

Chapter One

The Tides in History. The Challenge of Understanding the Tides on Earth

“ ... the earth sweats to create the oceans, which accounts for their saltiness.”

Aristotle

“ ... the body of the earth has its ocean, which also rises and falls every six hours with the breathing of the world.”

Leonardo da Vinci

By the summer of 325 B.C, Alexander the Great had extended his march of conquest all the way to the Indian Ocean. When Alexander was a boy of thirteen, his father, King Philip, had persuaded Aristotle to come from Greece and tutor the young prince. Historians have described this merger as, “genius meeting genius.” Alexander acquired scientific knowledge only known to a small circle of Greek and Macedonian scholars who were fortunate enough to study under Aristotle, the great apostle of Plato. King Philip understood that knowledge was power. He was grooming his successor to venture out and bring the spoils of war back to Macedonia.

Later, while prosecuting a military campaign, Alexander learned that Aristotle had published his lectures for wider distribution. Though occupied with managing 15,000 troops, he sent an angry message to his tutor: “In what shall I surpass other men, if those doctrines wherein I have been trained are to be all men’s common property?”

A ruthless warrior and a brilliant strategist, Alexander's victories made him flagrantly egotistical. He promoted the myth that before his birth, his mother dreamed that she was, "penetrated by lightning, and her womb gushed fire, which spread around the world." Nonetheless, he always knew that Aristotle's lessons had provided him with a distinct advantage over his fallen adversaries.

Alexander launched his army aboard a fleet of thirty-oar galleys, in order to cross the broad delta of the Indus River. At a point near the open sea, a sudden monsoon forced them into the safe harbor of a side channel. This temporary setback would not have concerned the seasoned military man — he had traveled 17,000 miles and crossed many rivers, although he didn't know how to swim.

What *did* disturb Alexander was that all of the water gradually disappeared from the creek, leaving his immobilized army at the mercy of his enemies. His biographers report that the officers wandered about the mudflats, avoiding giant crabs and other unpleasant creatures.

As Mediterranean sailors with a meager knowledge of the tides, they had no reason to expect that the water would ever return. Their general had never seen an ocean before, and had no idea why the creek had gone dry in only a few hours.

Then the stream began to fill with water again. In this particular estuary, the incoming tide is an alarmingly rapid "tidal bore" (see Chapter 9). I suspect that Alexander had mixed emotions about this new flood, which first mobilized his army, and then sank his galleys damaged by grounding. As a general rule, tidal bores are not welcomed by men wearing uniforms of leather and iron. He must have been thinking, "Oh, this is terrific. Old Aristotle forgot to mention one small detail: that the entire ocean goes up and down ten feet, twice a day!"

The “cradle of civilization” was a mixture of Arabic and Greek science and philosophy. The Renaissance, stretching from Leonardo da Vinci to Galileo, began in Italy. Early western civilization was completely ignorant of the tides, because all of this took place on the shores of the Mediterranean Sea, which as it happens, has no significant tidal range.^(a) This will be explained in chapter eight. The ebb and flow in this vast sea is only a few inches in twenty-four hours, barely noticeable among the waves on the shore. Thus, the early scientists and seamen did not misunderstand the tides — they simply never gave it any more thought than the residents of Tahiti gave to snowflakes.

Soon however, early navigators ventured out of the Mediterranean, to the British Isles and beyond. In an interesting twist of fate, civilization departed one of the least tidal ranges on earth (the Mediterranean — a few inches) and soon sailed into one of the greatest tidal ranges on earth (the Bristol Channel, England — over thirty feet). This unexpected phenomenon demanded an explanation. These early Greek and Italian explorers were quick to see a relationship between the tides and the phases of the moon. Of course they were unable to understand this relationship, since astronomy was still astrology, and everyone believed that the earth was the center of the universe. We can safely say “everyone,” since all dissenters had been burned at the stake.

It would be fourteen centuries before Copernicus’s grand theory of the solar system, and another two hundred years until Newton connected the orbits with gravity. For ten centuries before these accomplishments, the general consensus was that the moon passing near the earth compressed the atmosphere, which pushed down on the oceans and set them in motion, bobbing up and down.

^(a)The range of the Mediterranean tides is less than 12 inches on most shores. There are pockets of higher tides in the Mediterranean, such as the three foot tides that occur at Venice, Italy.

During the middle ages, some of the greatest minds in Europe took the logical approach that since light was the only thing extending from the moon to the earth, the tides must be related to moonlight. It was widely accepted that: (1) the angle of the moonlight on the surface of the ocean varied at different times of the month, and (2) this light warmed the ocean, and (3) the resulting heat released gases trapped in the depths of the ocean, which (4) lifted the surface and created the tides.

Even the great Galileo, who understood that the moon orbited the earth orbiting the sun, misunderstood the tidal motion. He was struggling with the tide problem while on a ship passage in the Adriatic Sea. Foul weather set the boat decks pitching about, and Galileo noted that the ship's cargo of fresh water was agitated into waves within the water-vessels sitting on the deck. Observation: the motion of the ship's deck causes waves in the fluids onboard. Conclusion: The tides are due to the oceans being set in motion by the rotation of the earth. He reasoned that the earth's motion caused the oceans to move, much as a bowl of soup loses its equilibrium when the waiter sets the tray in motion across the room. He even considered that the tides were proof of the rotation of the earth. What was needed, of course, was gravity. And so, Isaac Newton was born in the same year that Galileo died.

Think back on what you were doing in your early twenties. Now consider this. In Newton's early twenties he concluded, by pure intuition, that the moon and the earth attracted each other in exactly the same way that a falling apple is attracted to the earth. In order to explain why the moon stayed up there, he developed his Laws of Motion. The prior generation (Galileo and Johannes Kepler) had provided him with a moon *in motion*, in orbit around the earth. Little Isaac learned this in school.

Every schoolchild knew that a ball thrown horizontally would not fall to the ground until it lost its motion. After school they would throw rocks with a sling, like David used to slay Goliath.

To the other boys this was a game. To young Newton this was an experiment, proving that although a rock will fall to the earth, a rock in circular motion in a sling will, “stay up there,” so to speak.

By the time Newton was forty-five, he had derived the simple but profound mathematics describing the exquisite balance of gravitational attraction and the momentum of motion, which we all take for granted today. For those readers who don't really understand the true nature of gravity: how does it work from a distance? — it may be some consolation to know that Newton was also unable to fathom this mysterious force. The greatest scientific treatise of all time was his *Philosophiae Naturalis Principia Mathematica*, in which he finally concluded: “To us it is enough that gravity does really exist and acts according to the laws which we have explained, and abundantly serves to account for all the motion of the celestial bodies and of our sea.”

Principia was published in 1687. We still do not know the true nature of gravity.^(b) However, after *Principia*, everyone soon became comfortable with the idea that gravity causes the liquid oceans to bulge up (or out) toward the moon and the sun. Our intuition is easily satisfied that the clocklike cycles of celestial orbits, and the ponderous revolving of our planet on its polar axis, explain the rhythmic rise and fall of the tides on our shores.

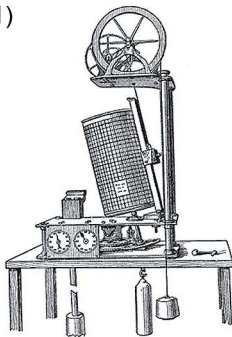
The first systematic theory of the tides on earth was the Equilibrium Theory, first supported by Newton's new gravity. This was a simplistic understanding of how lunar and solar gravitation cause an elliptical deformity in the earth's oceans, with no consideration of the complications caused by the rotation of the earth nor the geography of the continents. Newton was followed by Lord Kelvin, who advanced the new science of hydraulics. Next, Bernoulli in 1740, and then Laplace in 1775, refined the mathematics and the physics of waves into a Dynamic Theory of

^(b) See the supplement to chapter one, at the end of this chapter.

Tides. It accounted for the interaction of celestial forces and earthbound influences due to the interruption of tidal movement by the continents on a rotating planet, as well as the hydraulics over the continental shelf. Scientists began to envision the advancing tides as great oceanic waves, measuring 12,000 miles from crest to crest, moving westward around the globe.

In 1833, the British Admiralty published their first tide tables. These tables were largely empirical. That is, they were based on a series of measurements of recent tides around the calendar and around the world. They showed that the actual measured tides were manifest in many different patterns on diverse shores. It was abundantly clear that neither the pattern nor the height of the tide in any given bay or harbor could be predicted solely by the gravitational attraction of the moon and the sun. The early attempts at the Dynamic Theory were also insufficient to predict future tides. The ability to predict future tides by calculation would have to await another century of scientific progress. Eventually, twentieth century oceanographers condensed this learning into a cohesive and comprehensive model, which is the subject of this book.

(1-1)



Early tide gauge used by the British admiralty to produce the first published tide tables.

Lord Kelvin also used this type of gauge in early research on hydraulics.

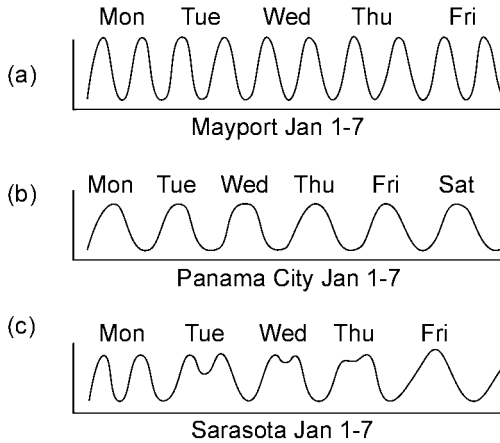
In the early twentieth century, a model called Response Analysis attempted to explain the complexity of the tides on the basis of input-output through a “black box.” The celestial forces

provided the input into the black box, which was the oceans; the output was the tide patterns. The current model of the tides on earth is the Harmonic Theory. The “pure harmonic model” was developed by Doodson and Proudman, and is the most commonly used model in recent decades. It explains the tides as the sum of a finite number of simultaneous, independent, sinusoidal (waveform) constituents, with the *frequencies* determined by the astronomical forces, and the *amplitudes* resulting from the effects of oceanography, shallow water hydraulics, and coastal geography. A revised set of mathematical formulas for tide prediction, known as the “almost harmonic” model, was offered by George Darwin. This sounds suspiciously like the theory that my wife uses when singing in church. It accounts for more variation in the astronomical forces, which repeat in a cycle every 18.6 years. Although it is theoretically an improvement over the pure harmonic model, it has not supplanted the more straightforward mathematics developed by Doodson. The Harmonic Theory is the model used by most oceanographers, the basis of tide prediction at NOAA, and the subject of the following chapters.

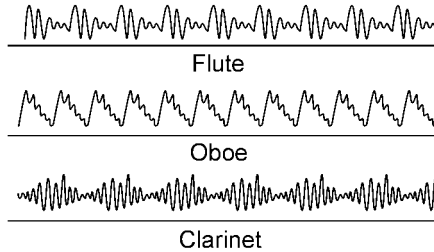
One of these oceanographers, Dr. F. E. Wylie, constructed a wonderful analogy between the tides and music. To state that the tides are caused by the gravitation of the moon^(c) is only true in the same sense that the music of a symphony orchestra is caused by the breath of the musicians, and the movement of their arms and fingers. It would be more accurate to say that orchestral music begins with and takes its energy from the breath and action of the musicians.

^(c)There is a subtle difference between gravitation and gravity. Gravitation refers to the force of attraction between two masses, the force described in Newton’s Law: $\mathbf{G} = \text{mass}_1 \times \text{mass}_2 / \text{distance}^2$. Gravity is a more specific term for the force(s) that act on a mass within the sphere of influence of the earth, the force(s) that determine the *weight* of an object. For an object on earth, such as an apple on a tree, this involves the gravitation of the earth, the gravitation of the apple, and the centrifugal force arising from the earth’s rotation (more precisely, the apple’s rotation because the tree is attached to the rotating surface of the earth).

(1-2) Tide Patterns



(1-3) Acoustic Patterns, "C" note



In an overly analytical sense, music is highly organized sound waves, passing through the air from the instruments to our ears. The *energy* of these sound waves *is* taken from the breath and motion of the musicians, just as gravitation sets the oceans in motion. But when the breath enters a flute, the music is very different from a trumpet. When the motion is exerted on a violin, the sound waves are very different from a cello. And, when the great energetic wave of the oceanic tide reaches the coastline of a continent, with its myriad beaches and bays, the tide is played out in myriad patterns.

The global tides derive all of their energy from the gravitation of the moon and sun and from the motion of the earth, while the complex and various patterns of the tides on the shores of different bays, gulfs, and seas are analogous to the various patterns of sound from different musical instruments, all set in motion by the same breath, the same energy.

This is a useful metaphor, to be sure. Illustration 1-2 shows the tide tables for several points on the coast of Florida, all on the same day, and all resulting from the same vertical displacement of the Atlantic Ocean moving westward. Illustration 1-3 depicts the sound waves of three different wind instruments playing the “C” note. These different patterns are all energized by moving air, which is essentially the same as it *enters* an oboe or a clarinet. However, the acoustic waves *within* each instrument are unique, because the instruments are different lengths and shapes, and made of different materials, just as the Mediterranean Sea and the Bay of Fundy have unique geography and hydraulics.

Hold onto this image, and carry it with you as we proceed together to investigate the forces of nature that influence the tides. I understand perfectly well that what you really want is the “how and why.” How can the Bay of Fundy have a tidal range of fifty feet on the same day that Cape Hatteras’s tides are two feet, all on the same east coast of the same continent? Why is there one high tide every twenty-four hours in the Gulf of Mexico, and two high tides each day on the opposite side of Florida, only 250 miles away? See illustrations 1-2(a) and (b). How can there be one high tide in twenty-four hours on Monday, and two high tides on Friday, at the same point on the coastline? See illustration 1-2(c).

The following chapters will decipher all of the curious and confounding tide tables that you will ever encounter. Never again will you endure this conversation on your vessel. First Mate, “Charlie dear, why are the tides so much higher here than at

home?” Captain Clueless, “The tides are caused by the moon, sweetheart.” Mate, “But they have the same moon here, Charles.” Captain C., “Not exactly dear. The moon ... and, oh yes, the sun ... the sun is also involved ... and ... they have a different angle in the sky here.” Mate: “Are you sure about that, captain?”

Captain Clueless might be facing a mutiny if his first mate knew this one fact from the following chapters. In the twentieth century we know the exact mass of the sun, moon, earth, and ocean. We have measured the exact distances between them and the strength of their gravitational fields. We now know that **the gravitation of the moon is only capable of displacing the water on the surface of the earth by approximately twelve vertical inches. The gravitation of the sun can only displace the oceans by approximately six vertical inches. Therefore, when the moon and sun are aligned to pull in the same direction over the center of the Atlantic Ocean, the maximal tidal range (due to the moon and sun) is approximately eighteen inches. The corollary to this fact is that all tidal ranges greater than eighteen inches must be due to something other than the gravitation of the moon and sun.**^(d)

Before we begin a detailed study of the natural forces that explain all tide tables, let's fast-forward from the British Admiralty to the National Oceanographic and Atmospheric Administration for one more glimpse of what's in store. When the decision was made to drill for oil in Alaska, the United States government wisely decided to prepare very precise tide tables for Prince William Sound and its tributaries, where the tankers would remove the hazardous cargo. The computers were programmed with 114

^(d)The scientific fact that the lunar and solar gravitation can cause only 18 inches of vertical displacement of the earth's oceans is true for a stationary planet (not rotating) which has a featureless surface (no continents). This is what the Equilibrium Theory predicted, but it is only true in the center of the deep oceans, and it does not hold up at the continental coasts.

independent variables which have influence on the tides — that is, the gravitation of the moon and sun, and 112 other important constituents necessary for these precise tide tables.

In the calculation of the standard tide tables issued annually to the boating public, The National Oceanographic and Atmospheric Administration includes 37 major independent constituents which have a measurable influence on the earth's tides. Again, the gravitation of the moon and sun, and 35 other factors. Before you conclude that the Prince William Sound tables were unnecessarily meticulous, you should know that by including 114 variables they ignored 282 other known influences on the earth's tides. The total is 396, according to the prominent oceanographer, Dr. Arthur Doodson.^(e) These other factors are, of course, the “how and why” the patterns of the tides are as variable as the instruments in a symphony orchestra. Likewise, these factors are the “something other” than gravitation that causes all tides greater than 18 inches.

This book does not require 396 chapters. You can make sense of every tide table you will ever encounter using high-school science and without mathematical equations. Incidentally, you can stay off of the rocks or plan a fishing day without understanding the tables. By the same token, you can cross the Pacific Ocean even if no one aboard knows how to repair a diesel engine. But it is better to know; and there is an inherent satisfaction and pleasure that comes from mastering something as primal as the tides. I don't know why. It's just human nature.

^(e)Dr. Arthur Doodson dedicated his life to the practical application of science in the prediction of the tides. He was the oceanographer chosen to predict the tides for the D-day invasion during World War II.

Supplement to chapter one:

You may be thinking, “Didn’t Einstein figure out gravitation?” Well, Einstein said that gravitation was a distortion of the space–time continuum, where straight lines were curved lines, and the difference between velocity and acceleration was relative to the observer. Sorry you asked?

Actually, it is possible for us to gain some understanding of what Einstein was talking about. He wanted his revolutionary theories to be accessible to laymen, and he wrote about them in plain English. For example: A man is inside an elevator, which is accelerating upward at 12 feet/sec./sec. Another man shoots a bullet parallel to the ground, and the bullet passes through the elevator. The bullet enters the east wall of the elevator six feet above the floor. Because the elevator is accelerating upward, the bullet exits the west wall of the elevator two feet above the floor.

The question is: “What is the path of the bullet through the elevator — straight or curved?” The answer is that this depends on whether the observer is inside the elevator or outside. In other words, the path of the bullet can only be measured relative to an observer (relativity).

An observer outside the elevator would say that the bullet traveled in a straight line with a constant velocity, while the elevator accelerated through its path. A scientific observer inside the elevator would observe the bullet traveling in a curved path, accelerating toward the floor at 12 feet/sec./sec.

Is the bullet accelerating toward the elevator floor, or not? The answer is absolutely yes. Is this because the elevator floor pulls on the bullet from a distance? Absolutely not, but that is the only rational conclusion for an observer inside the elevator.

The point of Einstein's "thought experiment" (his term for this exercise) is that perhaps objects appear to be attracted toward each other according to the Law of Gravitation, because we observe these interactions within *our* framework of three dimensional space plus a dimension of time; but, there are other possibilities.

The idea that gravitation and magnetism can cause objects to act on other objects from a distance is a very peculiar idea. Einstein is saying that perhaps objects don't act on other objects from a distance at all; perhaps the nature of space and time make it appear to happen, just as the acceleration of the elevator creates the frame-of-reference of the observers inside. In other words, perhaps the nature of time and space constrains all objects with mass to interact with each other in a way that appears to be due to "action from a distance." This sort of explanation does not really provide an understanding of gravitation, but it does provide some insight into the nature of such a cosmic problem.