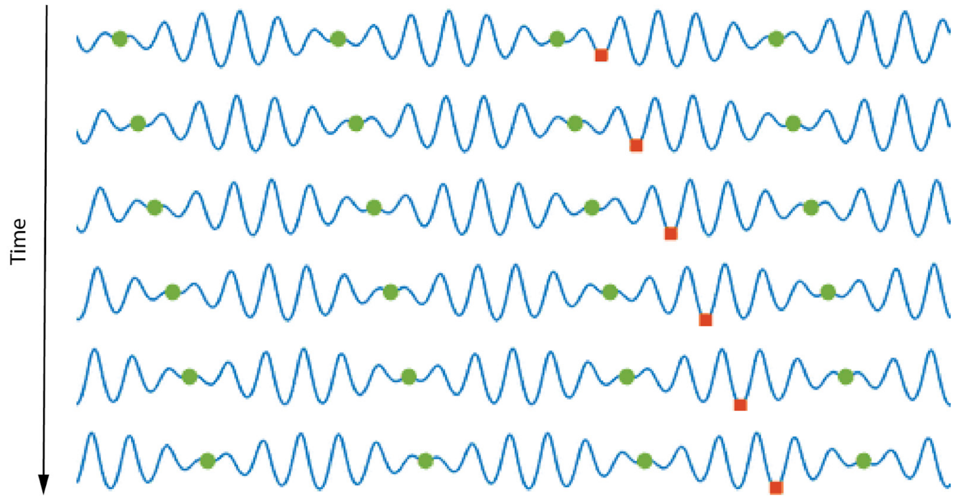

Figure 4: A wave advancing through space with different phase and group velocities. *The red square marks one peak of the wave, which moves more quickly than the green circles, representing the position of the wave as a whole. This means that the phase velocity is greater than the group velocity.*

light can exceed the group speed of light in a vacuum, much like the crests of an ocean wave moving more quickly than the wave itself. This increased phase speed is caused when the free electrons within the plasma are exposed to an electric field from a radio wave and match the wave's oscillation. Therefore, within a plasma, the refractive index of light can be less than one.[6]

At first, it seems as if this should violate the laws of physics, since nothing can break the speed of light. However, the more accurate statement is that no information can travel faster than light. This is because of causality: information traveling faster than light allows an effect to occur before its cause. Because the phase speed of light does not change the speed with which light travels, and therefore how quickly it transmits information, it cannot break the laws of causality.[7] In Marconi's good fortune, the solar wind—a stream of high-energy particles emanating from the sun—creates a plasma when it encounters the Earth's upper atmosphere, forming a layer called the ionosphere. Because the ionosphere has a refractive index less than one, it can facilitate total internal reflection and return a radio wave towards the Earth. This method of radio propagation, in which the signal is bounced off of the ionosphere, is known as skywave or "skip."[8]

SKYWAVE

In the modern age, radio towers and satellites serve as consistent alternatives to skywave communication. However, this ultra long-distance form of broadcast is far from obsolete. The reliance of AM radio on skywave may explain why your favorite station stops broadcasting at 7 p.m.. Since it is created by the stream of high-energy particles emanating from the Sun, the thickness and elevation of the ionosphere is dependent on the time of day. Counterintuitively, skywave works best at night, when this stream of particles dwindles. The elevation of the lowest layer of the ionosphere increases during the night, allowing radio signals to travel further with each bounce. AM radio stations, which can have ranges of hundreds of miles during the day, can see their reach extend into the thousands of miles after sunset. Since there are only a finite number of frequencies available for public broadcasting, an increase in range means multiple channels sharing the same radio frequency may be received at a single location. In order to resolve this issue, many AM radio stations are forced to shut off during nighttime.[9]

Another thrilling application of skywave is its use in so-called Numbers Stations—radio towers used by governments to communicate with spies. Because they can be planted in their home country but heard continents away, spy agencies will use them to broadcast encrypted messages to their agents across the globe. Critically, nobody can track who tunes into a skywave station, and it requires no special equipment that could raise red flags.[10]

Over a decade after his groundbreaking (or skybreaking?) achievement, Marconi entered the public spotlight yet again. On April 14, 1912, a Marconi Wireless Telegraph was used by the sinking Titanic

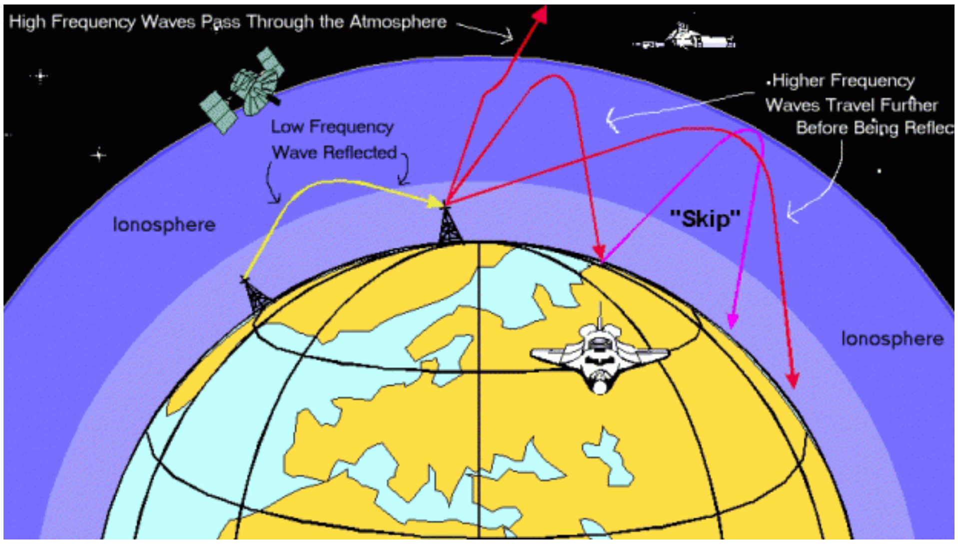

Figure 5: Skywave can be used to broadcast radio signals across vast distances. *Distance increases if the wave travels further before reflection, which can be achieved by increasing the frequency of the radio wave and by broadcasting during nighttime.*

to broadcast a signal into the Atlantic. Thankfully, it did not have to cross an entire ocean; the alarm was picked up by the cruise liner Carpathia a mere 60 miles away, which was responsible for the rescue of the Titanic survivors. Marconi was heralded as a hero for his invention and was credited for saving over 700 lives. And it had done so with a simple signal.

dit dit dit - S.
dah dah dah - O.
dit dit dit - S.

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