HYDROGRAPHIC SERVICES
HYDROGRAPHIC SURVEY TRAINING FACILITY

MODULE 5: WATER LEVELS & FLOW

TIDAL THEORY

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ISSUED	:	JUNE 2006
CHECKED	:	JUNE 2006
REVISED	:	
INTENDED FOR	:	BHSO & SURVEY RECORDER PART 3

LIST OF CONTENTS

REFERENCES

AMHS Vol 2 Ch 2.
Admiralty Manual of Tides.
Admiralty Manual of Navigation Vol 1.
Admiralty Tide Tables Vol 1 (European Waters).

1. INTRODUCTION

1.1 At most places on the coast it is possible to detect a periodic rise and fall of the sea level, varying from a few millimetres (eg in parts of the West Indies) to 15 metres or more (eg Avonmouth, England).

1.2 The change in sea level is caused as water is added or removed from an area due to the effects of tides.

Tides. Tides are periodic vertical movements of water on the Earth's surface.

Tidal Streams. In rising and falling the tides are accompanied by periodic horizontal movements of the water called tidal streams.

1.3 Tides are caused by the gravitational pull of heavenly bodies on the Earth and the water over the Earth. The magnitude of the pull is defined in Newton's *Universal Law of Gravity*. The two heavenly bodies having the greatest effect are the Sun and Moon, other heavenly bodies are too small or too far away to exert any appreciable effect.

2. NEWTON'S LAWS OF MOTION AND GRAVITY

2.1 There are 3 Laws of Motion and one of Gravity.

<u>1st Law</u> Every body continues in a state of rest or uniform motion in a straight line unless acted upon by an external impressed force.

<u>2nd Law</u> When a body is acted upon by an external force, its acceleration is directly proportional to that force, and inversely proportional to the mass of the body, and acceleration takes place in the direction in which the force acts.

<u>3rd Law</u> Action and reaction are equal and opposite.

<u>Law of Gravity</u> Any two particles of matter attract one another with a force directly proportional to the product of their masses and inversely proportional to the square of the distance between them. This law may be expressed as:

$$F \propto \frac{m_1 \ m_2}{d^2}$$

where F is the force, m_1 and m_2 the masses of the two bodies and d their distance apart.

2.2 It is Newton's Law of Gravity which concerns us most. Although the Sun has a greater mass than the Moon, its gravitational effect on the Earth is less because it is further away. The relative sizes of the effects of Sun and Moon are approximately 5:11.

3. THE EARTH-MOON SYSTEM

3.1 The Earth and Moon may be considered as forming an independent system rotating around a common centre of gravity known as the Earth-Moon barycentre (*figure 1*). The barycentre lies on a line joining the centres of gravity of the Earth and Moon at a point about 1000 miles below the Earth's surface.

3.2 The Earth describes a very small ellipse about the Earth-Moon barycentre, while the Moon describes a much larger ellipse about the same barycentre, taking 27.5546 mean solar days (*Anomalistic Period*) to complete one orbit.

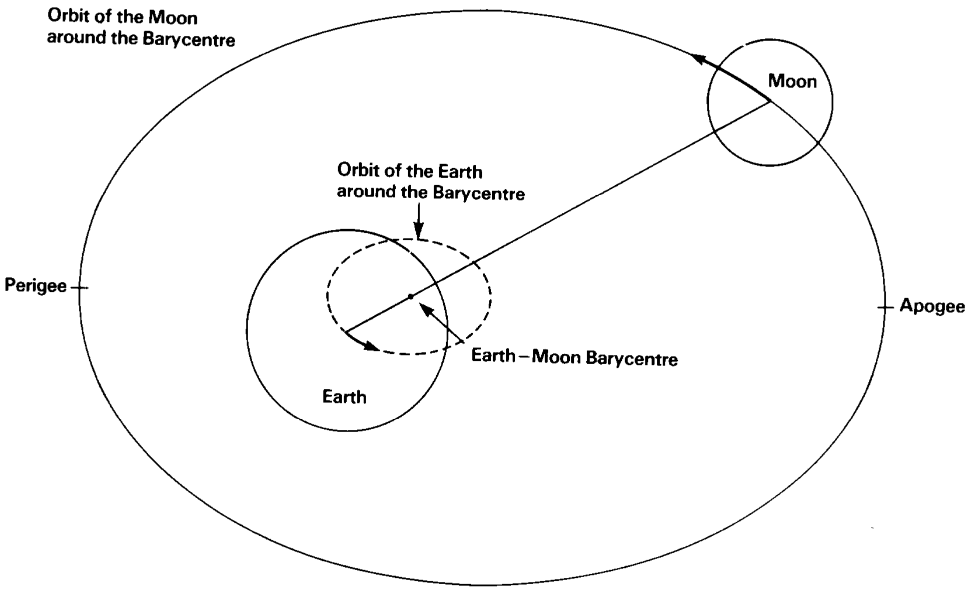

Figure 1. The Earth-Moon system.

4. THE GRAVITATIONAL (ATTRACTIVE) FORCE

4.1 In order to simplify matters, first consider only the Earth and the Moon, with the Moon situated directly over the equator, ie with a declination of 0°. To keep the Moon in orbit around the Earth there must be a force continually attracting it towards the Earth. This is required by the 1st Law of Motion and, in accordance with the 3rd Law, there must be an equal and opposite force acting on the Earth.

4.2 The gravitational force of the Moon acts on the Earth as a whole, affecting the structure of the Earth itself, on the atmosphere and on the water on the Earth's surface. Accepting the Earth as a solid object, this force will act at the centre of gravity of the Earth and can be given a value *G*. Again, for simplicity, assume at this stage that the Earth is a smooth sphere, completely covered with water and there is no friction between the sea and the Earth. At the North and South Poles the distance to the Moon is the same (for all practical purposes) as that from the centre of gravity. Hence the gravitational force exerted by the Moon at these positions and at all points on the meridians at right angles to the Earth/Moon line will be the value *G*.

4.3 In *figure 2*, $M\ M_1$ is the diameter of the Earth on a line joining the centres of the Earth and Moon. Point *M* on the Earth's equator lies directly under the Moon and is known as the *sublunar point*. M_1 is on the opposite side of the Earth and is known as the *antipode*. At *M* the distance to the Moon has decreased; thus, the gravitational force acting at *M* is increased by a small amount δG. At a point M_1, on the equator on the far side from the Moon, the gravitational force has decreased by a similar (though not identical) amount. Thus, the total gravitational force acting at *M* is $(G + \delta G)$ and that at M_1 is $(G - \delta G)$.

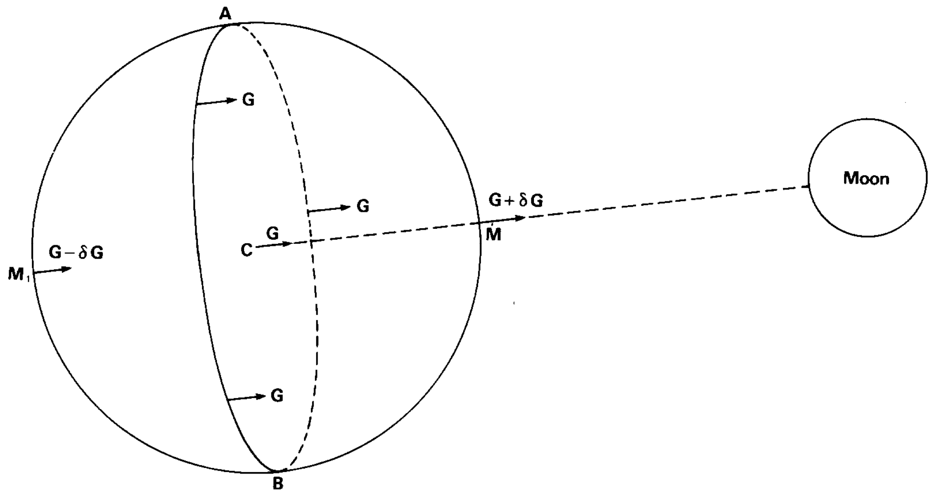

Figure2. The gravitational force of the Moon acting on the Earth.

4.4 To consider the movement of the sea over the Earth (the cause of tides), there is a need to take into account the differences in gravitational attraction at various points over the Earth. This can be illustrated by subtracting the value of *G*; the results are shown in *figure 3* overleaf.

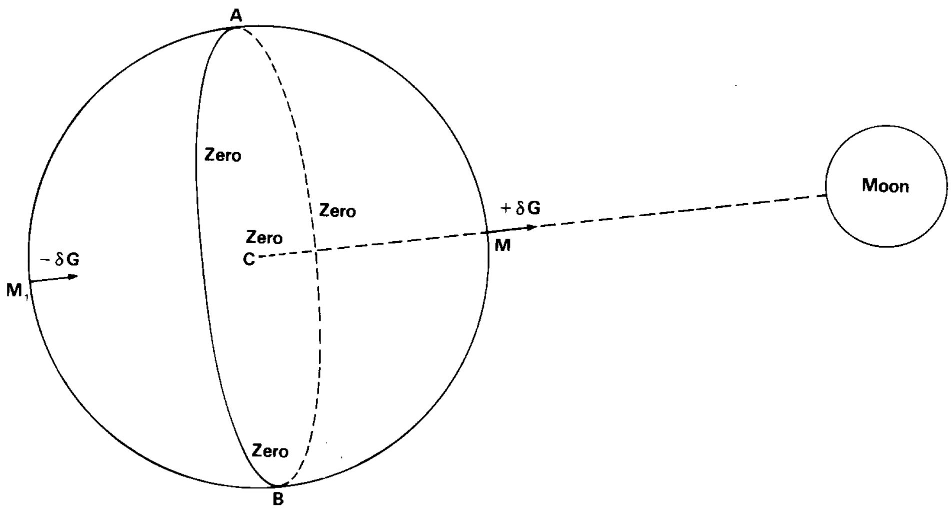

Figure 3. The differential gravitational force on the Earth's surface.

4.5 The force acting on the waters may be considered as the <u>difference</u> between the gravitational force G, acting at the centre of the Earth, and the actual force anywhere else on the Earth's surface. There is no difference between the force acting on the solid Earth and units of sea at the North and South Poles nor at any point on the meridian at right angles to the Earth/Moon line (the meridian A/B in *figure 3*). It will be observed that, at the antipode M_1, the *differential gravitational force*, is negative, ie $-\delta G$. This is equivalent to saying that the differential force at M_1 is positive but acting in the opposite direction, as shown in *figure 4*. At some other point D on the Earth's surface (*figure 4*), the differential force acting on the waters at this point must be somewhere between δG and *zero*. If D is ϕ° above (or below) the sublunar/antipodal plane, then the differential gravitational force at D is equal to $\delta G\cos\phi^{\circ}$. Similarly, at D_1 the force is also equal to $\delta G\cos\phi^{\circ}$, but acting in the opposite direction.

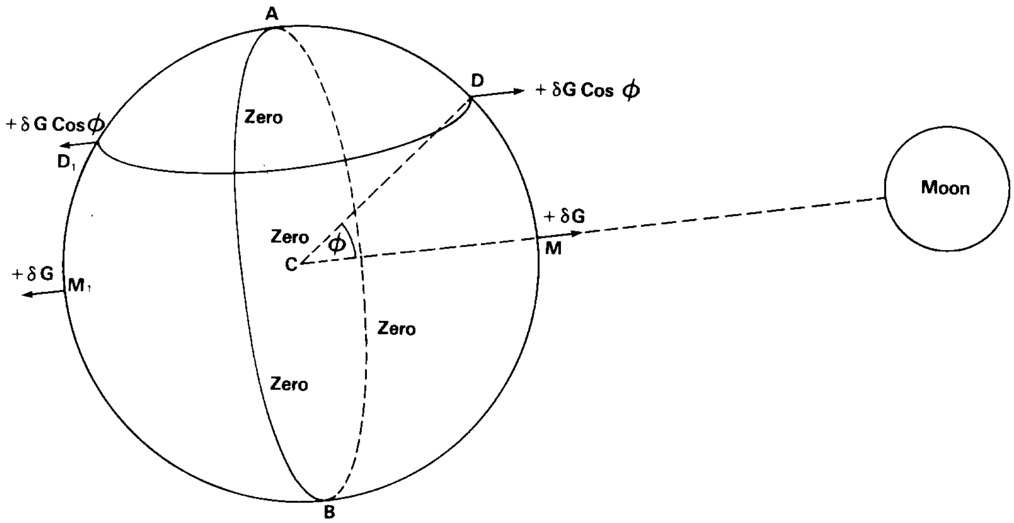

Figure 4. The differential gravitational force on the Earth's surface.

5. THE TIDE-RAISING (TRACTIVE) FORCE

5.1 The next step is to consider how these force differences affect the water relative to the Earth. If we continue to assume that the entire surface of the Earth is covered with a uniform layer of water, these differential forces may be resolved into a *vertical component (F_V)* at right angles to the Earth's surface and a *horizontal component (F_H)* directed towards the sublunar or antipodal points, as shown in *figure 5*.

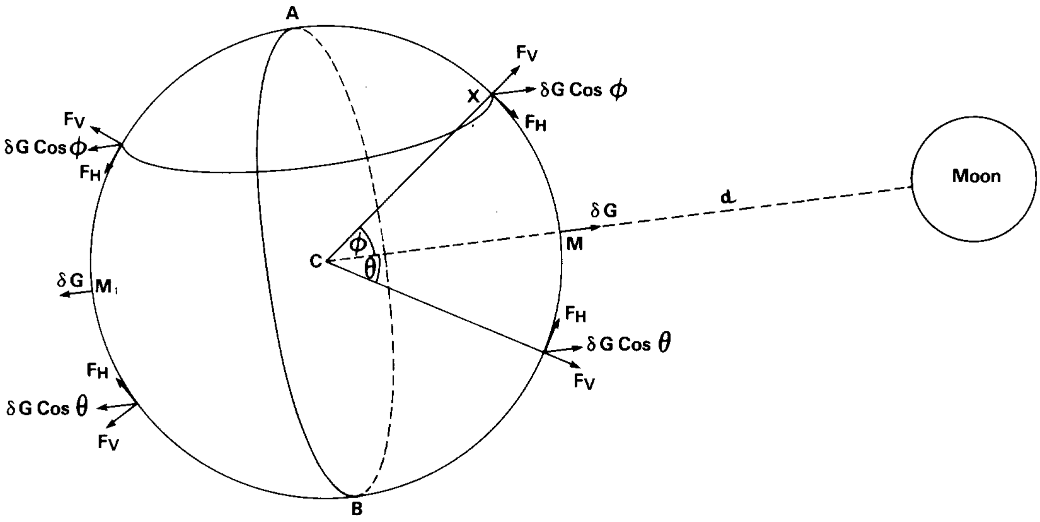

Figure 5. Resolution of the different forces.

5.2 The *vertical force* is only a very small portion of the Earth's gravity, such that the actual lifting of the water against gravity is infinitesimal (for a ship weighing 30,000 tonnes the apparent reduction in weight due to the total differential force amounts to less than 3kg). However, it is the similarly small *horizontal component* which produces the tides, by causing the water to move across the Earth and pile up at the sublunar and antipodal points until an equilibrium position is found. The *horizontal component* of the *differential gravitational forces* is known as the tide raising or tractive force. Its magnitude at a given point *X* (*figure 4*), may be expressed as:

$$F_H \;\; \alpha \;\; \frac{3\ m_2 r\ \sin\ 2\phi}{2d^3}$$

where: F_H is the magnitude of the tide-raising (horizontal) force.
m_2 is the mass of the Moon.
r is the radius of the Earth.
d is the distance between the Earth's and Moon's centres.
ϕ is the angle at the centre of the Earth between the line joining the sublunar and antipodal points, and the line joining the Earth's centre and *X*.

The tide-raising force caused by the Moon varies directly as the mass of the Moon and the radius of the Earth, and is inversely proportional to the *cube* of the distance between Earth and Moon.

5.3 The effect of the tide-raising (tractive) force is shown in *figure 6*. The force is zero at the sublunar and antipodal points *M* and M_1 and along the great circle *AB* the plane of which is perpendicular to $M\ M_1$. The maximum tractive force may be found along the small circles *EF* and *GH*, which are 45° from the sublunar point and antipode respectively.

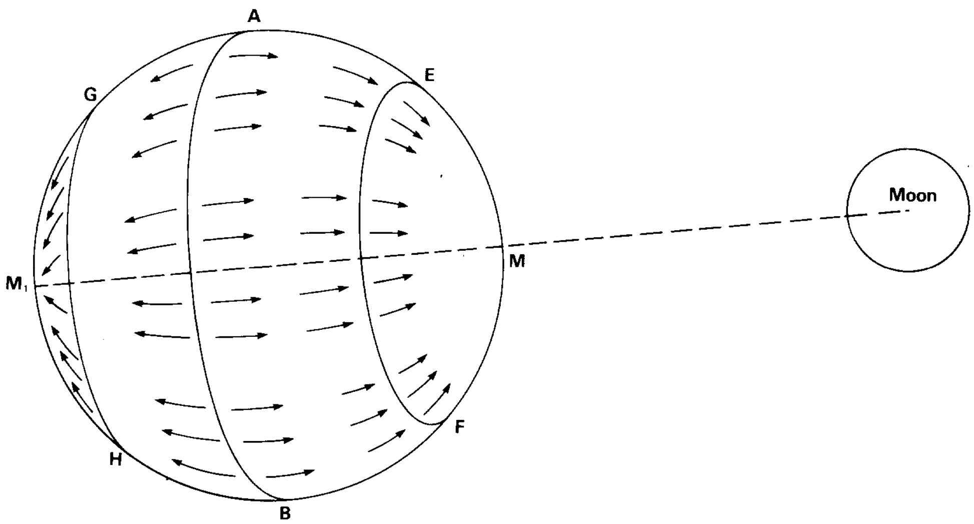

Figure 6. The effect of the tide-raising force.

5.4 Equilibrium is reached when the tides formed at the sublunar and antipodal points are at such a level that the tendency to flow away from them is balanced by the tide-raising force. The tide caused in these circumstances is known as the *lunar equilibrium tide* (*figure 7*), with a *high water* at *M* and M_1 and a *low water* at *A* and *B*.

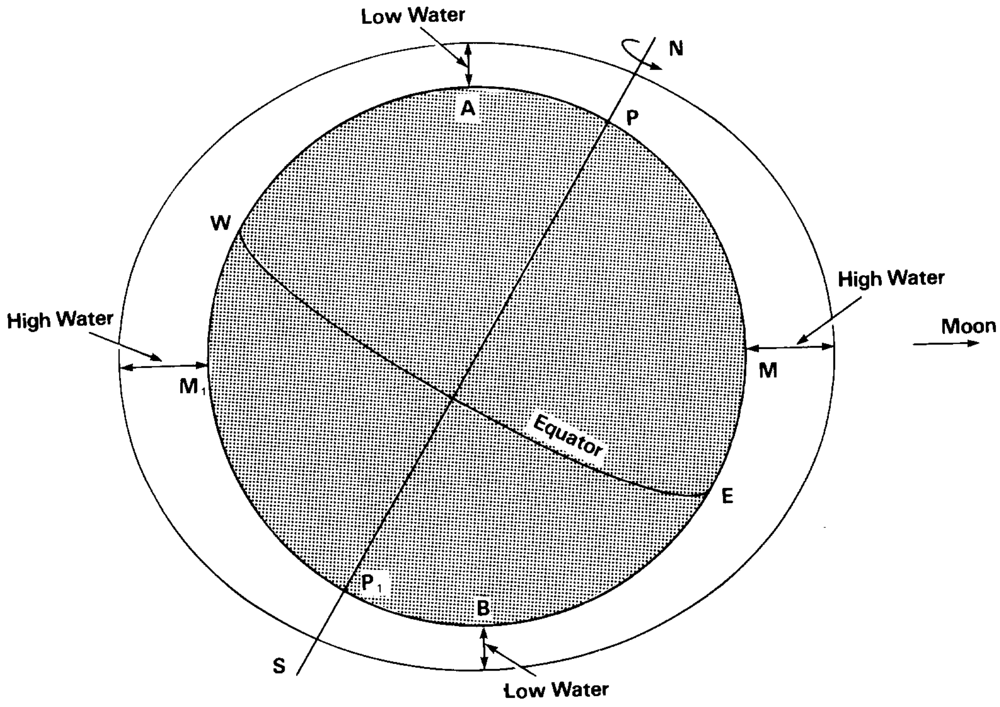

Figure 7. The lunar equilibrium tide.

6. EFFECT OF EARTH'S ROTATION

6.1 The tide-raising effect on the Earth when the Moon is above the Earth's equator ie declination 0°, is shown in *figure 8.*

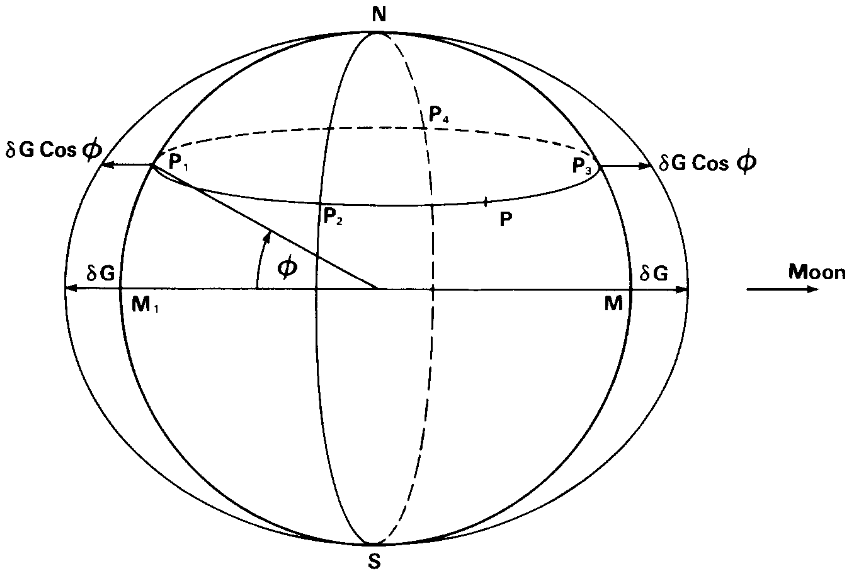

Figure 8. The effect of the Earth's rotation.

6.2 The Earth rotates relative to the Moon once every lunar day of 24 hours 50 minutes approximately and thus, during this period, an observer at point *M* will experience two high waters once every 12 hours 25 minutes, interspersed with two low waters also 12 hours 25 minutes apart. The range of this equilibrium tide at the equator is less than 1 metre.

6.3 When the Moon's declination is zero, its tide-raising force on the equator will be equal. At any other point *P* on the Earth's surface north or south of the equator, the tide-raising force will still be equal but not so great as at the equator and will vary approximately with the cosine of the latitude. The time intervals between successive high and low waters will still be the same as those on the equator, 6 hours 12½ minutes approximately.

6.4 Such tide-raising forces, producing two equal maxima and two equal minima tides per lunar day at equal time intervals, are termed semi-diurnal. When the Moon's declination is zero, the tide-raising forces are semi-diurnal for all latitudes. Typical tidal curves for observers at points *M* and *P* are illustrated in *figure 9*.

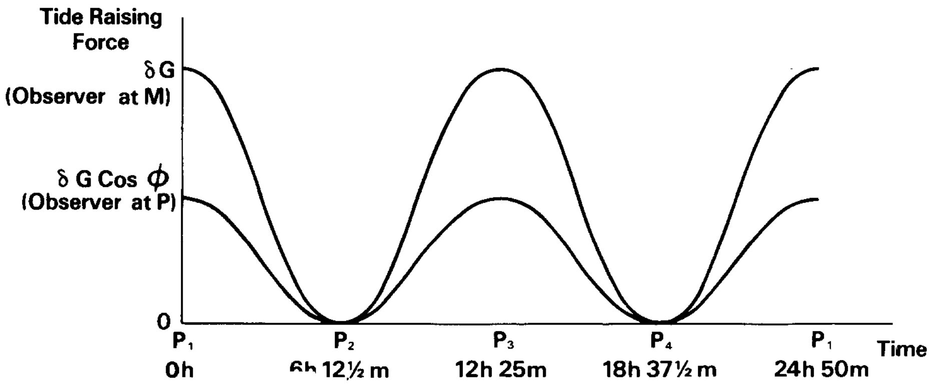

Figure 9. The lunar equilibrium semi-diurnal tide, declination 0°.

7. CHANGE OF MOON'S DECLINATION

7.1 The effect of changes in the Moon's declination is shown in *figure 10*. The maximum tide occurs as before at the sublunar and antipodal points M and M_1.

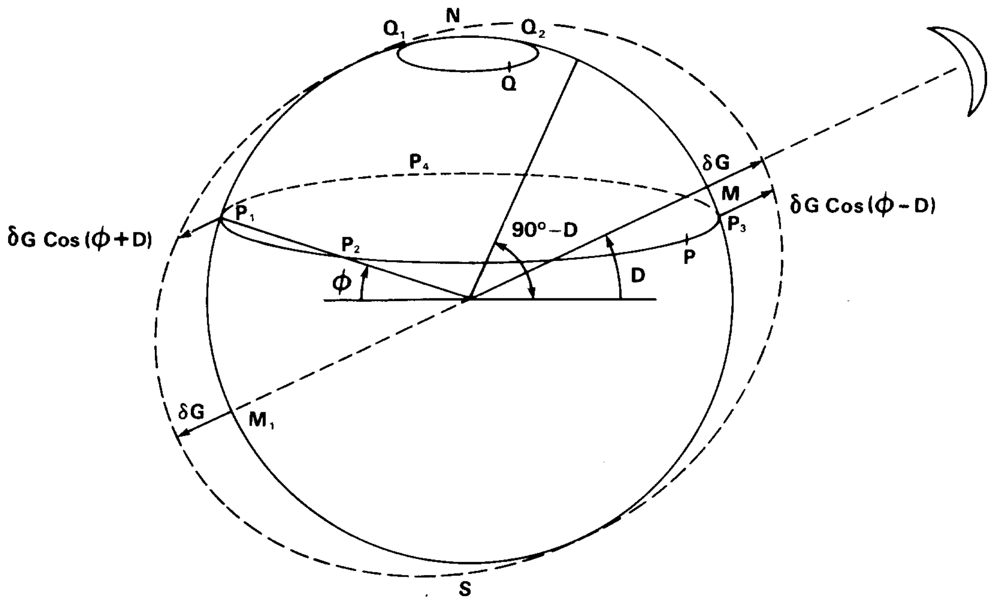

Figure 10. Effect of the Moon's declination.

7.1.1 At any point P on the Earth's surface, not only are the heights of successive high and low waters different, the time intervals also change, as the tidal curve in *figure 11* shows. This effect is known as the diurnal inequality.

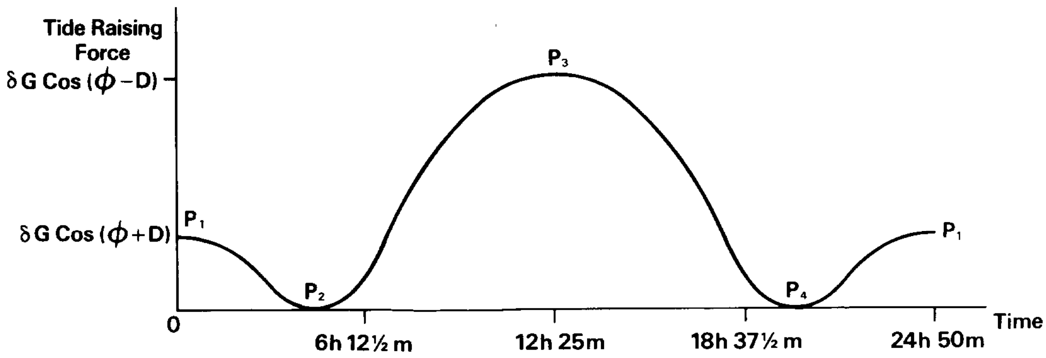

Figure 11. The diurnal inequality.

7.1.2 At another point, *Q*, on the Earth's surface (*figure 10*), where the latitude is greater than (90° minus the Moon's declination), there is only one high water and one low water every lunar day; this type of tide is called diurnal. A typical diurnal tidal curve is at *figure 12*).

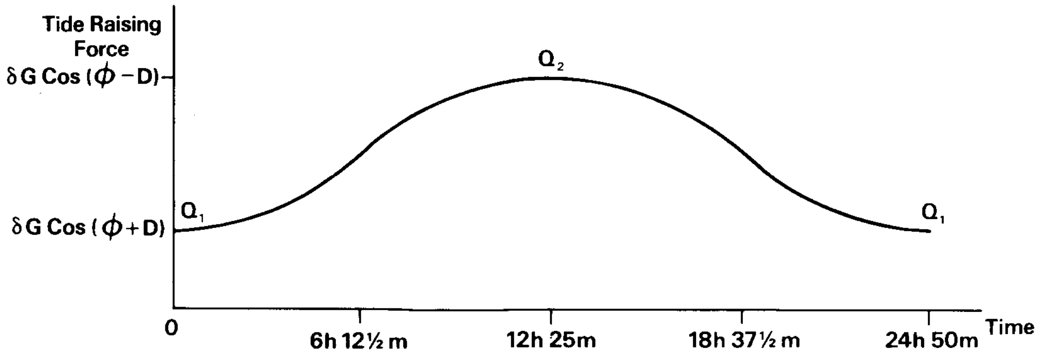

Figure 12. The diurnal tide.

7.2 The Moon's declination changes from a maximum north to a maximum south and back again once every 27.3 days approximately; thus, a similar effect on the tide caused by the Moon's declination alone will be experienced roughly every two weeks.

7.3 In summary it can be said:

At latitude 0° the tide is pure semi-diurnal.

Between the equator and (90° - Moon's declination)(up to about 65°) the tide is semi-diurnal but with a diurnal inequality until at:

A latitude equal to (90° - Moon's declination) the tide is purely diurnal.

From this latitude to the pole the tide remains diurnal but with diminishing amplitude until at:

The pole the tide remains unchanged throughout the day.

8. THE DISTANCE OF THE MOON

8.1 The Moon rotates around the Earth in an elliptical orbit once every 27.5546 mean solar days (*Anomalistic Period*). The tide-raising force is strongest when the moon is closest to the Earth, at its *perigee* (perigean tide). The tide-raising force is weakest when the Moon is furthest away, at its *apogee* (apogean tide), see *figure 1*. The points of perigee and apogee may be referred to collectively as "apsides".

8.2 The variation in the Moon's distance can cause a difference in the lunar tide-raising force of between 15% and 20%; thus tides at perigee are likely to be appreciably higher than those at apogee.

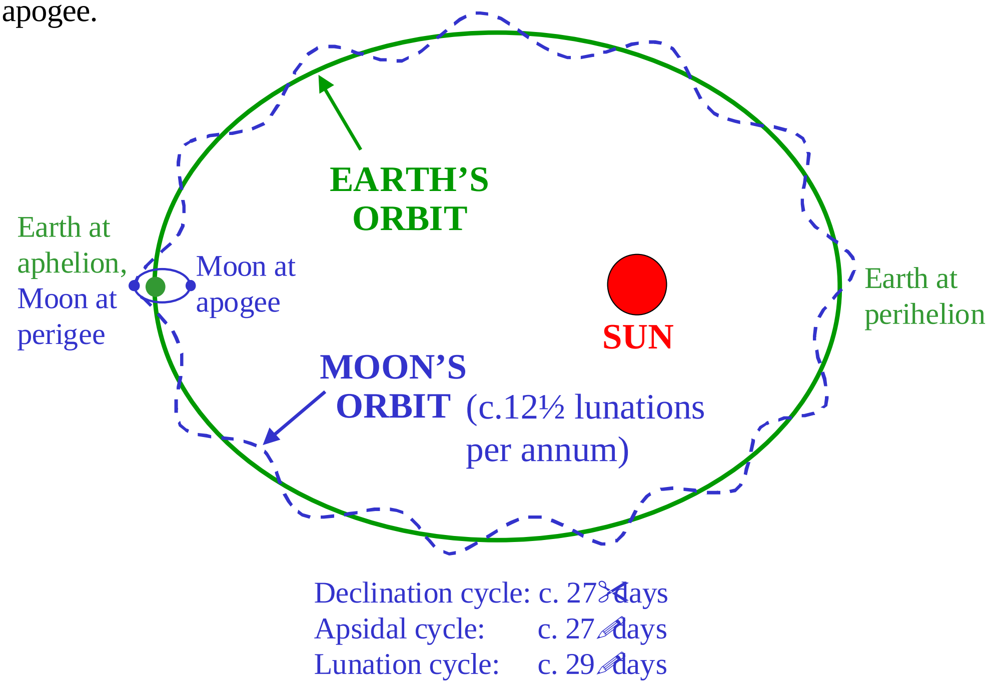

Figure 12a. The orbits of the Earth and Moon.

9. THE EARTH-SUN SYSTEM

9.1 The Earth and Sun may be considered as forming another independent tide-raising system. Although the Sun has a much greater mass than the Moon, the Sun's tide-raising force is nevertheless only about 45% that of the Moon. This is because the tide-raising force is inversely proportional to the *cube* of the distance.

9.2 The tide-raising effects of the Sun on the Earth are similar to those of the Moon, though of a lesser magnitude. Thus, the tides caused by the Sun will vary according to:

9.2.1 *The Earth's rotation*. The Earth rotates about its polar axis, from west to east, within a period of 24 hours. Thus, the solar equilibrium semi-diurnal tide, when the Sun's declination is zero, will have two high waters 12 hours apart, interspersed with two low waters also 12 hours apart. The time interval between successive high and low waters will be 6 hours.

9.2.2 *Change of Sun's declination*. The *ecliptic* is the apparent path of the Sun through the heavens, as seen from Earth. The plane of the ecliptic is inclined at an angle of 23° 27′ to the plane of the celestial equator (*figure 13*). This angle is known as *the obliquity of the ecliptic* and is decreasing by approximately ½″ per year.

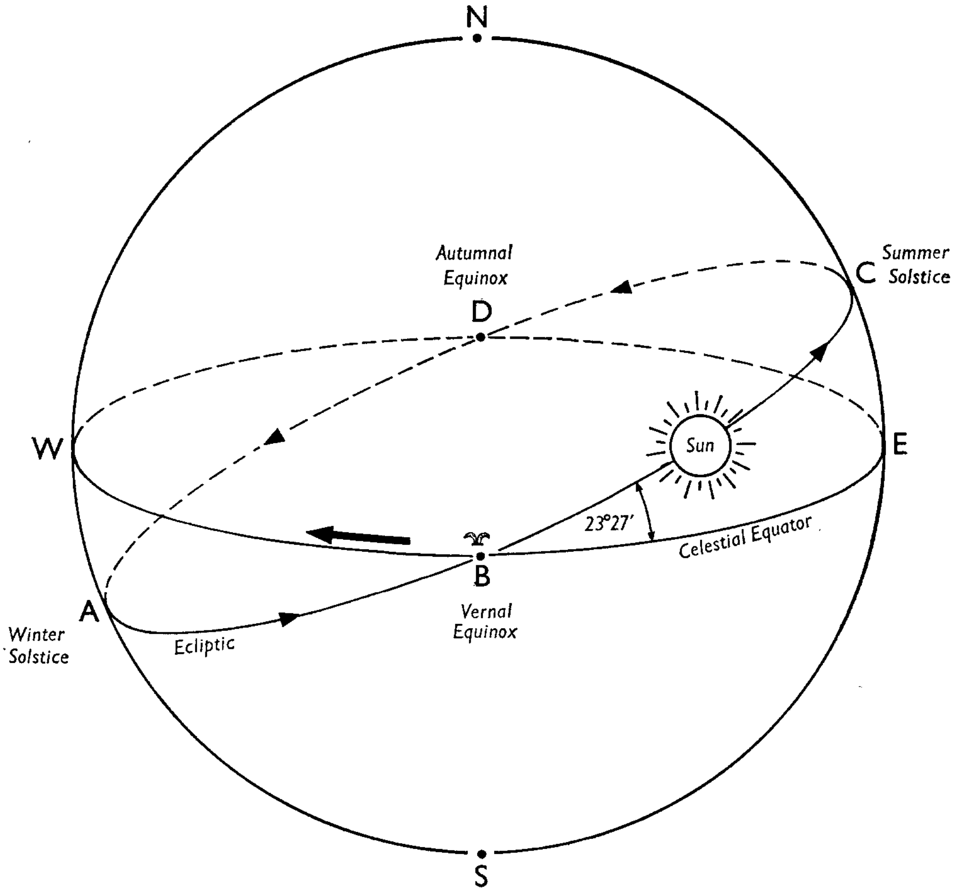

Figure 13. Obliquity of the ecliptic.

9.2.2.1 *Vernal Equinox.* The point where the ecliptic crosses the equator from south to north is called the First Point of Aries (γ), or the *Vernal Equinox*. The Sun passes through this point on about 21st March each year. For all practical purposes the Sun's apparent orbit is fixed in space. The position of γ does, however, move around the celestial equator, one revolution taking about 26,000 years (*The Precession of the Equinoxes*).

9.2.2.2 *Autumnal Equinox.* The *Autumnal Equinox* (about the 21st September) is the point where the ecliptic crosses the celestial equator north to south, 180° away from the Vernal Equinox. The apparent motion of the Sun is such that a complete revolution of the ecliptic is made in a mean solar year of 365.2422 mean solar days.

10. EQUINOCTIAL AND SOLSTITIAL TIDES

10.1 When the declinations of the Moon and the Sun are the same, the tide-raising force will clearly be acting more in concert than when the declinations differ.

10.2 Equinoctial Tides. At the *equinoxes* in March and September, when the declinations of Moon and Sun are *both zero*, the *semi-diurnal luni-solar* tide-raising force will be at its *maximum*, thus causing the *equinoctial tides*. At these times, where semi-diurnal tides are concerned, spring tides higher than normal are experienced.

10.3 Solstitial Tides. At the *solstices* in June and December, when the declinations of Moon and Sun are *both at maximum*, the *diurnal luni-solar* tide-raising force will be at its *maximum*, thus causing the *solstitial* tides. At these times, diurnal tides and the diurnal inequality are at a maximum.

11. THE LUNAR ORBIT

11.1 The apparent path of the Moon oscillates somewhat about the ecliptic (*figure 14*). Observation shows that while the Moon completes a revolution, measured along the ecliptic, in a period of 27.3216 mean solar days (the *Sidereal* period), the cycle of oscillation north and south of the ecliptic is completed in 27.2122 mean solar days (the *Draconite* period). The ascending node (the point where the Moon crosses the ecliptic from south to north) thus travels westwards (backwards since the Moon and Sun travel eastward) by 0.1094 day in every 27.2122 days (or 0.053° per mean solar day). This is called the *regression of the Moon's nodes*. A complete regression cycle takes 18.61 years.

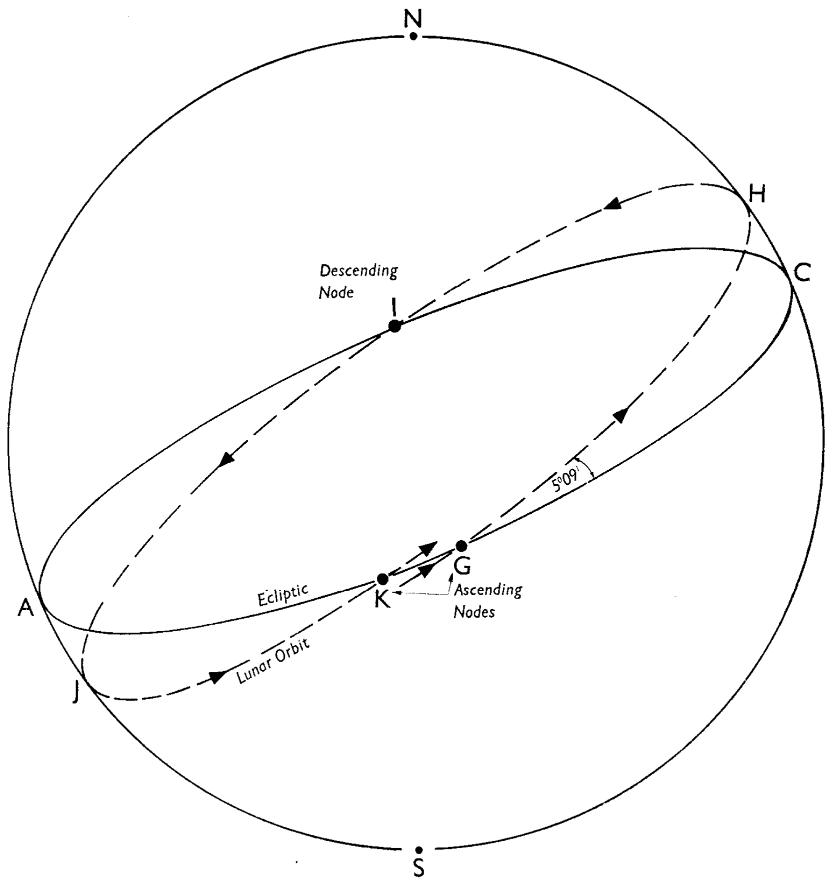

Figure14. Regression of the nodes.

11.2 Furthermore, it is known from observations that the lunar orbit is in a plane which is inclined to the plane of the ecliptic by a near-constant angle of 5° 9′ (variations are of the order 5° 0′ to 5° 17½′). Thus from *figure 14,* the maximum declination of the Moon (measured from the equator) will occur when the ascending node is at the Vernal Equinox, when the north declination will rise during the following month to 5° 9′ above the ecliptic (23° 27′ + 5° 9′ = 28° 36′). Two weeks later, the southerly declination will have an equal value.

11.3 If however, the descending node is at Vernal Equinox (*figure 14*), which occurs some 9¼ years later, the maximum declination (north or south) will not be more than (23° 27′ - 5° 9′ = 18° 18′). For example, in 1978 the Moon's declination varied between 18° north and south, whereas in 1987 it varied between 28½° north and south. The effects of this are particularly important when the tidal predictions for tidal ports are considered. The declination values will recur at intervals of 18.61 years, and therefore, any tidal variations associated with lunar declination will have a regular variation with a period of 18.61 years.

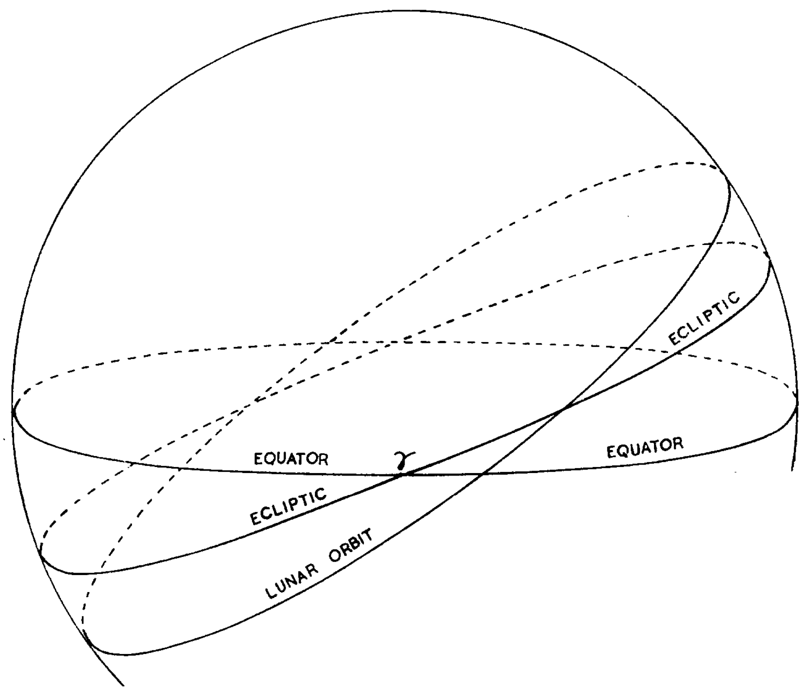

Figure 15. Ecliptic and lunar orbit.

11.4 *The distance of the Sun*. It takes the Earth approximately 365¼ days to complete its elliptical orbit around the Sun. *Perihelion*, when the Earth is closest to the Sun, occurs about 2nd January, and *Aphelion*, when the Earth is furthest away, is about 1st July. Thus, the Sun's tide-raising force will be at its maximum in January and its minimum in July. The variation in this force is, however, very small indeed, of the order of 3%.

12. THE EARTH-MOON-SUN SYSTEM

12.1 When the tide-raising effects of the Moon and Sun are combined, they sometimes work together and sometimes against each other.

12.2 Spring Tides. Twice every lunar month, the Moon and Sun are in line with each other and with the Earth (*figure 16*).

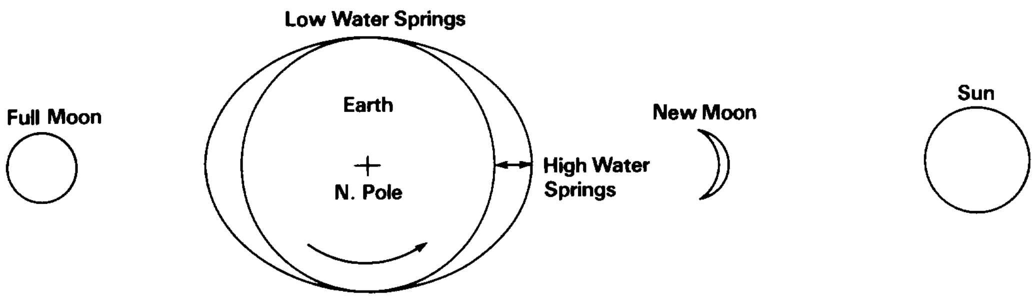

Figure 16. Spring tides.

At new Moon, the Moon is passing between the Sun and the Earth; the Moon and Sun are said to be in *conjunction*. About 14.75 days later, at full Moon, the Earth is between the Moon and Sun, which are now acting in *opposition*. Both these situations are known as *Syzygy*. The net result in both cases is a *maximum* tide-raising force, producing what is known as a *spring tide*. At springs, therefore, higher high waters and lower low waters than usual will be experienced, these occurring at about the time of new and full Moon (see paragraph 10.5).

12.3 Neap Tides. Twice every lunar month, about every 14.75 days, the Moon and Sun are at right angles to each other (*figure 17*). At these times the Moon and Sun are said to be in *quadrature*.

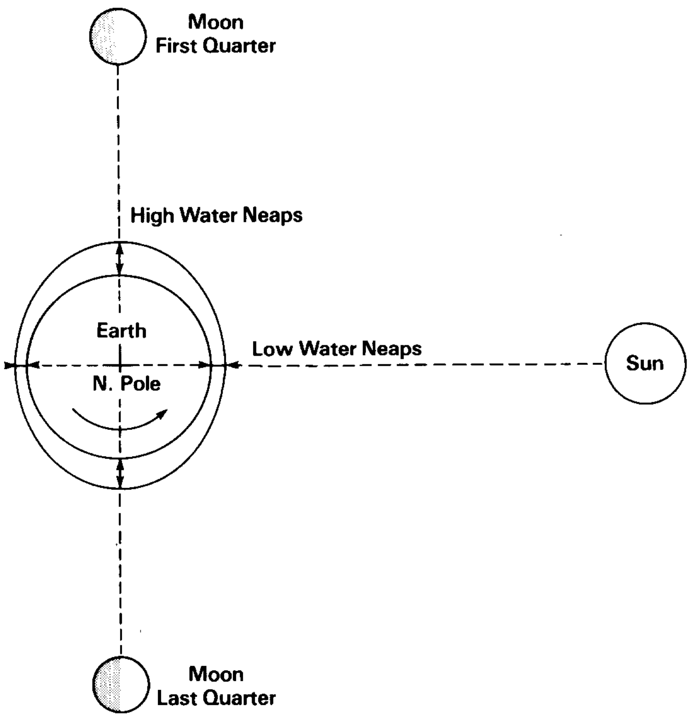

Figure 17. Neap Tides.

This situation occurs when the Moon is in the first and last quarters, and at this time the lunar and solar tide-raising forces are working at right angles to each other. The net result in both cases is a *minimum* tide-raising force, producing what is known as a *neap tide*. At neaps, lower high waters and higher low waters than usual will be experienced, these occurring at about the time of first and last quarters.

12.4 Frequency of springs and neaps. The *lunar month*, or period between successive new Moons is 29.5306 mean solar days; this is called the *Synodic period*. From the foregoing it may be seen that two spring tides will occur each lunar month interspersed with two neap tides; the interval between successive spring and neap tides being about 7½ days. This phenomenon is found at many places in the world, although other inequalities sometimes occur to alter these timings.

12.5 Spring and neap tides usually follow the relevant phases of the Moon by 2 or 3 days. This is because there is always a time-lag between the action of the force and the reaction to it, caused by the time taken to overcome the inertia of the water surface and friction. The period when spring tides occur after New and Full Moon is quoted in Admiralty Tide Tables on the page preceding daily high and low waters listings.

12.6 Spring and neap tides will occur at approximately the same time of day at any particular place, since the Moon at that time is in a similar position relative to the Sun. For example, at Devonport in 1996, low water Springs occurred at times ranging from 1237 hours to 1319 hours throughout the year, and high water Springs occurred at times ranging from 1843 hours to 1922 hours.

13. SUMMARY OF TIDAL EFFECTS

The following list gives the main tidal effects:

Cause of Change	Time Scale	Tidal Effect
Moon's Longitude	12 hr 24 min	Semi-diurnal
Sun's Longitude	12 hr	Semi-diurnal
Moon's Declination	13.6 days	Diurnal
Sun's Declination	182.6 days	Diurnal
Moon's Distance	27.5 days	Minor variations
Sun's Distance	365¼ days	Minor variations
Regression of the the nodes	18.61 years	Minor variations

14. THE REAL TIDE

14.1 The motions of the Moon and the Sun are well known and their mathematical relationships can be used to predict components of the tide-raising force. In practice, the tides may differ considerably from the luni-solar equilibrium tide given by the pure theory above. There are many effects which will distort the tidal predictions given by theory alone. These include:

a. Natural resonance of the water body.

b. Friction.

c. Land masses and shallow water.

d. Coriolis effect and derived wave types.

e. Weather.

14.2 The theory of the Equilibrium Tide is not wasted as it describes the relative sizes and timing of the range of components that make up the tide-raising force that drive the sea to produce variations in tidal height.

15. NATURAL RESONANCE

15.1 The forces involved in the equilibrium theory are extremely small and, even allowing for the very small amount of friction that will occur in the sea, only comparatively small tidal movements would be experienced were it not for the phenomenon of *resonance*.

Every body of water of any size whatever has a natural frequency of oscillation. This frequency is dependent on the size of the body of water (or, more precisely, on its east-west dimension). When this natural frequency of oscillation of a body of water is the same, or very nearly the same, as the frequency of an imposed force, resonance will occur and very large movements result from very small applied forces.

The natural period of oscillation is the decisive factor in determining whether the water responds to the diurnal or the semi-diurnal tide-raising force or a mixture of the two. Hence, tides in practice are often referred to as being semi-diurnal, diurnal or mixed.

15.2 <u>Semi-Diurnal</u> The *Atlantic* tends to be more responsive to semi-diurnal forces; thus, tides on the Atlantic coast and around the British Isles tend to be *semi-diurnal* in character (two high waters and two low waters per day) and *are more influenced by the phases of the Moon* than by declination. Large tides occur at springs near full or new Moon. Small tides occur at neaps near the quarters. The largest tides of the year occur at springs near the equinoxes when the Sun and Moon are on the equator. In Nova Scotia, the Bay of Fundy has a natural resonance period of 12½ hours, exactly coincident with the semi-diurnal cycle, and experiences the world's greatest tidal range.

15.3 <u>Diurnal</u> The *Pacific* is on the whole more responsive to the diurnal forces, and so tides in this part of the world tend to have a large *diurnal* component. In these areas, the *largest tides are associated with the greatest declination of Sun and Moon*, that is, at the summer and winter solstices. Areas in the SW Pacific off New Guinea, Vietnam, in the Gulf of Tonking and in the Java Sea, are predominately diurnal.

15.4 <u>Mixed</u> Mixed tides, where the diurnal and semi-diurnal tide-raising forces are both important, tend to be characterised by a large diurnal inequality. This may be apparent in the heights of successive high waters, low waters or both. Occasionally the tide may even be diurnal. Such tides are common along the Pacific coast of the United States, the east coast of West Malaysia, Borneo, Australia and the waters of SW Asia.

15.5 As bodies of water, the Mediterranean Sea and the Baltic are too small to enable any appreciable tide to be generated. The Strait of Gibraltar is too restricted to allow the Atlantic tides to have any appreciable effect other than at the extreme western end. In the Mediterranean the maximum tides are to be found in the Adriatic, where they are predominately mixed, with a diurnal inequality at high and low water. The range may exceed 0.5 metre in several places, but is rarely greater than 1 metre.

16. FRICTION

16.1 As with all fluids, there is internal drag between water molecules. Additionally, when water flows over sediment lying on the seabed, there is frictional drag between the water and the sediment. The influence of the friction extends upwards some way towards the surface of the water. The effect of this friction is to slow the water flow so that the actual speed of the water is much greater than that occurring near the seabed. The lower part of the flow which experiences frictional retardation is known as the boundary layer. In the sea the boundary layer normally extends between 1m and 10m above the seabed but in shallow water it may well occupy the whole water depth.

17. LAND AND SHALLOW WATER

17.1 Land Interposition and shape of various land masses, with local conditions of resonance, will affect the tidal characteristics, to the extent that the theoretical characteristics are entirely meaningless (eg semi-diurnal tides off North Cape, Norway, above 65°N).

17.2 Shallow Water Effect A further complication arises when account is made of the depth of the sea. When a wave travels into shallow water its shape is changed; this can be seen when waves run in on to a shelving beach, as illustrated in *figure 18*. A wave produced by tide-generating forces will be regular in shape in the open ocean. In shallow water noticeable effects occur due to the friction between the sea and the sea-bed and the restrictions due to complex shapes of land masses. In general, friction causes a distortion of the tidal curve from its basic sinusoidal shape, the curve steepens and the circular motion of the water particles becomes elliptical. As waves approach the shelving shore, orbital motion under each wave becomes flattened to an ellipse, and the wave slows down. Crests pile up and eventually break to form surf. This is possible in any area where depths are less than 100 metres.

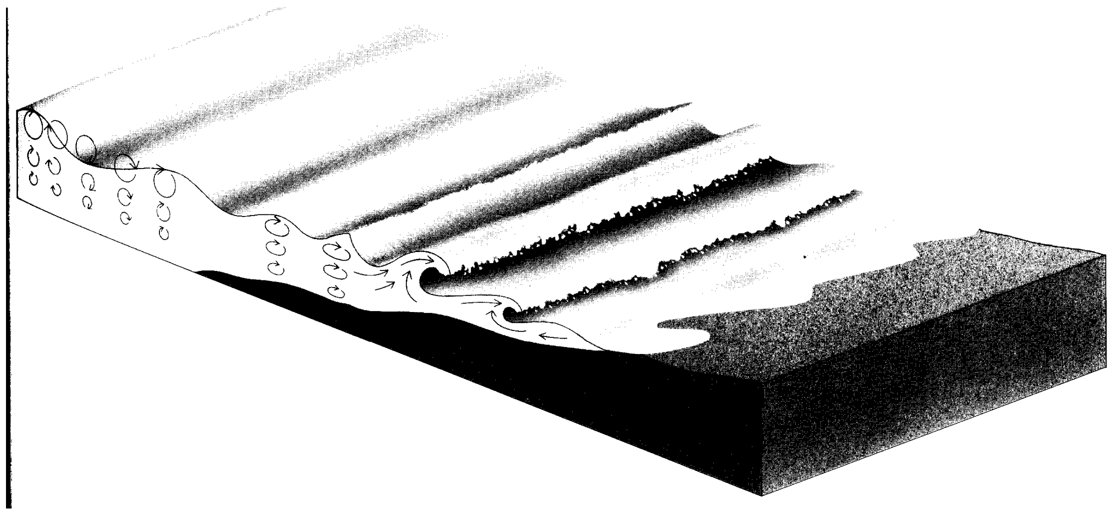

Figure 18. Shallow water effect.

As the incoming tide travels it encounters land forming river estuaries. The amplitude (height) of the tidal wave increases as it travels up an estuary, water is forced from a wide entrance up the narrower reaches of the river, giving distortions in the tidal heights. These distortions can become of great importance and result in a very large tides such as those found in the Bay of Fundy in Nova Scotia, the Severn Estuary and around the Channel Islands. Observations of these distortions can be analyzed and introduced into tidal predictions by the use of further curves which are direct multiples of the basic tidal curves or which have frequencies which are obtained from the addition or subtraction of the basic frequencies.

17.3 Bores Extreme cases of shallow water effects can be found when a tide with a large range is funnelled into a river or estuary with a steeply shelving bottom, giving rise to a phenomenon known as a *bore* (or eagre). It will usually occur at low water springs. The tide rises rapidly and suddenly, producing a wall of water which moves up the channel over the rapidly shelving bottom. The wave front is steep and in some cases vertical; it may vary in height from 0.25 metre to 5 metres. This front advances up the river, usually against the last traces of the ebb stream, at a speed of anything from about 3 to 20 knots. It may or may not break. Behind it the water level continues to rise steeply, and half-tide level may be reached in less than half an hour. Bores are experienced in the Seine and Severn, and many other places around the world.

17.4 At certain places, shallow water effects are such that more than two low waters or two high waters may be caused in a day.

17.4.1 At Portland, the predominating factor is a double low water (*figure 19*).

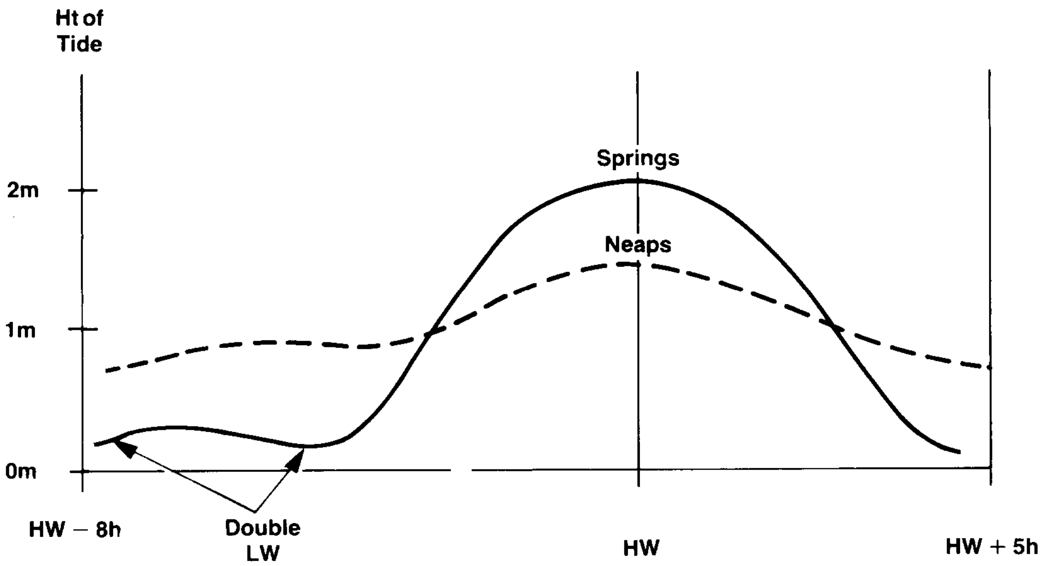

Figure 19. Double low waters at Portland.

17.4.2 Further east, at Southampton, for example there are two high waters with an interval of two hours between them (*figure 20*). Double tides also occur on the Dutch coast and at other places. The practical effect of this is to create a longer stand at high or low water. The stand of the tide is the period at high or low water between the tide ceasing to rise (fall) and starting to fall (rise).

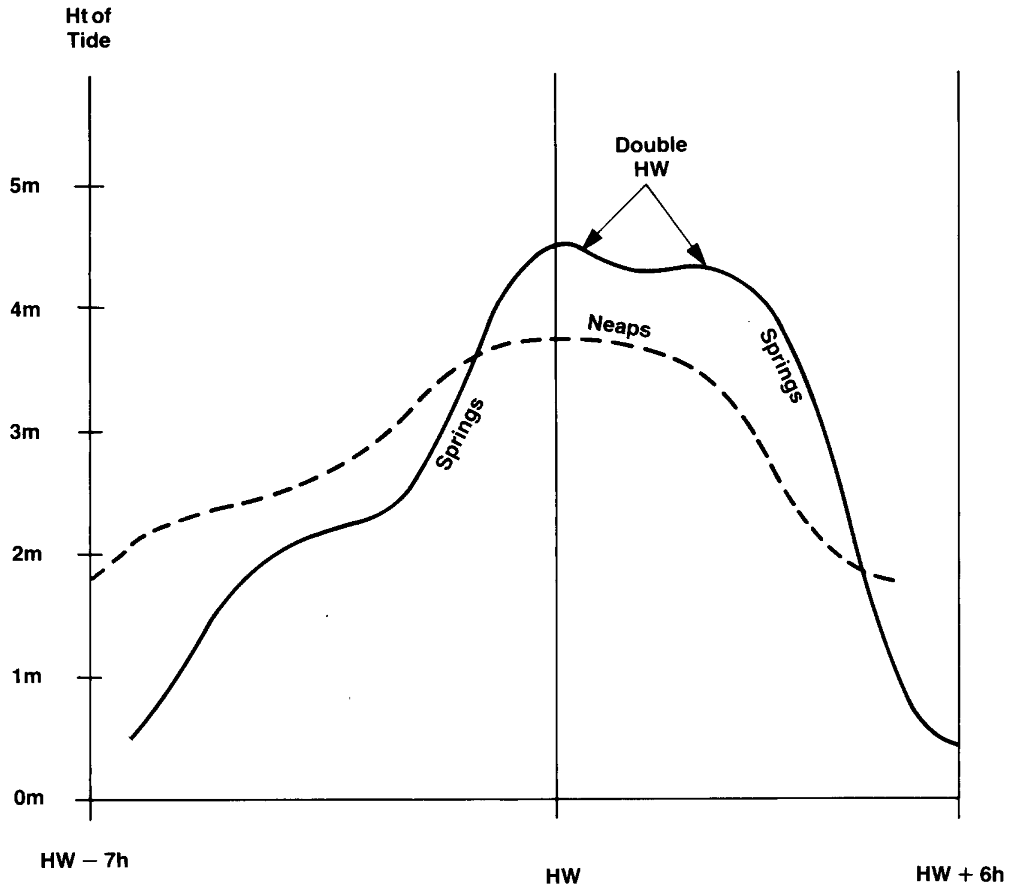

Figure 20. Double high waters at Southampton.

18. CORIOLIS

18.1 Coriolis Force In simple terms, Coriolis describes the movement of a particle due to the rotation of the Earth. The Coriolis force will tend to move a particle clockwise in the northern hemisphere and anticlockwise in the southern hemisphere.

19. AMPHIDROMIC (NODAL) POINTS AND ROTATING WAVES

19.1 Ocean basin geometry and the influence of the Coriolis force result in the development of *amphidromic systems*, in each system the crest of the tidal wave at high water circulates around an *amphidromic (or nodal) point* once during each tidal period, creating a rotating wave.

19.2 With few exceptions, the tidal waves of amphidromic systems tend to rotate anticlockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. At first, this pattern of rotation appears to contradict the statement regarding Coriolis force described in paragraph 18.1 above.

However, consider the development of an amphidromic system in a hypothetical enclosed bay in the Northern Hemisphere. The flooding tide (north flowing), water is deflected to the right by Coriolis force, and the water is piled up on the eastern side of the bay. Conversely, when the tide ebbs (south flowing), the water is again deflected to the right and becomes piled up on the western side. Because the tidal wave is constrained by land masses, an anticlockwise amphidromic system is set up. In practice the North Sea can be considered such a bay, but with much more complex tides and resulting amphdromic systems.

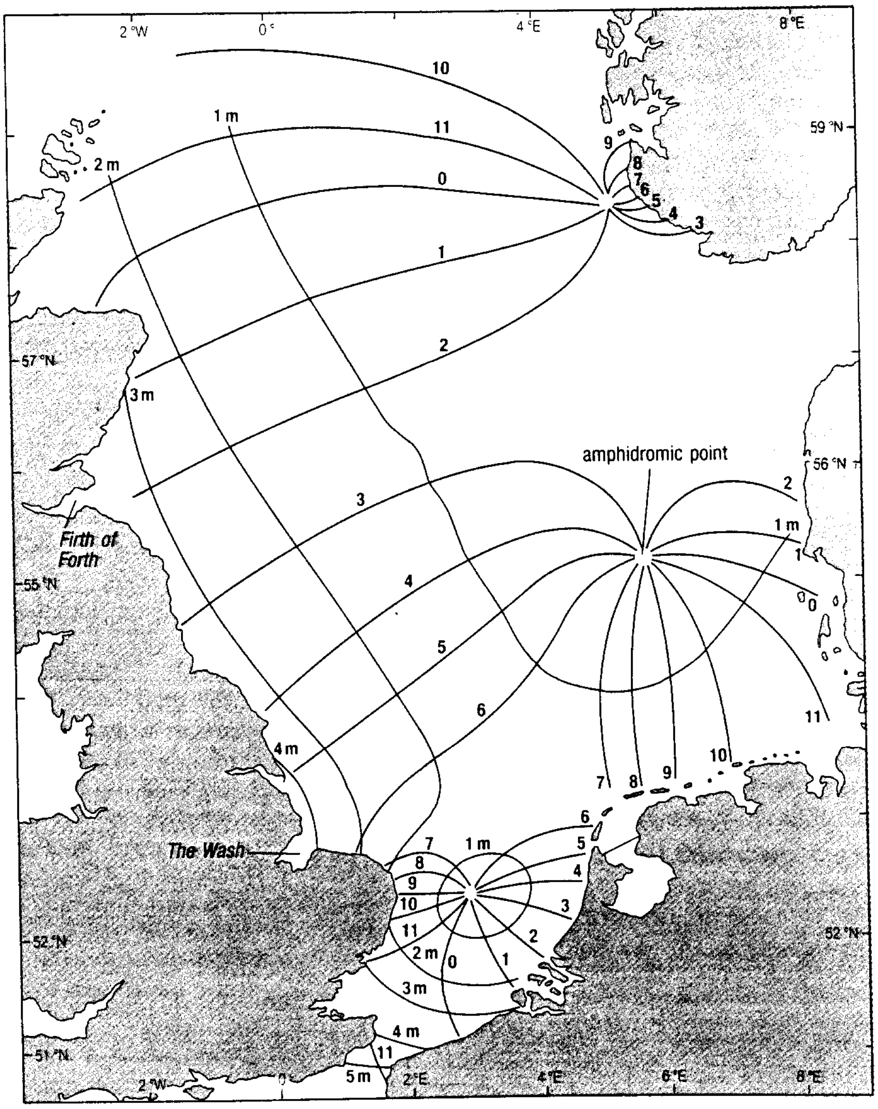

Figure 21. Amphidromic points in the North Sea.

19.3 *Figure 21* above, shows three amphidromic points in the North Sea. In each amphidromic system the crest of the tidal wave circulates around an *amphidromic point* once during each tidal period. The tidal range is zero at each amphidromic point, and increases outwards away from it. Tidal stream is maximum at the amphidromic point and decreases away from it. Each amphidromic system has a series of *co-tidal lines* radiating outwards from the amphidromic point; cutting across the *co-tidal lines*, approximately at right angles to them, are *co-range lines*. *Co-tidal lines* link all the points where the tide is at the same stage (or phase) of its cycle, ie all points along a particular line will experience high water at the same time. *Co-range lines* join places having equal tidal range.

19.4 <u>Kelvin Wave</u>. The rotation created by Coriolis has a particular effect when restricted in a channel. Such confined amphidromic systems create a feature known as a *Kelvin Wave*. An example of a Kelvin Wave is found in the English Channel, where the *flood* *stream flows eastward* and the *ebb stream flows westwards* (see *figure 22*). Here, there is a nodal point on dry land (in the vicinity of Salisbury, Wiltshire), which causes a tilting of the surface water and creates a Kelvin Wave. This causes the range of tide on the French coast of the English Channel to be greater than that on the English coast. So:

On the flood tide: the north French coast receives a *higher* HW, the south coast of England receives a *lower* HW.

On the ebb tide: the north French coast receives a *lower* LW, the south coast of England receives a *higher* LW.

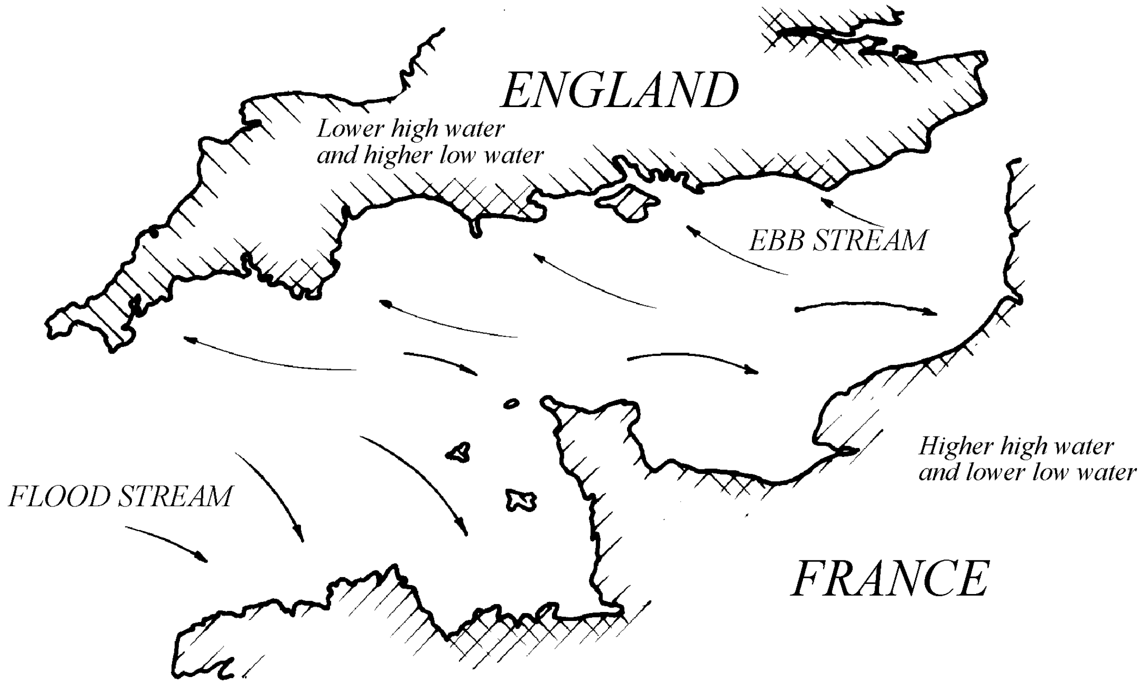

Figure 22. Kelvin wave in the English Channel.

20. METEOROLOGICAL EFFECTS ON TIDES

20.1 Meteorological conditions which differ from the average will cause corresponding differences between the predicted and the actual tide.

Variations in tidal heights are mainly caused by strong or prolonged winds and by unusually high or low barometric pressure.

Differences between predicted and actual times of high and low water are caused mainly by wind.

20.2 Statistical analysis indicates that 1 standard deviation (1σ) of the differences between observed and predicted heights and times amounts to 0.2 metre and 10 minutes respectively.

20.3 Barometric Pressure. Tidal predictions are computed for average barometric pressure. A difference from the average of 34 millibars can cause a difference in height of about 0.3 metre. A low barometer will tend to raise sea level and a high barometer will tend to depress it. The water level does not, however, adjust itself immediately to a change of pressure and it responds, moreover, to the average change in pressure over a considerable area. Changes in level due to barometric pressure seldom exceed 0.3 metre but, when Mean Sea Level is raised or lowered by strong winds or by storm surges, this effect can be important.

20.4 Effect of Wind. The effect of wind on sea level - and therefore on tidal heights and times - is very variable and depends largely on the topography of the area. In general, it can be said that wind will raise sea level in the direction towards which it is blowing. A strong wind blowing straight onshore will pile up the water and cause high waters to be higher than predicted, while winds blowing off the land will have the reverse effect. Winds blowing along a coast tend to set up long waves which travel along the coast, raising sea level where the crest of the wave appears, and lowering sea level in the trough. These waves are known as *storm surges* (see 19.6).

20.5 Seiche. Abrupt changes in meteorological conditions, such as the passage of an intense depression or line squall, may cause an oscillation in the sea level known as a *seiche*. The period between successive waves may be anything between a few minutes and about 2 hours, and the height of the waves may be anything from 1 centimetre or so up to 1 metre.

20.6 Positive and Negative Surges. A change in sea level is often caused by a combination of wind and pressure, such changes being superimposed on the normal tidal cycle. A *rise* in sea level is often referred to as a *positive surge* and a *fall* as a *negative surge*. A *storm surge* is an unusually severe positive surge. Both positive and negative surges may appreciably alter the predicted times of high and low water, often by as much as an hour.

20.6.1 A *positive surge* will have the greatest effect when it is confined to a gulf or a bight such as the North Sea. It rarely increases the general sea level height by more than 1 metre, although greater heights are not unknown (see storm surges below). In a bight such as the North Sea, northerly winds will raise the general sea level at the southern end, causing a positive surge.

20.6.2 *Negative surges* are of great importance to large vessels navigating with small under-keel clearances. These surges are most evident in estuaries and areas of shallow water, and appear to occur when strong winds are tending to blow water out of a bight or similar area. For example, in the North Sea, strong southerly winds will tend to cause a negative surge at the southern end. Falls in sea level of up to 1 metre are not uncommon, and falls of as much as 2 metres have been recorded.

20.6.3 *Storm surges* occur in bights or estuaries when the speed of the tidal wave is reduced by shallow water effect to that of the speed of the storm. The tidal wave is thus being "fed" by the storm and gradually increases in amplitude. In certain circumstances, it may attain a considerable height, 3 metres is not unknown and, if this peak occurs at high water springs, considerable flooding and damage may be caused along the coastline.

A storm surge may be anticipated when an intense depression moves at a critical speed across the head of a bight with storm force winds blowing into the bight. They may be proceeded by an abnormal stand of low water.

Such surges have been experienced in the southern North Sea and in the Bay of Bengal. During the last major storm surge in the North Sea, in the early 1950s, there was considerable damage and loss of life, particularly in East Anglia in England and in the low counties of Holland. This led to the establishment of the Storm Tide Warning Service based at Bracknell, and also to the construction of the Thames barrier, designed to prevent the flooding of London.

21. TSUNAMIS (SEISMIC WAVES)

21.1 *Tsunamis* (or *seismic waves*) are wave events generated by seismic activity. The popular description of them as 'tidal wave' is a misnomer because they lack the regularity associated with tides. Virtually all tsunamis are generated by submarine earthquakes, but landslides into the sea, and slumping (for example, sediments on the continental slope) may occasionally be responsible. These waves travel with great rapidity in the deep waters of the oceans, reaching speeds of over 400 knots, a wavelength of over 100 miles (thus, a period of about ¼ hour) and a height of only 0.5 to 1 metre. On reaching shallow water, however, they increase rapidly in height with 15 to 17 metres being recorded.

21.2 The first wave is often preceded by a very rapid lowering of the water level; a warning that the tsunami will arrive in a few minutes. The tsunami typically consists of a series of waves, the second and third being higher than the first, the rest gradually decreasing over a period which may be as little as a few hours and as long as several days.

22. DEFINITIONS

Solar Day:	The Earth rotates about its polar axis, from west to east, within a period of 24 hours. The polar, or spin, axis does not point towards a fixed position in space, but is subject to both precession and nutation causing a change in direction of up to 20″ per annum.
Lunar Day:	Because the Moon is moving around the Earth in the same direction at the Earth rotates, it takes approximately 50 minutes longer than a solar day for the same point on Earth to be directly in line with the Moon.
Synodic Period:	Also known as "Lunar month" or "Lunation" and is the period between successive new Moons. A period of 29.5306 mean solar days.
Sidereal Period:	A period of revolution of the Moon's orbit measured along the ecliptic. A period of 27.3216 mean solar days.
Draconite Period:	The Moon's cycle north and south of the ecliptic, ascending node to ascending node. A period of 27.2122 mean solar days.
Anomalistic Period:	The period between successive perigees (Moon at its minimum distance from the Earth). A period of 27.5546 mean solar days.
Regression of the Moon's Nodes:	The westward movement of the Moon's nodes due to the difference between the Sidereal and Draconite periods (27.3216 - 27.2122 mean solar days) of 0.1094 mean solar days in a 27.2122 mean solar day period (or 0.053° per mean solar day). On average the regression of the nodes will be completed in: $\frac{27.3216}{0.1094} \times \frac{27.2122}{365.25}\ years = 18.61\ years$ 3
Aphelion:	The point at which the Earth is at its maximum distance from the Sun.
Perihelion:	The point at which the Earth is at its minimum distance from the Sun.
Apogee:	The point at which the Moon is at its maximum distance from the Earth.
Perigee:	The point at which the Moon is at its minimum distance from the

Earth.

Equinox: The maximum tidal ranges occur at the Spring and Autumn equinoxes (21 March and 21 September). This is when the Sun and Moon are in line not only in azimuth but with zero declination.

Vernal Equinox: The point where the ecliptic crosses the celestial equator from south to north (the First Point of Aries).

Autumnal Equinox: The point where the ecliptic crosses the celestial equator from north to south.

Solstice: The minimum tidal range occurs when the Sun and Moon have the greatest degree of declination. This occurs around 21 June and 21 December each year, when the Sun is at its maximum declination north or south. These dates are called the Solstices.

Equilibrium Tide: The total tide-raising force, given a frictionless sea on a spherical Earth without land masses is called the Equilibrium Tide.

Syzygy: The term used to define the situation where the Sun, Moon and Earth are in line (giving rise to 'spring' tides).

Quadrature: The situation where the Moon is at 90° to the Sun (giving rise to 'neap' tides).

23. SUMMARY

The semi-diurnal tide raising force is maximum when the Moon's declination is nil, and minimum when the Moon's declination is at its greatest.

The same is also true of the effect of the Sun's declination but, whereas the Moon's declination attains a maximum value north or south of the equator every 15 days or so, the Sun only reaches a maximum twice a year, in June and December at the solstices.

The orbits of the Moon around the Earth and Earth around the Sun are elliptical, changes in their distances from the Earth cause variations in the tide-raising force, that for the Moon being significant (15-20%), that for the Sun being minimal (3%).

Spring and neap tides occur at intervals of about 14.75 days, caused by the Moon and Sun either working together at full and new Moon (springs) or against each other at first and last quarters (neaps).

The Sun's tide-raising force is always a great deal less than that of the Moon, approximating to some 45% on average.