



## The Earth

*{Abstract— In this first segment of our video book, we introduce the most basic distance measurement techniques, and illustrate their use in my back yard. These include direct measurement and triangulation. We introduce minutes and seconds of arc in a degree, and describe a theodolite. We then triangulate the Grand Canyon, Mt. Everest and more.*

*We then introduce lightning as an example where some basic scientific understand about observed phenomena is needed to help determine how far away it is. We discuss what lightning and thunder are, and the speed of sound in air to calculate how far away a lightning strike is.*

*Next, we cover “going there” as a technique for determining distance, using our atmosphere as the prime example. From balloons to the space station, we cover the troposphere, stratosphere, mesosphere and thermosphere.*

*Then, we illustrate how geometry can play a key role in determining distance as we cover in detail how Eratosthenes actually calculated the size of the Earth in 200 B.C. We use how many students could fit inside the Earth to highlight just how vast the Earth really is.*

*We conclude our coverage of the Earth with a look at distances to a number of cities using pictures and video taken by the international space station at night. We start close to home and move out to the most distant cities – much like we’ll be moving from neighboring celestial objects out the furthest reaches of space in subsequent video book chapters.*

*We then introduce the distance ladder and show how we have just built the foundational rungs in the ladder. We end with a preview of the coming distant ladder rungs and the video book segments organized around them.}*

### Introduction

The Earth: It’s big, really big. In this section we’ll cover how we came to just know how big the earth really is.

In so doing, we’ll build the first rungs in the distance ladder that will take us across our galaxy.

We’ll begin our journey to the edges of the visible very close to home.



**[Music: Johann Sebastian Bach’s - Zion Hort Die Wachter Singen.  
“Zion Hears the Watchmen Calling” is a church cantata written in 1731.  
Here we use it’s famously lyrical melody to introduce our trip to the stars.]**



### Direct Measurement

Here I am in my backyard. This is where we will begin building the ladder that will take us to the stars.

There's a post. If you want to know how far away it is, the simplest thing to do is to measure the distance with something like a tape measure. If we take a look at this one, it's 2 meters (6.56 feet) away.

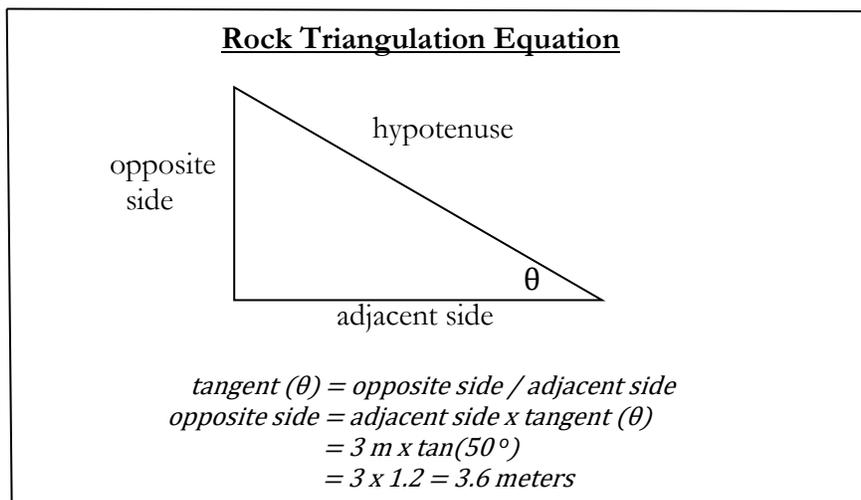


[Note: accuracy of instruments is key]

### Triangulation

But what do you do if you want to measure something that you can't reach with a tape measure, like the rock on the other side of the water. For that, we do something called triangulation.

Take a point. Measure an angle of 90 degrees. Step off a known amount, say 3 meters (10 feet). Measure the angle from the second spot – 50 degrees. Triangulation gives us the distance – 3.6 meters - to that rock from that first spot.



That combination of direct measurement and angular measurement – triangulation – with triangulation we can triangulate everything there is on the planet Earth that you can see.

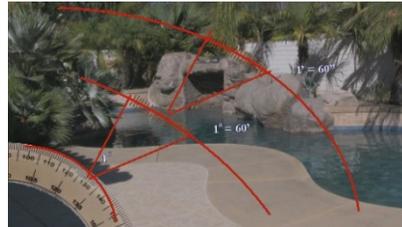
### Extended triangulation

**[Music: Gabriel Fauré - Pavane Op.50. This music was chosen by our space station astronauts as they watched city lights below them dance across the night. In 1887, Faure obtained its rhythm from the slow processional Spanish court dance of the same name.]**



Triangulation is mathematical. The only errors that are introduced are with the accuracy of the angle and baseline measurements. Although tape measures and protractors work OK in a backyard, they are rather crude instruments. They don't scale well to distances beyond the back yard. If we use more accurate instruments than the protractor and tape measure, triangulation can take us a long way.

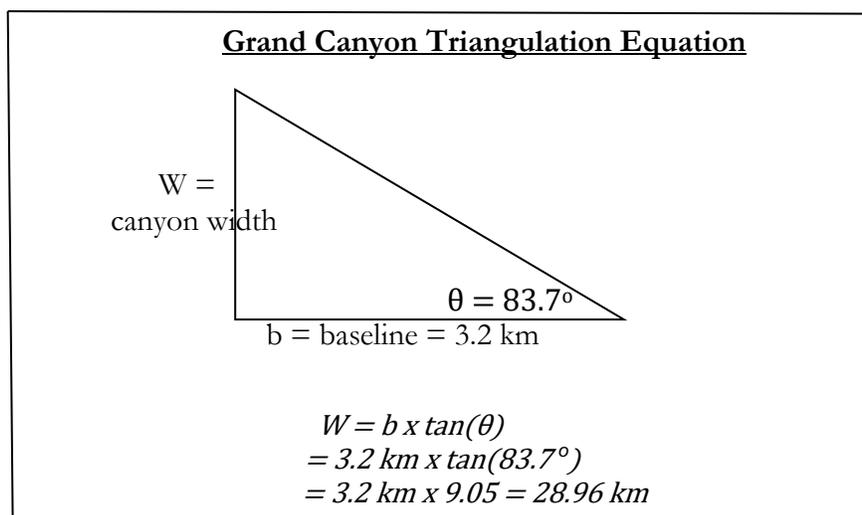
A protractor can give you an estimated angle to the granularity of a degree. A circle has 360 degrees. For greater accuracy, we break up a degree into 60 arc minutes and each arc minute is broken up into 60 arc seconds.



Here we see a theodolite. It's a surveyor's instrument that measures angles in the horizontal and vertical planes down to a second of arc.

Using industrial instruments like these, we can answer “how far away is it” questions like: How wide is the Grand Canyon? and How high is Mt Everest?

In 1902, an extended survey of the Grand Canyon was conducted where 18 primary triangulation stations were marked. The survey found that the Grand Canyon is 446 km (277 miles) long and up to 29 km (18 miles) wide.

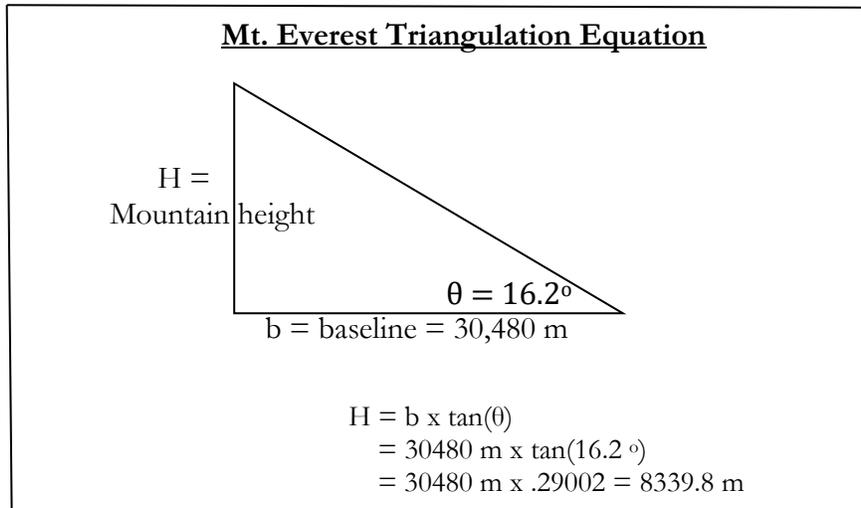




In 1856, the Great Trigonometric Survey of India established the first published height of Everest at **8,840 meters** (29,002 ft).



**[Additional info:** Modern methods have it at **8,848 meters** (29,029 ft.) the highest mountain on Earth, and the highest point on the Earth's crust.]



**[Additional info:** Surveyors have created networks of triangulations that covered entire countries like France, Great Britain, and India using spherical trigonometry to account for the curvature of the planet. With these networks, we can triangulate everything that can be seen on our planet.

*Of course Global Positioning Systems (GPS) have made the technique rather obsolete for mapmaking these days, but you still see surveyors with their instruments on the streets mapping out project locations.]*

The only limits on triangulating the distance to an object are:

- 1) You have to be able to see the object in order to measure angles to it, and
- 2) You have to be able to measure or calculate the baseline

These might not sound like serious limitations. But

- lightning doesn't wait around long enough to take any of these measurements
- and you can't see the top of the sky.

Methods for finding distances to things like these have relevance for the methods that will take us to the planets and the stars, so let's go over them.



### Lightning

For some things, you need to know something about the physical processes at play. For example, “How far away is lightning?” To answer this question, it helps to know something about what lightning and sound are. For example, we know that a lightning flash is caused by a massive move of electrons across the sky. This creates a vacuum in the air and thunder is the sound of the air collapsing back into the vacuum. We also know that sound is a wave. The speed of sound is variable and depends on the properties of the substance through of which the wave is travelling. In air, the speed of sound is approximately .32 km (.2 miles) per sec.

So all we need to do, to see how far away the lightning is, is to start counting the seconds at the flash and multiply the number of seconds by .32 to get the number of kilometers (miles) away it is. Here we have a 6 second delay between the light and the sound, so the lightning is 1.9 km (1.2 miles) away.



As we move up the distance ladder, we’ll be using knowledge about stars and light waves in similar ways to our use of lightning and sound waves here.

### The Atmosphere

For some things, you simply have to go there to find out how far away it is. For example, “How high is the sky?” It’s not something you can see, so triangulation won’t work. To answer this, you need to go there or send something there and report back how far away it is.

In the beginning, all we could say for sure about the atmosphere was that clouds were closer to the surface of the Earth than the sun, moon, planets and stars. We knew this because clouds always covered up the surface and those objects – never the other way around.



Our knowledge in this area didn’t really begin until the late 1700s when high flying balloons came into use. Here’s a scientific balloon launch. High altitude balloons have been used for over 70 years for atmospheric exploration. They fly at altitudes in excess of 32 km (20 miles) above the surface of the earth for days on end.

It wasn’t until the 1900s that aircraft, rockets, and space craft were put to use to travel high into the atmosphere and figure out just how high it went and how it was structured.

It turns out that the atmosphere doesn’t have an exact top like a lid would be on a jar. What happens is that the air gets thinner and thinner and eventually merges into and then becomes outer space.

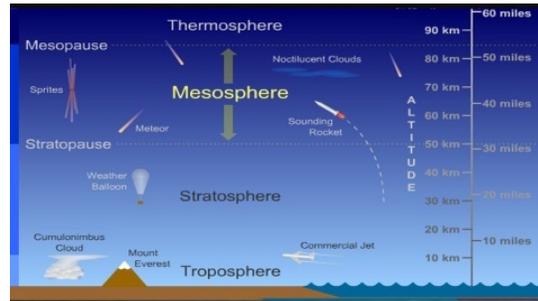


## Atmospheric Layers

The **troposphere** begins at the surface and extends to around 20 km (12.4 miles). It contains roughly 80% of the mass of the atmosphere. This is where we get all our weather and it is where our passenger jets fly over that weather.

The **stratosphere** extends from the troposphere to about 50 km (32 mi). The balloons we discussed fly in this area.

The **mesosphere** extends from the stratosphere to around 84 km (52 mi). It is the layer where most meteors burn up upon entering the atmosphere.



The **Thermosphere** extends up to 386 km (240 miles) and is considered outer space. The air is so rarefied that an individual molecule travels an average of 800 meters (1/2 mile) between collisions with other molecules. The International Space Station orbits in this layer.

Going there is a technique we can repeat for distances throughout our solar system, but it won't take us to the stars.

## Size of the Earth

Now, let's find out "How big is the Earth", using geometry as a key technique.

**[Music: Samuel Barber - Adagio for Strings. Written in 1936, Barber envisioned a small stream that grows into a river. Here we use it as we grow an idea into the full massive size of the Earth itself.]**

In 200 B.C., Eratosthenes actually calculated the size of the Earth and came pretty close! Eratosthenes used Aristotle's ideas that:

- 1) If the Earth was round, the Sun would appear at different positions to observers at different locations; and
- 2) If the Sun was very far away, the light rays would be almost parallel between any two locations.

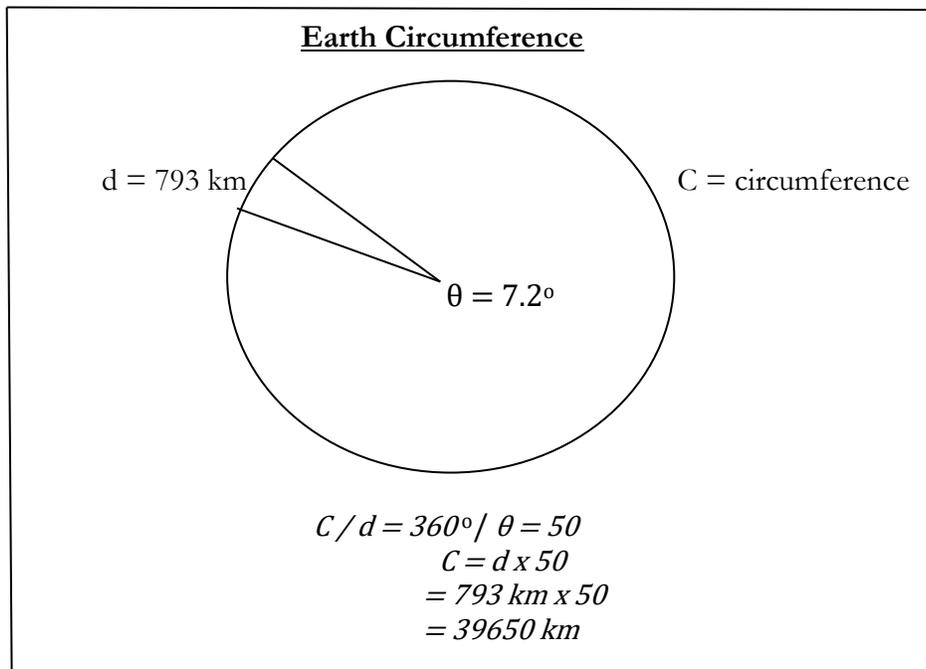
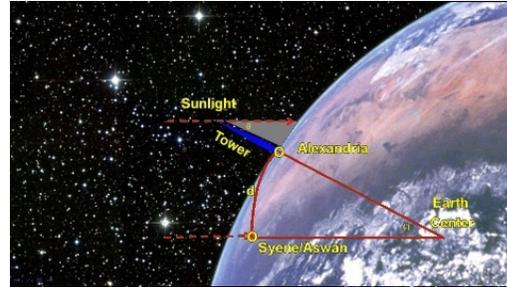
For his two locations, Eratosthenes chose Alexandria and Syene (now Aswan). He knew how far apart these two cities were – 793 km (493 miles) in today's units. Eratosthenes knew that on the first day of summer, the Sun passed directly overhead at Syene.

At midday, of the same day, using a tower in Alexandria, he measured the angular displacement of the Sun from overhead. He found that the angular displacement was 7.2 degrees – that's equivalent to 1/50 of a circle.



Geometry tells us that the angle measured at the tower is the same as the angle between lines connecting the two cities to the center of the Earth. This is because when a straight line crosses parallel lines, it crosses them at the same angles.

So given that the angle is  $1/50^{\text{th}}$  of a circle, the distance between the cities will also be  $1/50^{\text{th}}$  of the circumference of the Earth. Thus the circumference can be estimated by multiplying the distance between the two cities, 793 km, by 50, equaling 39,650 km (24,650 miles). The actual number at the equator is 40,074 km (24,901 miles). He was only 1% off.



This is an experiment anyone can do. In fact, in 2005, it was a science project for a number of schools around the country. I'll point you to details in the Credits in case you'd like to try it yourself. **[Go to: [www.physics2005.org/projects/eratosthenes](http://www.physics2005.org/projects/eratosthenes)]** Once we have the circumference, Geometry gives us the rest. For a spherical Earth:

- The diameter  $D$  is equal to the circumference divided by  $\pi$ 
  - $D = C / \pi = 40074 / 3.1416 = 12756 \text{ km}$
- The radius  $R$  is half the diameter
  - $R = D / 2 = 12752 / 2 = 6378 \text{ km}$
- The surface area  $A$  is 4 times the radius squared times  $\pi$ 
  - $A = 4 \pi R^2 = 12.57 \times 6378^2 = 511 \text{ million sq. km}$
- The volume  $V$  is  $4/3$  the radius cubed times  $\pi$ 
  - $V = 4/3 \pi R^3 = 4.12 \times 6378^3 = 1.07 \text{ trillion cubic km}$



Needless to say, this is very large! A high school teacher calculated the number of students that could fit inside the Earth. It came to 137,188,690,000,000,000 students. This number of students is so large that if you could count one number per second it would take you more than 4 trillion years to count this high. So, you can see, the earth is very large indeed!

### Cities at Night from Space

[Music: *Back to Gabriel Fauré's Pavane*]

Now that we have a feel for how large our planet Earth is, how high the sky goes, and how we measure and calculate these distances, we'll finish this Chapter with a look at some of our great cities at night from space and identify their distances from our home base - San Diego, California.



Astronaut Don Pettit went to significant lengths to get high def pictures of the Earth's cities at night from the International Space Station back in 2008. I combined his pictures with the time lapse photos taken by the crew of Expeditions 28 & 29 aboard the Space Station in 2011. The space station orbits 370 km (230 miles) above the earth.



We start with nearby cities. Like nearby stars, these are the most familiar to us. Distances are measured in hundreds of kilometers. Nearby star distances are measured in trillions of kilometers.

As we move east across the North American continent, distances grow to thousands of kilometers. Similarly, distances to far away stars grow to hundreds of trillions of kilometers.



We jump by thousands of kilometers as we cross the voids created by great oceans such as the Atlantic. This reminds me of the galaxy voids in the structures known as superclusters.

Here's one of the furthest cities. From here, because the Earth is round, we start measuring distances to the west. It's interesting to wonder if the same sort of thing could happen if the Universe is curved enough to be closed.





**Distance Ladder**

[Music: *Back to Samuel Barber - Adagio for Strings.*]

The Distance Ladder is a set of techniques for determining an objects distance. Each step works for a particular situation and distance range and supports the steps above it. This is how we work our way from Earth to the stars and on to the most distant galaxies.

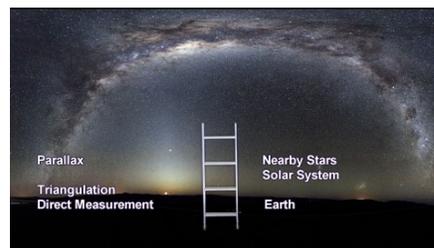
We have just built a solid first rung for our ladder. We can now use the entire diameter of the Earth (12,756 km - 7,926 miles) as our baseline for triangulating off the Earth and into the Solar System.

Here’s an overview of the rest of the ladder.

**Parallax**

Direct measurement doesn’t work for figuring out how far away the planets are. For that we use an extension of triangulation called Parallax. If you hold your finger up in front of your eyes, and close one eye at a time, you see a shift in your finger’s relative position with respect to distant objects. This is parallax! It can be used to calculate the distance to our Solar System neighbors

and nearby stars. All you need for this to work is a more distant star that doesn’t move when the target object is viewed from different locations.

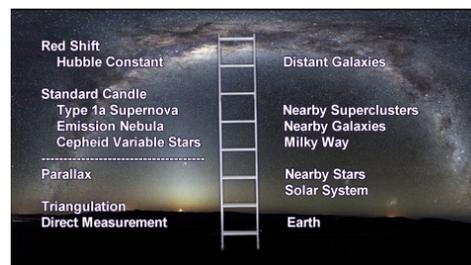


**Standard Candles**

Parallax accuracy goes down as the distance goes up, and it doesn’t work at all for stars and galaxies that don’t have more distance objects that remain stationary as the earthbound observer moves. For those objects we use a technique called ‘Standard Candles’. Once we know the intrinsic brightness of a star, we can use the simple inverse square rule for the drop-off in apparent brightness as the object is seen on Earth.

Some objects lend themselves to this technique better than others. Some of the most prominent are:

- Cepheid variable stars –
- Emission nebula –
- Type 1a Supernovas –





## Red Shift – Hubble Constant

The final rung on the ladder is Red Shift. The most distant galaxies are too far away to see Cepheid stars or Supernova explosions. For these, we owe our thanks to Edwin Hubble who discovered a relationship between the speed that a galaxy is traveling away from us and its distance from us. Based on his evidence for an expanding Universe, the faster a galaxy is receding away from us, the further way it is. We get the receding speed from the red shift in the light from the galaxy. This method works all the way out to near the big bang, around 13 billion light years away.

We'll be building the Cosmic Distance Ladder, rung by rung, as we move through the "How far away is it" video book chapters.

## Video Book Preview

Here's a preview of the "How far away is it" video book chapters.

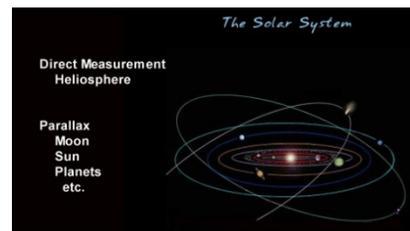
### Earth



In this segment, we used direct measurement, triangulation, and other geometric formulas to calculate 'How far away is it?' for the Earth

### Solar System

In the next chapter, we'll use parallax to measure how far away the moon and planets are, and triangulate the distance to the sun. We'll take the direct method to measure the extent of the Sun's Heliosphere. And we'll use geometry to determine how far away comets are.





### Solar neighborhood



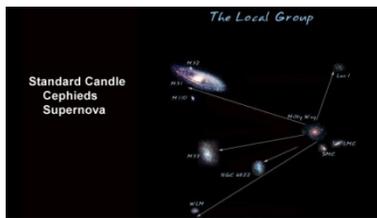
Parallax will take us to the stars in our local neighborhood such as Alpha Centauri and Wolf 359.

### Milky Way

Going deeper into the Milky Way, we'll add Cepheids, Supernova, Nebula, Supergiants, and Globular Clusters to work our way across the galaxy.



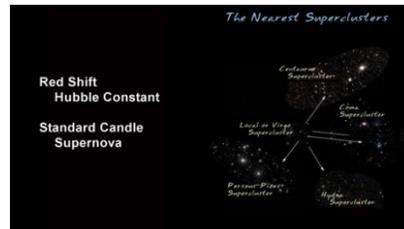
### Local Group



A number of these methods drop out as we move into the Local Group of galaxies around us.

### Superclusters

As we move further out, only Super Novae can be relied upon. Also, we move into distances where Red Shift begins to work.



For the **furthest reaches of space**, we have only Red Shift.





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