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Speaking in Phases

The tiny spacecraft we have sent to explore our solar system "phone home" across millions of miles of space using only about as much electricity as the light bulb in your refrigerator! How do they do it?

This question has been one of the biggest that space scientists and engineers have had to answer. The spacecraft are very tiny, from about the size of a washing machine to the size of a delivery truck. (New ones being planned are even smaller.) Most of them use solar panels to generate electricity from the sun. However, none of them makes enough electricity to operate a big, powerful transmitter that could beam a strong radio signal back to Earth.

One part of the answer is to focus the weak signal into a very narrow beam. Another part of the answer is pointing that tiny beam very accurately toward Earth. And another big part of the answer is the Deep Space Network (DSN for short) of giant receiving antennas here on Earth.

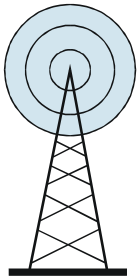
The Power of Good Listening

The DSN has three groups of antennas, spaced more or less evenly around Earth. One set is in California, one set is in Spain, and one set is in Australia. As the Earth turns, at least one set of antennas is "visible" to a far-away spacecraft at all times.

DSN's huge dish-type antennas are especially designed to detect radio waves, and very faint ones at that. By the time the spacecraft signal reaches Earth, it is so weak, you would have to collect and save the energy from the signal for 40,000 years to have enough energy to light a Christmas tree bulb for 1 millionth of a second!

This 70-meter antenna in Madrid, Spain, is part of the Deep Space Network.

Radio waves are like light waves, but much longer. Our eyes cannot see them. Radio waves rain down on Earth all the time from stars, galaxies, and even some planets (Jupiter is a good example). A little more than 100 years ago, humans learned how to make radio waves too. Now we use them to carry the signals for our radio, TV, and other types of communication on Earth, as well as to communicate with our spacecraft, whether in orbit around Earth or way out in "deep space." Radio and TV stations use powerful transmitters mounted on giant towers to broadcast their program signals in all directions, so that anyone within a certain distance who has a radio or TV receiver can tune in to their programs.

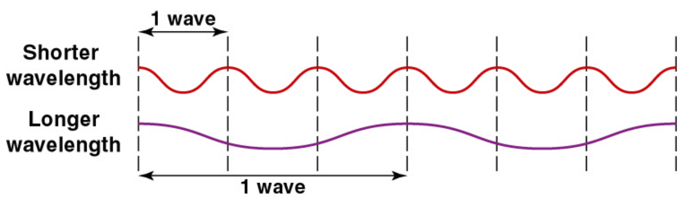


Now, the next question might be, how do the radio or TV programs here on Earth, or the pictures and other information collected by a spacecraft in space, get carried by the radio waves being transmitted? How can a TV show be carried invisibly (and without a sound) through the air? How can a picture of Saturn or Jupiter be carried by very weak waves of radio energy passing through millions of miles of cold, empty space?

Waves of all Shapes and Sizes

First, let's look at what we really mean by a wave. A wave appears on the surface of the ocean when a burst of energy passes through the water. Lots of bursts of energy in a short time make short, choppy waves. Fewer bursts of energy in the same time make longer, drawn out, more graceful waves—great for surfing.

Light waves and radio waves are both electromagnetic energy. The only difference between them is the size of the waves. Light waves are kind of like tiny ripples on the surface of the ocean. Radio waves are more like the long, slow ocean waves that move a whole boat up and down. Electromagnetic energy comes in every wavelength in between these two, as well as waves much shorter than light waves and much longer than the radio waves we use for communication. As a matter of fact, we don't know how long or how short electromagnetic waves can be. We know only the ones we have eyes or instruments to detect.

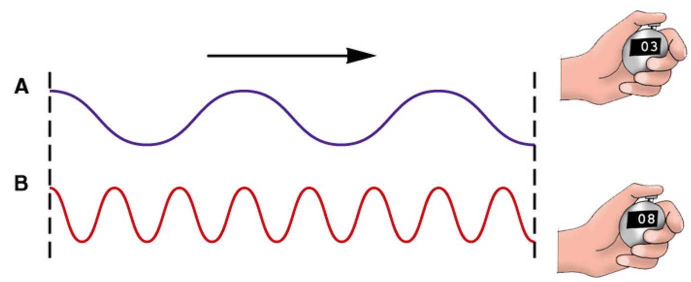


We could pick any wavelength to carry information as long as we could build an instrument that could transmit energy through the air or through space at that wavelength. But it turns out that light waves and shorter wavelengths, besides taking more energy to transmit, get scattered and absorbed easily by Earth's atmosphere. Some short wavelengths (like x-rays and gamma rays) can't penetrate air at all. That's lucky for us, since these highly energetic waves would bombard Earth's surface from space and eventually kill off every living thing!

Wave to the Winning Wave

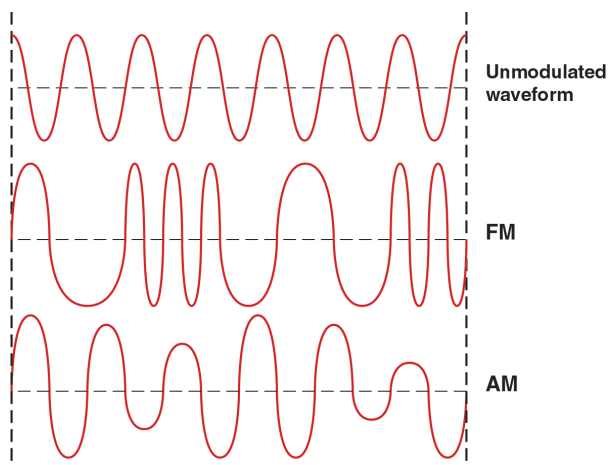
Radio waves, however, pass through Earth's atmosphere very nicely, without distortion. This property makes them ideal for sending signals. They also don't require as much energy to produce as shorter wavelength electromagnetic waves. And, by the way, they don't hurt anybody.

Frequency is another way to describe wavelength. Frequency refers to the time it takes for two *crests* (highest part of the wave) or *troughs* (lowest part of the wave) in a row to pass the same point in space. The longer the wave, the lower (or slower) the frequency (because it takes longer for the wave to pass a point). The shorter the wave, the higher (or faster) the frequency.



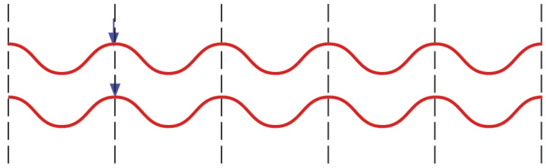
In the above drawing, more B waves than A waves will pass by a certain point in a certain time. So the shorter the wavelength, the higher the frequency.

TV stations and some radio stations put their program information on the wave by adjusting the frequency. FM (as in FM radio stations) means *frequency modulation. Modulation* means changing a radio signal so that it carries information. Some radio stations use *amplitude modulation* (AM). *Amplitude* is the height of the wave from crest to trough.

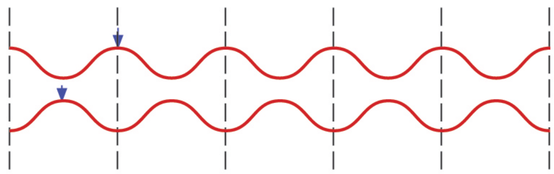


Going through a Phase

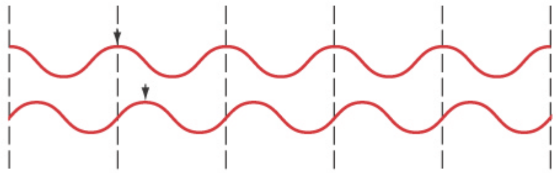
Spacecraft do not use either of these modulation methods, however. Spacecraft use *phase modulation*. *Phase* refers to the part of the wave passing a particular point at a particular instant. If two waves of the same frequency (that is, wavelength) are *in phase*, the exact crest or trough of both is passing the same point at the same time.



Two waves of the same frequency are out of phase if different parts of their wave forms are passing the same point at the same time.



We measure in degrees how much out of phase two waves are. The above two waves are 180 degrees out of phase. They are as far out of phase as they can get! Waves can be out of phase by lesser amounts. The waves below are about 90 degrees out of phase.



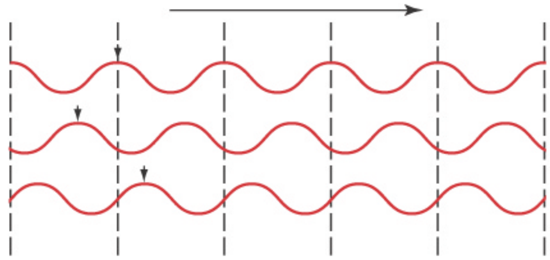
So, how does a spacecraft modulate phase in order to put information into the signal?

Simple as a Light Switch

Well, one thing you need to know is that spacecraft and computers understand only two ideas: *on* and *off*. Or, put another way, *one* and *zero*. From many sets of ones and zeroes, all other information is constructed, stored, and communicated.

So, to communicate all these ones and zeroes, the spacecraft's transmitter starts off sending its normal wavelength or, as more commonly called, its frequency. The DSN antenna receives the signal from the spacecraft and "locks onto" it, so that it "knows" exactly what phase of the spacecraft's normal wavelength would be coming in at any given time if the spacecraft kept transmitting only the normal frequency with no modulation.

Then the spacecraft begins sending information by shifting the wave just a little bit out of phase for a certain number of wavelengths. If, for example, the phase of the signal wave lags 90 degrees behind its normal beat, it might mean "1." If the phase of the signal wave is 90 degrees ahead of where it would normally be, it might mean "0." A "1" or a "0" is called a *bit* (as in a bit of information).



We can demonstrate how this works using sounds. We can even send secret messages using drumbeats! Perhaps the original Native Americans were the inspiration for this space-age technology.

Let's Get Rhythmic!

For this experience, you will need some way to make rhythmic sounds (without echoes or much reverberation). Perhaps your school's music teacher can help with this activity. You need to be able to make two different sounds, perhaps one low-pitched and one higher-pitched. Here are some example ways to do this:

> *Recommended option:* For the reference frequency, use a metronome or an electronic keyboard that can automatically maintain a steady beat. For the signal frequency, use a drum, piano key, ruler tapping on a desk, spoon tapping on a glass of water, or anything that can sound out a beat.

Alternative option: If you don't have a metronome or electronic keyboard, then find a way to make two different beat sounds, one lower and one higher, or one louder and one softer.

The only other materials you will need are paper and pencils, plus the table of codes in this article so you can translate back and forth from letters or numbers to symbols and bits (1 or 0).

Getting in the Groove

Here's the general idea: The metronome or electronic keyboard, or one of the "instruments" (preferably the lower or louder one) is used to create an imaginary reference frequency (or beat, in this case). Then, the other instrument will represent the signal. We need to maintain the reference beat so that we humans can make sense of the signal beat. If the two instruments are beating together—that is, are in phase—there is no information being transmitted. If the signal beat lags an instant behind the reference beat for four beats, that means 1. If the signal beat is just an instant ahead of the reference beat for four beats, that means 0. For every bit (1 or 0) being "transmitted" there must be four "in phase" beats to signal the break between bits.

So try this:

The metronome, electronic keyboard, or the person keeping the reference frequency (or beat) we will call "Reff." The person transmitting the signal frequency we will call "Sig."

Reff starts a slow, steady beat—about 50-60 beats per minute. The important thing is that it be very regular. If you don't have a metronome, hope there's a good drummer in the class!

Now, **Sig** comes in on the beat for four beats.

Now, **Sig** beats four beats just a little behind Reff. So, using "BUMP" to mean the reference beat and "bump" to mean the signal beat, it sounds sort of like

BUMP-bump (pause) BUMP-bump (pause)
BUMP-bump (pause) BUMP-bump (pause)

Get used to this sound. In our game, four of these beats means "1." In the spacecraft business, each beat (or phase-modulated wavelength) is called a *symbol*.

Now, after these four beats, **Sig** again gets back in phase with Reff for four beats, so mostly what you'll hear is

BUMP (pause) BUMP (pause)
BUMP (pause) BUMP (pause)

Note that after Sig's last beat in the "1" sequence, he or she will have to rush the next beat to be "in sync" with Reff.

Now, without missing a beat, **Sig** rushes ahead and beats just a little before Reff for four beats, like this:

bump-BUMP (pause) bump-BUMP (pause)
bump-BUMP (pause) bump-BUMP (pause)

Get used to this sound, too, because these four beats mean "0."

Now, again **Sig** beats in phase with Reff for four beats. Note that after the last beat of the "0" sequence, Sig has to pause a bit to get back in sync with Reff.

Altogether, this sequence will sound like

BUMP (pause) BUMP (pause)
BUMP (pause) BUMP (pause)

[1] BUMP-bump (pause) BUMP-bump (pause)
BUMP-bump (pause) BUMP-bump (pause)

BUMP (pause) BUMP (pause)
BUMP (pause) BUMP (pause)

[0] bump-BUMP (pause) bump-BUMP (pause)
bump-BUMP (pause) bump-BUMP (pause)

You might have to practice for a while to get the hang of these rhythm sequences.

The Beginnings of Communication

Now, let's transmit information! Here is a table showing the standard sequences of bits used by computers to mean each of the letters of the alphabet (capitals only here) and numbers 0-9. We already know it takes four symbols (off-phase beats) to make a bit. Now, in the table, notice that it takes eight bits (called a byte) to make a letter or number. Since we are using four beats (like wavelengths for a spacecraft)

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Binary Code	**Letter or Digit**
0011 0000	0
0011 0001	1
0011 0010	2
0011 0011	3
0011 0100	4
0011 0101	5
0011 0110	6
0011 0111	7
0011 1000	8
0011 1001	9
0100 0001	A
0100 0010	B
0100 0011	C
0100 0100	D
0100 0101	E
0100 0110	F
0100 0111	G
0100 1000	H

Binary Code	**Letter or Digit**
0100 1001	I
0100 1010	J
0100 1011	K
0100 1100	L
0100 1101	M
0100 1110	N
0100 1111	O
0101 0000	P
0101 0001	Q
0101 0010	R
0101 0011	S
0101 0100	T
0101 0101	U
0101 0110	V
0101 0111	W
0101 1000	X
0101 1001	Y
0101 1010	Z

in our game to make a bit (plus four beats between bits), it is going to take 64 beats to make a single letter! This is just how it's done by a spacecraft. It might take 64 symbols to make a byte of information.

Everybody needs a copy of the conversion table.

Sig picks one letter or number, but keeps it a secret from everyone else.

Then, with the metronome or reference beat going, Sig tries to beat out the correct sequence of symbols that will make the 1s and 0s that will communicate the number or letter he or she picked.

Others in the class must listen very carefully, with pencil and paper at hand. If you are a listener, each time you hear four beats out of phase, write down whether its a 1 (BUMP-bump) or a 0 (bump-BUMP). When you have 8 bits (1s and 0s), find that sequence on the table and you will know the letter or number Sig was transmitting!

From 1/0 to Shakespeare!

Now, when the drummer(s) gets very good at this, they can put together whole words, even sentences.

To signal the break between letters, you can add four more "in phase" beats, for a total of eight.

To signal a break between words, you can add another four or eight "in phase" beats, for a total of 12 or 16.

How fast can you transmit and receive information before there are lots of errors?

This game just begins to give you an idea how any kind and any amount of information can be communicated using only two states: 1/0, on/off, yes/no. This system is called *binary* (meaning 2) *notation*.

This is the only language computers or spacecraft understand.

For more on binary notation and how it is used in the computer and space business, see http://spaceplace.jpl.nasa.gov/vgr_fact1.htm . Also, learn more about the Deep Space Network at http://deepspace.jpl.nasa.gov/dsn/. For a fun activity related to how the DSN antennas "hear" the tiny voices of far distant spacecraft, go to http://spaceplace.jpl.nasa.gov/tmodact.htm . For more on spacecraft telecommunications, see the Basics of Space Flight on-line tutorial at http://www.jpl.nasa.gov/basics.

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