The Flight of the Space Shuttle *Discovery* (STS 119)

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This article is intended to model the ascent of the space shuttle for high school teachers and students. It provides a background for a sufficiently comprehensive description of the physics (kinematics and dynamics) of the March 16, 2009, *Discovery* launch. Our data are based on a comprehensive spreadsheet kindly sent to us by Bill Harwood, the "CBS News" space consultant. The spreadsheet provides detailed and authentic information about the prediction of the ascent of flight STS 119, the 36th flight of *Discovery* and the 125th shuttle flight to date. We have used the data for our calculations and the production of the graphs. A limited version of the ascent data is available on the "CBS News" STS-119 trajectory timeline.[1]

Using the NASA data

The complete description of the ascent of the space shuttle, placing the orbiter into a preliminary orbit, is a formidable engineering task, but it is clearly also a computational challenge. First, we had to decide what data were useful and relevant; second, we went through the task of converting the units into the SI system; and third, we looked for key positions of the shuttle's trajectory to illustrate the physics (kinematics and dynamics) of the ascent.

The immediate task of finding the important columns of the spreadsheet was difficult, mainly because the vast majority of the entries turned out to be irrelevant for our purpose. The columns we finally decided on can be seen in Tables I and II.

The second task, that of converting the units to the SI system, was straightforward. However, we are tempted to ask the following question: Why is NASA still using the British system of units?

For the third task, that of choosing representative points in the trajectory, we analyzed three key times, the first at the very beginning of the takeoff, the second when $t = 60$ s, and the third when $t = 480$ s. The first one is important because it discusses the near-static condition when forces are applied that allows the shuttle to rise in the gravitational field of the Earth. The second position is instructive because the shuttle is entering a curved motion, significantly departing from the near-vertical ascent during the first 30 seconds. This allows the analysis of the forces acting on the shuttle as well as on the astronauts, including the force of the air drag, which at this time is a maximum.

The third and last position chosen is the time just before main engines cut off (MECO). Here the horizontal acceleration is a maximum (almost 3*g*), the drag is zero, and the orbiter (plus external tank) is moving in a near-horizontal direction. In addition, the centripetal acceleration is 8.1 m/s^2 and the astronauts are beginning to feel being "weightless"; that is, they are in what NASA designates as *microgravity.* We will conclude with some suggestions for a number of additional problems.

The launching of the space shuttle

The following description of the flight of the space shuttle is partly based on the *News Reference Manual*[2] originally distributed to the press in 1988 and the shuttle reference data located on NASA's website.[3] However, the data we use are from a recent flight of the shuttle (Flight STS 119). It should be explicitly stated that data given to us, about six weeks before the launching, were a *prediction* and not the data of the actual flight. Please consult the tables when reading the description of the flight.

Initially, the space shuttle, consisting of three major components [the orbiter, the solid rocket boosters (SRB), and the external fuel tank], is launched vertically with all main engines firing. About 10 s into the flight, the shuttle turns so that the orbiter lies under the external fuel tank and the solid rocket boosters. This familiar roll is important for a number of reasons. First, it reduces the stress on the orbiter's delicate wings and the tail of the shuttle. Second, it makes it easier for the computer to control the shuttle during the remainder of the ascent. Third, it enables the astronauts to see the horizon, giving them a reference point, should the mission have to be aborted and the orbiter forced to land. The roll ends at about 18 s, when the shuttle is at an altitude of 976 m and a range of about 200 m. The velocity of the shuttle now is 120 m/s.

The shuttle then climbs along an arc, accelerating while its total mass decreases. As the shuttle continues to flatten in its trajectory, powering back the main engines to about 70% relieves stress. By about 40 s into the flight, the shuttle breaks the sound barrier with a speed of about 320 m/s. About 60 s into the flight, the shuttle encounters the highest air resistance (drag). At this time the phenomenon known as the Prandtl-Glauert singularity occurs, when condensation clouds form during the transition to supersonic speeds. Shortly after that, however, the pressure on the orbiter decreases and the shuttle engines are returned to full power. At this point, the shuttle is traveling at 454 m/s.

Two minutes (120 s) into the ascent, the Shuttle is about 45 km above the Earth's surface and traveling at Mach 4.1, or 1324 m/s. The SRBs, having used up their fuel, separate from the external fuel tank and fall back to Earth. The descent of the SRBs, some 225 km downrange, is slowed by parachutes that are ejected from the nose cone, marking the end of the

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Table I. The Flight of Discovery STS 119: Kinematics

Time (s)	Alt (m)	Range (km)	θ (°)	V (m/s)	Vy (m/s)	Vx (m/s)	Accel. (m/s^2)	NASA Accel "sensed" g	α (°)	28.608N 80.604W
0	-7	0	89.8	0	0	0	4.8	0.3	90	Launch
5	46	0	89.7	24	24	0	6.0	1.6	89	
10	236	0	87.4	55	55	0	7.0	1.7	89	Start roll
15	672	0.18	71.9	97	95	19	8.5	1.8	78	
18	976	0.18	69.2	120	115	34	8.6	1.9	73	End roll
20	1211	0.18	69.5	137	129	46	8.6	1.9	70	
30	2787	0.93	67.8	220	197	97	8.5	1.8	63	
36	4032	2.0	65.9	266	234	126	8.0	1.8	61	Throttle down
40	5214	2.2	63.8	300	257	154	8.1	1.7	58	
50	7890	3.3	61.3	364	300	206	7.1	1.8	55	Throttle up
60	11380	6.5	59.1	454	363	272	10.	2.0	53	Max.AirPressure
90	25496	19.4	38.7	882	576	667	16.	2.5	40	
120	44626	47	26.1	1324	660	1147	8.1	1.0	29	
124	47341	49	25.5	1339	644	1173	8.0	1.0	28	SRB STAGING
125	48162	51	23	1341	643	1176	9.0	1.0	28	
150	63018	84	19.7	1483	545	1379	8.0	1.0	21	
180	77732	129	16.9	1696	437	1638	8.3	1.1	14	
210	89304	181	14.5	1957	334	1928	11	1.2	9	Negative return (218)
240	97930	242	12.5	2258	340	2232	11	1.3	8	
270	104006	315	10	2614	151	2609	13	1.4	3	
300	107416	397	7.8	3007	74	3006	12	1.6	1	
330	108715	491	5.5	3452	10	3451	15	1.7	0	
360	108296	600	9.4	3960	-38	3959	18	1.9	-1	
390	106808	728	25.3	4562	-62	4561	21	2.2	-1	
392	106690	737	25.2	4603	-63	4602	21	2.3	-1	
420	104776	871	22.9	5249	-70	5248	24	2.6	-1	
440	103479	980	21.1	5788	-54	5787	27	3.0	-1	
450	103016	1036	20.3	6062	-40	6061	27	3.0	-1	
480	102661	1225	17.5	6912	26	6911	27	2.9	0	
503	104059	1394	13.6	7571	98	7570	1.4	1.2	0	MECO
510	104718	1444	12.8	7581	98	7580	0	0	0	Zero Thrust
514	105077	1471	12.8	7581		7581	0	0	0	37.356N 68.714W

Table i.

Altitude: **The height in m, above the imaginary geodesic point at the launch sight, which is 7 m (-24 ft) above the center of gravity of the shuttle at t = 0.**

Range: **The distance in km at time t, measured along the Earth's curvature to the shuttle.**

Pitch Angle (PA): **The angle from the horizontal to the shuttle in degrees.**

V = Velocity of the shuttle at time t in m/s.

V_y = Vertical component of the velocity of the shuttle at time t.

V_x = Horizontal component of the velocity of the shuttle at time t.

Accel.**: Acceleration of the shuttle at time t.**

Accel.**(NASA): The acceleration reported by NASA, as "sensed" by the astronauts.**

α: The angle that the tangent makes with the trajectory (See R-t graph)

Table II. The Flight of Discovery 119: Dynamics

Time	Mass kg	Fuel loss kg/s	Thrust %	Thrust (N)	Drag Pressure (N/m^2)	VI (Inertial) (m/s)	Accel (m/s^2)	
0	2047249		100	30200000	0	408	4.8	Launch
5	2000356	-11831	104.5	31559000	364	409	6.0	
10	1939932	-12806	104.5	31559000	1833	412	7.0	Start roll
15	1866473	-12274	104.5	31559000	5342	435	8.5	
18	1829536	-12334	104.5	31559000	7948	453	8.6	End roll
20	1804824	-12361	104.5	31559000	10012	465	8.6	
30	1687000	-11182	104.5	31559000	21585	528	8.5	
36	1622233	-10440	90	27180000	27691	566	8.0	Throttle down
40	1572745	-9672	72	21744000	30816	596	8.1	
50	1479240	-9304	104	31408000	33806	656	7.1	Throttle up
60	1385150	-9573	104.5	31559000	35059	736	10.	Max.AirPressure
90	1075485	-8782	104.5	31559000	14270	1163	16.	
120	874387	-2098	104.5	31559000	1737	1617	8.1	
124	866820	-1628	104.5	5486250	1233	1635	8.0	SRB STAGING
125	695925	-1427	104.5	5486250	1230	1637	9.0	
150	657211	-1440	104.5	5486250	614	1792	8.0	
180	612567	-1440	104.5	5486250	216	2014	8.3	
210	567923	-1440	104.5	5486250	33	2278	11	Negative Return (t=218s)
240	523660	-1422	104.5	5486250	4	2580	11	
270	478122	-1424	104.5	5486250	0	2935	13	
300	434007	-1423	104.5	5486250	0	3325	12	
330	389893	-1423	104.5	5486250	0	3767	15	
360	345778	-1423	104.5	5486250	0	4270	18	
390	300240	-1423	104.5	5486250	0	4868	21	
392	297394	-1423	104.5	5486250	0	4909	21	
420	256125	-1423	104.5	5486250	0	5551	24	
440	226241	-1423	104.5	5486250	0	6086	27	
450	212436	-1335	98	5145000	0	6359	27	
480	174764	-1114	80	4200000	0	7204	27	
503	150211	-1292	60	3150000	0	7860	1.4	MECO
510	149690	0	0	0	0	7871	0	Zero Thrust
514	149690	0	0	0	0	7871	0	

Table II.

Time: Time is given in s.

Mass: Mass of the shuttle in kg, at the time indicated.

***Fuel Loss Rate*:** The rate of fuel loss in kg/s at time *t*.

%Thrust: The value of the thrust in N, based on 100% being 30,200,000 N for the total thrust (SRB engines plus the three orbiter engines) up to SRB staging when *t* = 124 s After that it is based on the orbiter engines output of 5,250,000 N at 100%.

***Thrust*:** The thrust in N at time *t*.

Drag: The effect of the atmosphere on the shuttle, given in N/m^2 at time *t*.

***VI*:** The inertial velocity of the shuttle, i.e., the velocity relative to the center of the Earth. At the beginning of the launch, the Shuttle is already moving at 408 m/s in an easterly direction because of the rotation effect of the Earth at latitude 28.608 N.

first stage of the ascent. The second stage of the ascent begins at SRB separation, when the main engines have inadequate thrust to exceed the force of gravity since the thrust-to-weight ratio becomes less than one. However, as the engines burn fuel, the mass decreases, the thrust-to-weight ratio increases, and the vehicle starts its acceleration to orbit speed. (Note: at about 228 s the thrust-to-weight ratio is over 1, see Table II on the previous page).

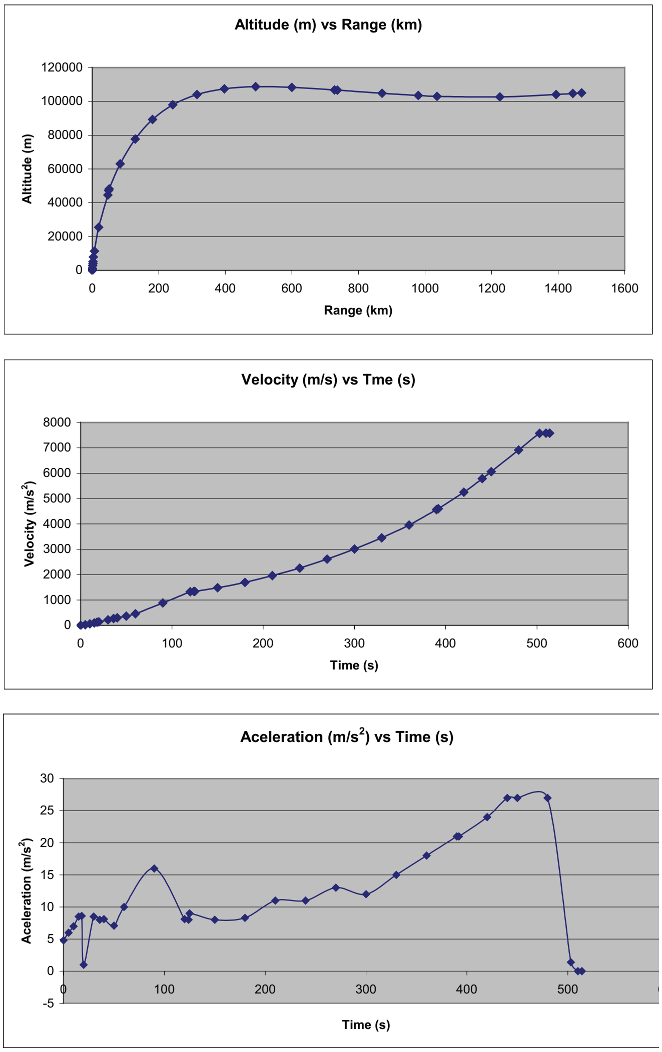

Fig. 1. The main graphs generated: The altitude–range, the velocity-time, and the "sensed" acceleration-time graphs.

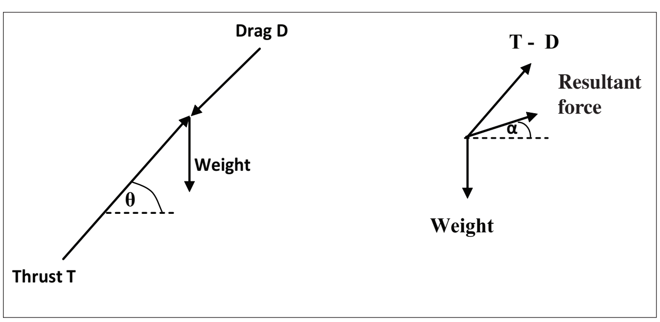

Fig. 2. Force diagram for the motion of the Shuttle.

The second stage of the ascent lasts about 6.5 min. With the solid rocket boosters jettisoned, the shuttle is now powered solely by its three main engines, reaching an altitude of over 104 km and a speed of 7.87 km/s, relative to the center of the Earth. (See altitude-range graph in Fig. 1). The three main engines, attached to the rear of the orbiter, continue to fire until about 8.5 min after liftoff. As the main engine completes its burn, the mass of the shuttle has decreased so much that the engines are throttled back to limit vehicle acceleration to 3*g*, necessary to maintain a safe and comfortable ride for the astronauts (see velocity-time and acceleration-time graphs in Fig. 1).

Finally, about 8.5 min after takeoff, the shuttle's engines shut down and the external fuel tank is jettisoned from the shuttle. At this time, the shuttle is traveling at about 8.0 km (5 miles) a second and the orbiter, with a mass of 118,000 kg (260,000 lb), is the last shuttle component that will orbit the Earth. Note that only about 7% of the original mass is left at the end of our description of the launch trajectory journey, when $t = 514$ s.

The motion of the shuttle

Using the data given by NASA of the predicted flight of the STS 119 flight, we can apply elementary physics and mathematics to understand the kinematics and dynamics of the launch. We begin with the description of the physics of the shuttle's motion as a function of time along the path of ascent. For each second we were given the following information: altitude (m); range (km); velocity (m/s); inertial velocity (m/s, relative to the center of the Earth); pitch angle (PA) θ(deg); vertical velocity (m/s); thrust (N); and "drag" or pressure of the atmosphere (N/m^2).

We have added another parameter, the pitch angle (θ), which is the angle that the shuttle makes as measured from the horizontal at a given time. The angle α described determines the tangent to the trajectory, or the direction of the motion of the shuttle at any given time, and is mostly different from the pitch angle. When the shuttle begins its lift, these two angles are almost equal (90° each). During the flight they deviate slightly, meaning that the shuttle is not parallel to its motion. For example, by $t = 480$ s, the angle α is close to 0° but the pitch angle is 17° (see Figs. 2 and 3).

For kinematics:

The above information allows us to calculate:

1. The angle α.
2. The horizontal velocity of the shuttle at any time t.
3. The acceleration of the shuttle in the x and y directions, that is, the horizontal direction and the vertical direction at given time, downrange.
4. The total acceleration on the shuttle.

This will constitute the content of Table I, which is essentially kinematics based on the data given by NASA. Next we will look at the dynamics of the trajectory and calculate the quantities listed below. We wish to know how well the laws of dynamics (essentially Newton's second law) can account for the kinematic results.

First, there will be a general discussion of how this is done and then we will illustrate the physics for three chosen times. The following will be calculated, using dynamics:

1. The unbalanced force acting on the shuttle.
2. The vertical and horizontal acceleration components of the shuttle.
3. The total acceleration of the shuttle.
4. The centripetal acceleration of the shuttle for high velocities (relative to the center of the Earth).
5. The acceleration "felt" by the astronauts (dynamics).

These calculations will be applied to three times: **Time 1:** Just as the shuttle lifts off the launch pad, $t = 0$; **Time 2**: When air drag is maximum, t = 60; and **Time 3:** When the thrust is lowered, just before main engines cut off (MECO), $t = 480$ s. Note: Our values for the acceleration were calculated for every second, based on the NASA data. The reader should refer to Table I (Kinematics) and Table II (Dynamics) on the previous pages while reading the next section.

Descriptions of the three times

1. **The angle α:** The angle of the tangent of the motion, or simply the direction of motion of center gravity of the shuttle, can be found by calculating the arctan of the vertical velocity divided by the horizontal velocity:

$$\alpha = \arctan(v_y/v_x)$$

2. **The unbalanced force acting on the shuttle at any time:** The net force **F** acting on the shuttle is given by the vector equation

$$\mathbf{F} = T + \mathbf{D} + m\mathbf{g},$$

where T is the thrust produced by the engines of the shuttle and **D** is the total air resistance on the shuttle, given by **pA**, (drag, in Newtons) and m**g** is the weight. The thrust (N) and drag per unit area **p** (N/m^2) at time t are given in the table. We will illustrate this when we describe the physics of the second position, when $t = 60$ s.

3. **The vertical and horizontal accelerations components of the shuttle:** The x and y components of the unbalanced force then are

$$\mathbf{F}_x = (\mathbf{T} - \mathbf{D})\cos\theta \quad \text{and} \quad \mathbf{F}_y = (\mathbf{T} - \mathbf{D})\sin\theta - mg,$$

where θ is the pitch angle, the angle between the shuttle and the vertical at a given time.

According to Newton's second law, then we get:

$$a_x = (\mathbf{T} - \mathbf{D})\cos\theta / m$$

and

$$a_y = [(T - D)\sin\theta - m\mathbf{g}]/m$$

4. **The acceleration of the shuttle:** The acceleration can be found by using Pythagora's theorem:

$$a = (a_x^2 + a_y^2)^{1/2}$$

5. **The centripetal acceleration of the shuttle (relative to the center of the Earth):**

When the shuttle reaches an altitude of about 10 km, the centripetal acceleration on the shuttle becomes significant. To determine the magnitude of the centripetal acceleration, we have to use the inertial velocity of the shuttle, that is, the velocity relative to the center of the Earth. Before launch, the shuttle already has a velocity of about 408 m/s east, in the direction of the latitude of 28.6°N. You can easily show that the rotation of the Earth here is 408 m/s east.

We will say that when the centripetal acceleration is 0.1g or larger, it becomes significant. At about $t = 210$ s the centripetal acceleration is about 0.81 m/s^2. So after this time this effect must be taken into account.

The centripetal acceleration is given by:

$$a_c = v^2 / R$$

where $\mathbf{R} = R_E + H$ and **v** is the inertial velocity **VI** as recorded in Table II. R_E = radius of the Earth, about 6.37 x 10^6 m, and H is the altitude of the shuttle in meters.

6. **The acceleration, as found in the NASA data:** You may have noticed that when comparing the accelerations calculated (Table II) and those given by NASA, the accelerations are different. The reason for that is that NASA's acceleration is not the acceleration that acts on the shuttle but the acceleration "sensed" or "felt" by the astronauts. For example, for $t = 5$ s, our acceleration is 6.2 m/s^2 and NASA's is 1.6g, or about 16 m/s^2. Note also that the acceleration given for the very start of the lift is 0.4g. This may be due to the fact that the negative altitude number of -7 m , or -24 ft (see Table I), is a reference to an "idealized geodetic surface." According to our communication with NASA, the shuttle's center of gravity is below this imaginary surface when it is sitting on the pad.

To calculate the acceleration "sensed" is complicated by the fact that the shuttle has a pitch angle at times significantly less than 90° and even more tricky when we enter the region after $t = 300$ s, when the centripetal acceleration has a significant effect.

The following may clarify the idea of "sensed" acceleration: When sitting on the surface of the Earth the acceleration is zero, but the sensation is 1g, whereas in free-fall acceleration the sensation is 0g. Thus, we can say that

$$a_{sy} = a_y + g \text{ (seen as a vector equation).}$$

The acceleration could be measured by a spring scale placed under the astronaut, that is, "sensed" acceleration is related to normal force.

We will now suggest a formula for the acceleration "sensed" by the astronauts and then test it for the three positions we want to investigate. Let us call acceleration "sensed" a_s, which has an x component and a y component. Clearly, the x component is simply

$$a_{sx} = a_x$$

and $a_{sy} = a_y + g + a_c$
(understood as a vector equation), where $g = 9.8\ m/s^2$ and $a_c = (\mathbf{VI})^2 / R$. Therefore the acceleration "sensed" is given by $a_s = (a_x^2 + a_{sy}^2)^{1/2}$.

Discussion of the three positions of the trajectory

Time 1, *t* = 0. The shuttle is resting on the platform and all the engines are fired, producing a thrust of 3.02×10^7 N after less than a second. The thrust is much larger than the weight (2.04×10^7 N) of the shuttle and therefore the shuttle begins to ascend. The force diagram here is very simple and the acceleration at that "moment" is given by

$$a = (T - mg)/m = (3.02 \times 10^7 - 2.04 \times 10^7)/(2.04 \times 10^4\ kg) = 4.8\ m/s^2$$

This is about 0.5*g*. In the NASA spreadsheet we read 1.5*g*. How was this figure obtained?

The acceleration "sensed" by the astronauts can be calculated using the formula suggested earlier. Prior to ascent, the astronauts "feel" the Earth's gravity and, according to the equivalence principle of inertial and gravitational masses, the effect is the same as if the shuttle were accelerating in gravity-free space at $9.8\ m/s^2$.

Upon launch we only have an a_y component and the total "sensed" acceleration is

$$a_{sy} = a_y + g + a_c$$
$$= a_y + g - 0 = 4.8 + 9.8 - 0 = 15.6\ m/s^2 = \text{about } 1.5g.$$

(See Tables I and II).

Time 2, *t* = 60 s. This situation is a little more complicated. The shuttle is climbing in a curve, the pitch angle θ is 59°, and there is now a significant *x* component of the thrust. Another complication is that we now have maximum air resistance of about 18% of the thrust. We have estimated the effective shuttle area to be $167\ m^2$.

$A_{eff} = 167\ m^2$
$m = 1.38 \times 10^6$ kg
$mg = 1.35 \times 10^7$ N
$T = 3.16 \times 10^7$ N
$p = 35059\ N/m^2$
$D = pA = 5.85 \times 10^6$ N

Using equations in section 3 and 4 we find that the *x* and *y* components of the accelerations are $a_y = 6.23\ m/s^2$ and $a_x = 9.62\ m/s^2$. The directly calculated acceleration (that is, the acceleration on the shuttle) then would be $a = (a_y^2 + a_x^2)^{1/2} = 11.4\ m/s^2$. The "sensed" acceleration can be obtained this way:

Since $a_{sy} = a_y + g + (VI)^2/R = (6.23 + 9.81 + 0)\ m/s^2$,

then $a_{sy} = 15.3\ m/s^2$
so that $a_s = (a_{sy}^2 + a_x^2)^{1/2} = 18.1\ m/s^2$, or about 1.9*g*.

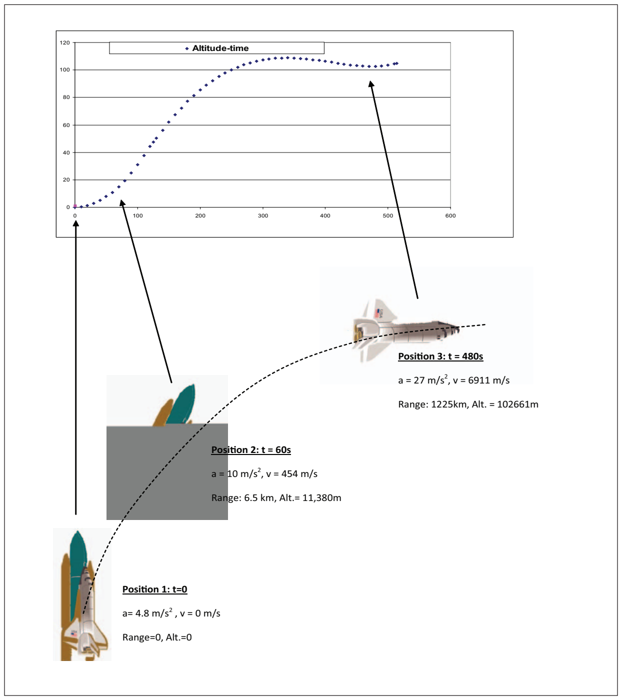

Fig. 3. The three times (positions) of the shuttle discussed.

The acceleration reported by NASA for this position is 2.0 *g*.

In which direction is the shuttle moving? Earlier we argued that $\alpha = \arctan(v_y / v_x)$. Substituting the values, taken from Table I, we get

$\alpha = \arctan(363/272) = 53°$.

The shuttle at $t = 60$ s then is pointing at about 59° (angle θ) from the horizontal, but the motion is tangent to the curve at 53° (angle α).

Time 3, *t* = 480 s. The shuttle (orbiter plus the large tank) is pointing at a pitch angle of 17°, but moving almost horizontally at 7204 m/s (inertial velocity) and at a high acceleration. Therefore, the angle α is close to zero and the air drag is negligible.

$T = 4.20 \times 10^6$ N
$m = 1.75 \times 10^5$ kg
$VI = 7204$ m/s

The horizontal acceleration is

$a_x = T_x/m$
and $T_x = T \cos 17° = 4.20 \times 10^6 \cos 17° = 4.02 \times 106$ N.
Therefore, $a_x = (4.02 \times 10^6)/(1.75 \times 10^5\ m/s^2) = 23\ m/s^2$.

The vertical acceleration is

$a_y = (T_y - mg + mv^2/R)/m = [T_y - m(g - v^2/R]/m$.

Note that at this high velocity the centripetal acceleration becomes a factor. For *v* we use the *VI* value of 7204 m/s. Clearly, when $v^2/R = g$, the astronauts are in microgravity

Then $T_y = 4.20 \times 10^6$ N

and $a_y = [4.20 \times 10^6 - 1.75 \times 10^5(9.7 - 8.1)]/ 1.75 \times 10^5$.
Therefore $a_y = 1.6 \text{ m/s}^2$.

The acceleration on the shuttle then is

$$a = (a_y^2 + a_x^2)^{1/2} = (232 + 1.6^2)^{1/2} = 23.2 \text{ m/s}^2 = 2.4g.$$

NASA has an acceleration of 2.9*g*.

One could discuss the reason for this difference. For example, one wonders about the accuracy of the pitch angle given for this position. Note that the shuttle is accelerating somewhat vertically at this point, as you can see in Table I.

Conclusion

We have devised a large number of additional problems that may challenge students, from very basic problems on thrust, acceleration, terminal velocity, longitude, and latitude, to advanced problems on Coriolis acceleration and the use of the rocket equation. A guided approach to solve these problems can be found on the website http://www.ArthurStinner.com. Our main objective in this article is to give physics teachers of secondary schools and colleges a good basis from which to present the launch of the space shuttle, in whole or in selected parts. The concepts and the level of the mathematics required to follow the arguments should be accessible to all physics teachers. The challenge of the physics instructor then is to find ways to present and discuss the ascent of the space shuttle in a comprehensible form that is appropriate to the students' mathematical and conceptual understanding. This is a rich context, and an example of a *large-context problem*, that will engage the attention of all students and may clear up many of the common misconceptions held about the flight of the space shuttle.

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