

A descriptive explanation of ocean tides.

by Donald E. Simanek

Anyone who has spent some time on a beach has noticed the periodic phenomenon of the tides. The water level at the shoreline rises to a maximum, then the tide goes out, and rises again about 12 hours and 25 minutes later. This tells us that this process is synchronized to the moon's apparent motion in the sky, with period 24 hours and 50 minutes. We also observe smaller tides that are synchronized with the motion of the sun in the sky. Water levels at shorelines vary in size considerably at different places on earth, resulting from variations in shoreline topography. And there are significant large variations of water level throughout the oceans, due to reflection of water from shorelines and resonant phenomena of water sloshing in the confines of an ocean basin. Yet the relentless time-regularity of tides, observed since the earliest history of mankind, is clearly driven by the positions of the moon and sun relative to our location on earth.

Ancient man considered the tides an occult or magical influence of these heavenly bodies. Now that we recognize that all motions of planets and their satellites are due to the universal gravitational force, we can better understand this connection in detail, removing its mystery.

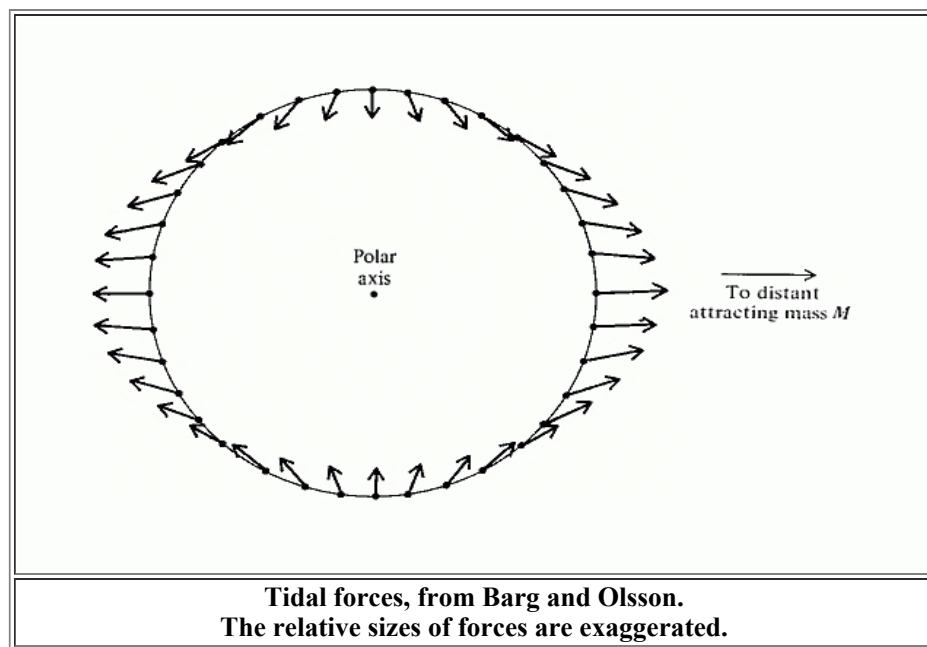
Not only does gravity rule the motions of the planets and moons, gravitational forces also stress material bodies, causing distortions of their shape. Those distortions are relatively small in magnitude, but represent a considerable expenditure of energy over the huge mass of a body like the earth. For example, the average radial distortion of the earth's crust due to the moon is less than 1 meter, and the mid-ocean water level is raised an additional meter in height. But the amount of mass that must move to achieve that height in the Atlantic or Pacific Ocean is huge. We call these land and water distortions "tidal bulges". As the earth rotates underneath the ocean's tidal bulges, the water acts much like the water in a dishpan as you try to carry it. The water "sloshes around" bumping against the container walls, setting up standing waves. This is why shoreline tides can be of much greater amplitude than the average size of the tidal bulge itself. It is also the reason that the timing of arrival of coastal high tides can be many hours "late" in arrival at places such as the North Sea, and why tides in the Mediterranean are so small in amplitude.

The tides synchronized with the moon are the largest, about 2.2 times greater than than tides due to the sun, so we will confine our attention to them.

Why is there usually a high tide when the moon is high in the sky, and also when the moon is on the opposite side of the earth? One often sees "explanations" that speak of "the moon pulling on the water". It's not that simple. The moon's gravitational force on earth acts on **all** parts of the earth with nearly the same force, differing by only

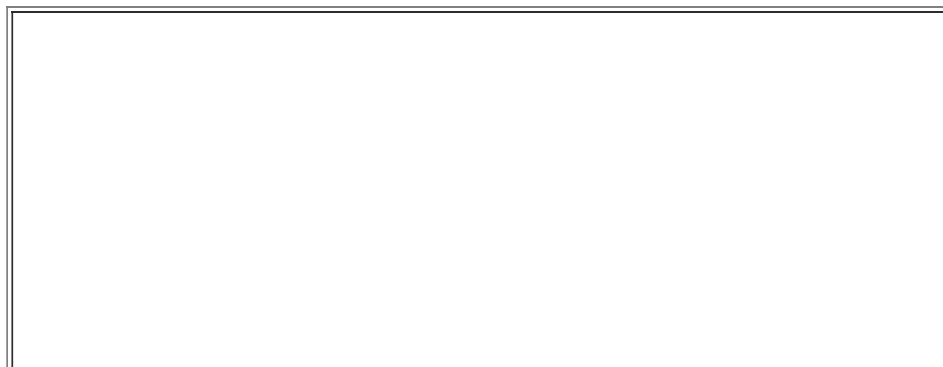
about 7% on the sides of earth nearest and farthest from the moon. And the differences from ocean surface to bottom are far smaller. But it's those small **differences** that are responsible for the **tidal force** or **tide-raising force** that distorts the earth's shape and the bodies of water on it.

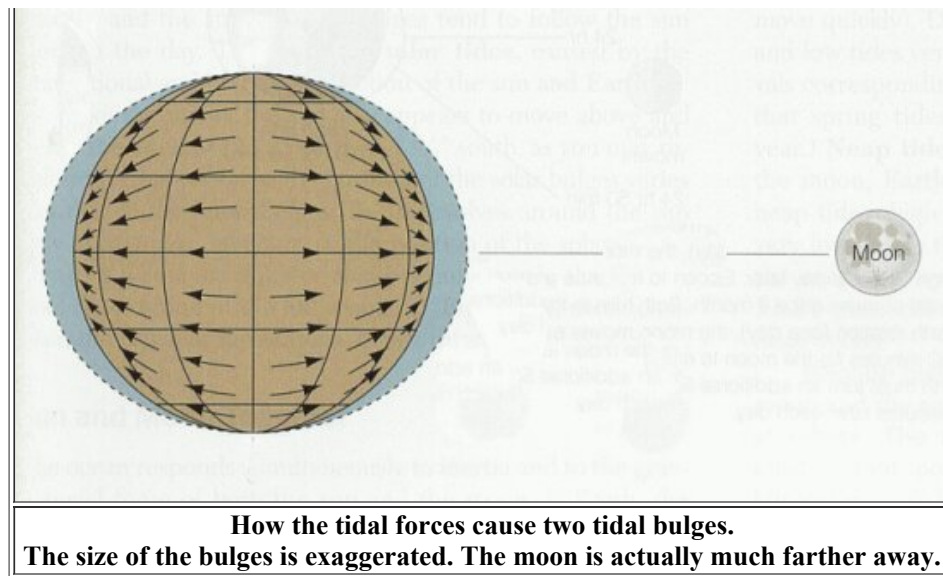
One way to get a feeling for the size and direction of these tidal forces is to use vector polygons to calculate the difference between the gravitational force the moon exerts at a point on earth and the force it would exert at the center of the earth. When this is done, a picture such as this emerges: [1]



The vectors in this diagram are usually called "tidal forces", but they are not themselves gravitational forces. They represent the differences between gravitational forces measured over distance. They show the deforming effect of gravitational forces upon the surface of the earth. Such deformations are also occurring throughout the volume of the earth.

These forces act on the earth's volume in two ways: (1) They stretch the earth along the earth-moon line, and (2) they move materials, especially fluid materials like water, toward the earth-moon line. Both of these effects contribute to **two** tidal bulges on opposite sides of the earth. This is the reason for the tidal bulges, and it is these bulges that drive the periodicity of the shoreline tides that we observe while basking on the beach, as the earth turns on its axis underneath these tidal bulges.





While gravitational forces depend on the inverse square of distance, these tidal forces, being **differences in force over length**, depend on the inverse cube of distance. That's why tidal forces on earth due to the sun are much smaller than those due to the moon. Even though the sun's mass is very much greater than the moon's mass its distance from earth is much greater than the moon's distance. [The reader may wish to do a "back of the envelope" calculation here.]

Note that gravitational forces alone are responsible for the tides. Some textbooks confuse the matter by talking about "effects due to rotation" or due to "inertia" or "centrifugal force". Rotation of the earth does indeed cause an "equatorial" bulge of land and sea, extending entirely around the earth. This is quite different from lunar and solar induced tides. For one thing, the equatorial bulge is constant in shape, and not in any way related to the position of the moon or sun. The lunar tides are an additional distortion added to that equatorial bulge, and they are relatively fixed in position relative to the moon, not to the earth.

But one effect of rotation does matter—a lot. If the rotating earth had no continents, oceans would still experience friction with the ocean floor, and their tidal bulges would be displaced from the earth-moon line.

When the oceans are confined by surrounding continents, the water reflects from shorelines, persistent ocean currents are established, and significantly large additional variations of water level are superimposed on the tidal bulges. These "sloshing effects" are complicated, but are still driven by the simpler considerations we have discussed above.

In smaller bodies of water, like your backyard swimming pool, or your own body, the differences in the earth's gravitational force over such small volumes are so slight as to have negligible affect. Do not expect to see tides in your morning cup of coffee. Tidal forces in these small volumes are unmeasurable by any instruments we possess. Even larger bodies, such as lakes, are too small to create significant tidal effects. The tides in the Mediterranean sea aren't very large, either. There isn't enough volume and

surface area of water.

Why are the heights of tides at a particular shoreline not strictly periodic each month? Why do they vary, month to month? The answer lies in the fact that the earth's axis is tilted with respect to the sun and the moon's orbit is tilted with respect to the plane of the earth's orbit around the sun. Therefore the tidal bulges move north and south with respect to earth's geography over the course of a year.

Endnotes.

[1] For those who want the details, here's a simplified description.

The diagram from Barger and Olsson is the result of assuming a near-spherical "primeval" earth, whose shape is the result of its own gravitation and its axial rotation. Even though it has an equatorial bulge, this is so small that on this scale the earth would appear spherical to the eye. It is shown as a sphere (solid line). This is a baseline from which we measure the tidal effects due entirely to the gravitation of the earth and moon. Since the moon's effects are greatest, we ignore the sun's effects in order to illustrate how this works. The effects due to the sun work the same way, only they are smaller, and can be added later.

The moon's gravitational forces aren't uniform over the surface of the earth. They are weaker farther from the moon, and they aren't parallel, but converge toward the moon.

For example, on a chunk of matter on the near side of the earth (the side nearest the moon), the forces on it would look like this (exaggerated sizes):

-----> o -----> O moon

This would stretch the chunk of matter along the line joining earth and moon. (Since the forces on it, left and right, aren't equal.) The difference between these two forces is called the tidal force on this chunk of matter.

The moon's gravitational forces acting on a chunk of matter on the far side of the earth would look like this:

--> o -----> O moon

This also causes stretching of the matter along the line joining earth and moon.

The situation is more difficult to draw at other places on earth.

Along the earth-moon line, this is happening all through the volume of the earth, causing a relaxation of stress along this line, and resulting in the earth expanding in diameter a bit along this line. This is the reason for the two tidal bulges of the "solid"

