Curiosity Heads for Mount Sharp

In July 2013, Curiosity began its long journey to the base of Mt Sharp, seen in the distance in this image. Because it is operated robotically, it only travels a few meters every hour and communicates with its Earth technicians after each step. Because radio waves take 20 minutes or longer to reach earth, 40 minutes elapse before a transmitted command is received and the results of the action can be verified.

The table below gives the progress made by Curiosity during several days of operation on Mars, called Sols.

Sol	Drive	Duration (minutes)	Odometer (meters)	Azimuth (degrees)	Pitch (degrees)
345	68	83	1490	235	-1
347	69	67	1550	236	-2
349	70	72	1621	190	+1
351	71	94	1706	249	+1
354	72	65	1763	304	+1

Problem 1 – What is the average time that Curiosity drove each day?

Problem 2 – What is the average distance traveled each day?

Problem 3 – 'Azimuth' is the direction you are pointing from North so that due North is 0^{o}, East is 90^{o}, South is 180^{o} and West is 270^{o}. What is the average azimuth angle that Curiosity traveled along during the tabulated period?

Problem 4 – 'Pitch' is the tilt angle of the land, with straight up being $+90^{o}$, horizontal being 0^{o} and straight down being -90^{o}. What is the average pitch of Curiosity's travels during this period and what can you tell about the ground over which it traveled?

Problem 5 – The direction to Mt Sharp is at an azimuth of 225^{o}. What does Curiosity's average azimuth have to be during the next 5 days so that it is back on course to Mt Sharp?

Problem 6 – Mt Sharp is located 7.5 km from Curiosity. About how many more Sols will be required for Curiosity to get there?

Answer Key

Problem 1 – What is the average time that Curiosity drove each day?

Answer: T = (83+67+72+94+65)/5 = 381 minutes/5 = **76 minutes/day**

Problem 2 – What is the average distance traveled each day?

Answer: D = (60 + 71 + 85 + 57)/4 = 273 meters/4 = **68 meters/day**.

Problem 3 – 'Azimuth' is the direction you are pointing from North so that due North is 0^o, East is 90^o, South is 180^o and West is 270^o. What is the average azimuth angle that Curiosity traveled along during the tabulated period?

Answer: A = (235+236+190+249+304)/5 = 1214/5 = **243^o**

Problem 4 – 'Pitch' is the tilt angle of the land, with straight up being $+90^o$, horizontal being 0^o and straight down being -90^o. What is the average pitch of Curiosity's travels during this period and what can you tell about the ground over which it traveled?

Answer: P = (-1 + -2 + +1 + +1 + +1)/5 = 0^o So the terraine was very level and horizontal.

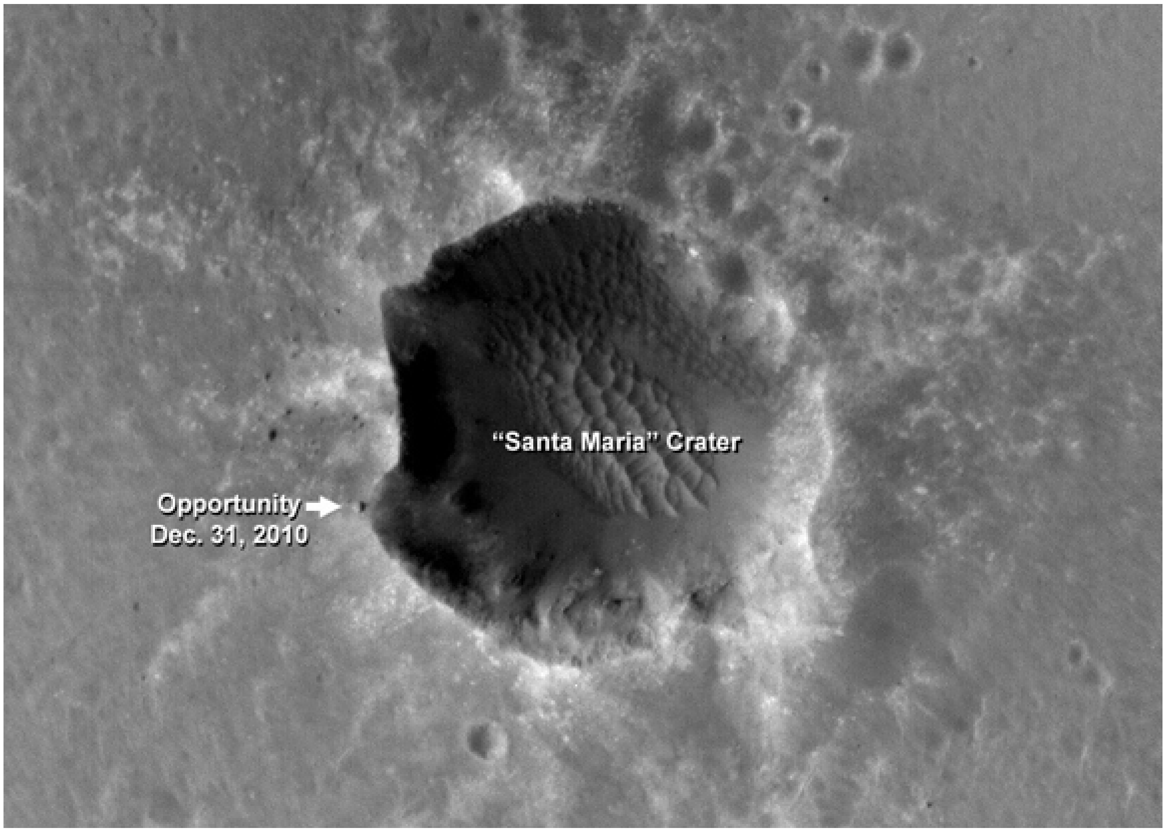
Problem 5 – The direction to Mt Sharp is at an azimuth of 225^o. What does Curiosity's average azimuth have to be during the next 5 days so that it is back on course to Mt Sharp?

Answer: 225 = [5 (243) + 5(X)] / 10
2250 – 1214 = 5X so **X = 207^o**

Problem 6 – Mt Sharp is located 7.5 km from Curiosity. About how many more Sols will be required for Curiosity to get there?

Answer: The average distance traveled was 68 meters/day so to travel 7500 meters will take T = 7500/68 = 110 Sols if Curiosity does not stop along the way.

Taking a Stroll around a Martian Crater



The High Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter acquired this image of the Opportunity rover on the southwest rim of "Santa Maria" crater on New Year's Eve 2010. Opportunity arrived at the western edge of Santa Maria crater in mid-December and will spend about two months investigating rocks there. That investigation will take Opportunity into the beginning of its eighth year on Mars. Opportunity is imaging the crater interior to better understand the geometry of rock layers and the meteor impact process on Mars. Santa Maria is a relatively young, 90 meter-diameter impact crater, but old enough to have collected sand dunes in its interior.

Problem 1 - Using a millimeter ruler, what is the scale of this image in meters per millimeter to one significant figure?

Problem 2 - To one significant figure, about what is the circumference of the rim of this crater in meters?

Problem 3 - The rover can travel about 100 meters in one day. To one significant figure, how long will it take the rover to travel once around this crater?

Problem 4 - A comfortable walking speed is about 100 meters per minute. To one significant figure, how long would it take a human to stroll around the edge of this crater?

Problem 1 - Using a millimeter ruler, what is the scale of this image in meters per millimeter to one significant figure?

Answer: The shape of the crater is irregular, but taking the average of several diameter measurements with a ruler gives a diameter of about 55 millimeters. Since this corresponds to 90 meters according to the text, the scale of this image is about 90 meters/55 mm = 1.8 meters/millimeter, which to one significant figure becomes
2 meters/millimeter.

Problem 2 - To one significant figure, about what is the circumference of the rim of this crater in meters?

Answer: Students may use a piece of string and obtain an answer of about 200 millimeters. Using the scale of the image in Problem 1, the distance in meters is about 200 mm x 2 meters/mm = **400 meters**.

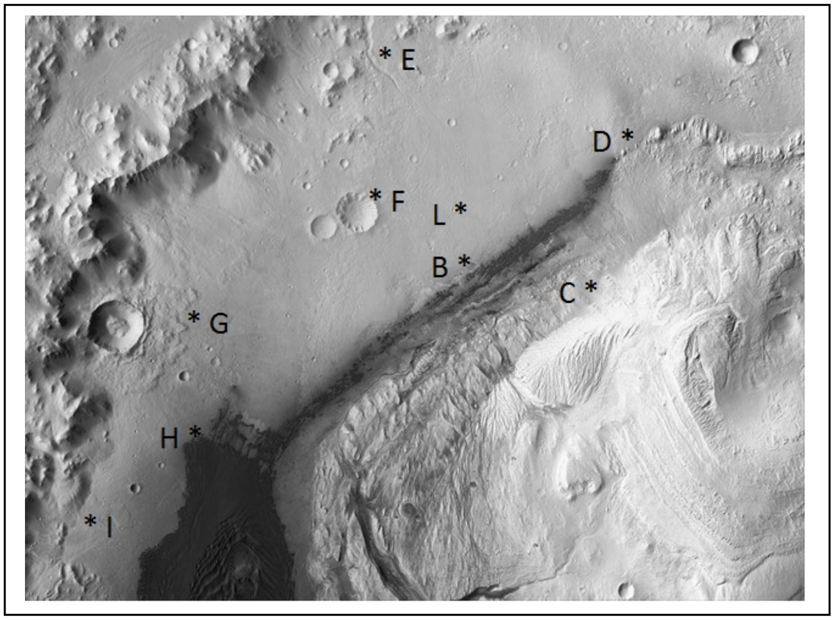
Problem 3 - The rover can travel about 100 meters in one day. To one significant figure, how long will it take the rover to travel once around this crater?

Answer: 400 meters x (1 day/100 meters) = **4 days**.

Problem 4 - A comfortable walking speed is about 100 meters per minute. To one significant figure, how long would it take a human to stroll around the edge of this crater?

Answer: 400 meters x (1 minute/100 meters) = **4 minutes**.

Exploring Gale Crater with the Curiosity Rover



The table below gives the coordinates for the locations to be visited by the Curiosity Rover shown in the figure above. The X and Y coordinates are given in kilometers. Although Curiosity is free to travel between most points on the map, Point C is at a much higher elevation than the other points located in the crater floor, and a steep and impassible cliff wall exists between points B and C and runs diagonally to the lower left.

Label	Name	(X,Y)	Label	Name	(X,Y)
L	Landing Area	(45,40)	F	Crater Wall	(38,43)
B	Layered Wall	(50,35)	G	Mudslide	(17,30)
C	Alluvial Fan	(60,32)	H	Dark Sands	(17,19)
D	Summit Access	(65,50)	I	Mystery Valley	(5,10)
E	River Bed	(37,58)			

Problem 1 – Curiosity can travel at a top speed of 300 meters/hr. As soon as it lands, Curiosity will be instructed to travel to the highest priority location first, just in case the mission prematurely fails. To the nearest kilometer, what is the distance traveled, and to the nearest hour, how long will it take to travel between Point L and Point B?

Problem 2 – To the nearest kilometer, what is the distance from Point D to Point I, and to the nearest hour, how long will it take Curiosity to travel this far?

Problem 3 – One possible path Curiosity might take that connects all of the points is represented by the sequence L-B-D-C-D-E-F-B-G-H-I. To the nearest kilometer, what is the total distance traveled, and to the nearest tenth, how many days will this journey take?

Answer Key

Problem 1 – Curiosity can travel at a top speed of 300 meters/hr. As soon as it lands, Curiosity will be instructed to travel to the highest priority location first, just in case the mission prematurely fails. To the nearest kilometer, what is the distance traveled, and to the nearest hour, how long will it take to travel between Point L and Point B?

Answer: L (45,40) and B (50,35). Using the Pythagorean Theorem and distance formula for Cartesian points $D = ((50-45)^2 + (35-40)^2)^{1/2}$ = **7 km**. Traveling at 300 m/hr, this will take 7000m/300m = **23 hours**.

Problem 2 – To the nearest kilometer, what is the distance from Point D to Point I, and to the nearest hour, how long will it take Curiosity to travel this far?

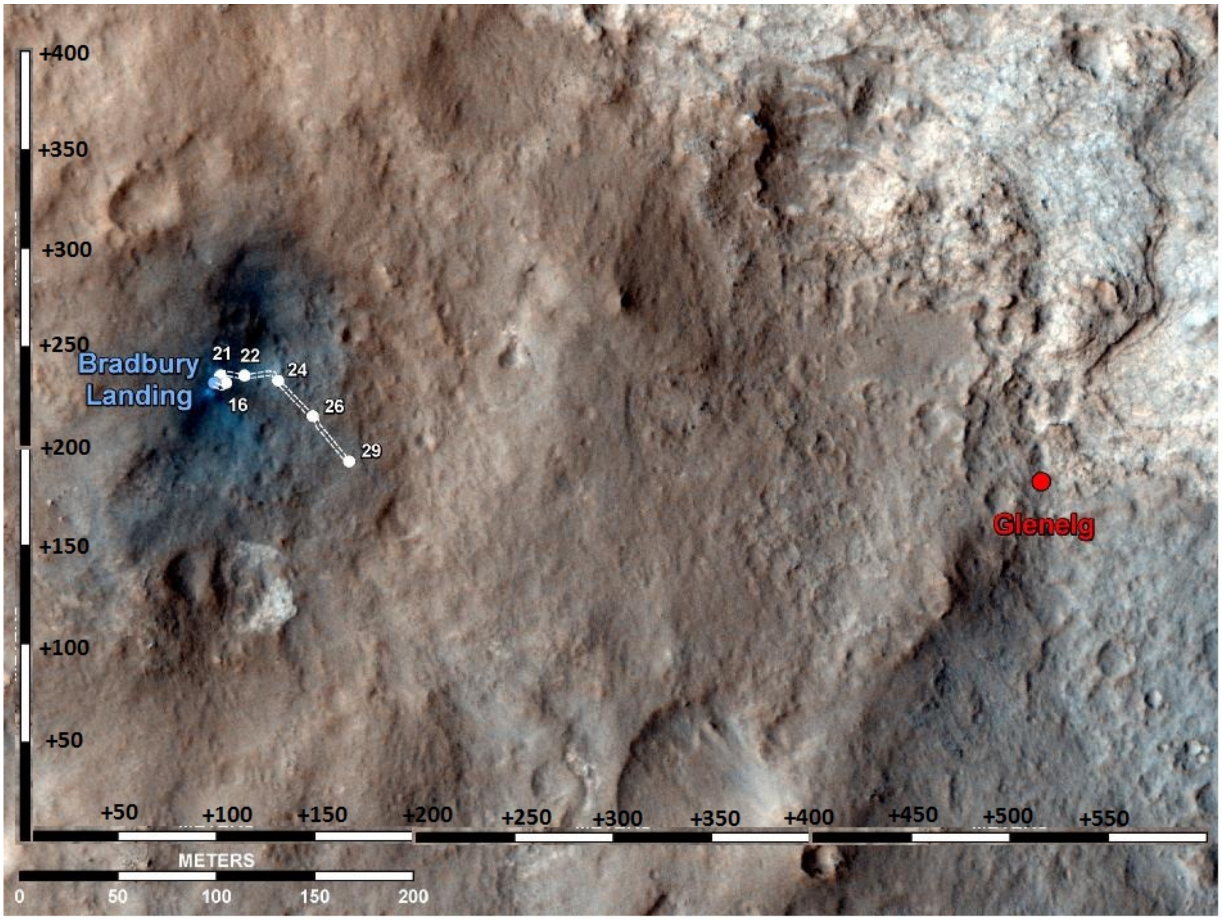
Answer: Point D (65,50), Point I (5,10). $D = ((5-65)^2 + (10-50)^2)^{1/2}$ = **72 kilometers**. Traveling at 300 m/hr, this takes 72000/300 = **240 hours** (or 10 days).

Problem 3 – One possible path Curiosity might take that connects all of the points is represented by the sequence L-B-D-C-D-E-F-B-G-H-I. To the nearest kilometer, what is the total distance traveled, and to the nearest tenth, how many days will this journey take?

$D(LB) = ((50-45)^2 + (35-40)^2)^{1/2} = 7$
$D(BD) = ((65-50)^2 + (50-35)^2)^{1/2} = 21$
$D(DC) = ((60-65)^2 + (32-50)^2)^{1/2} = 19$
$D(CD) = ((65-60)^2 + (50-32)^2)^{1/2} = 19$
$D(DE) = ((37-65)^2 + (58-50)^2)^{1/2} = 29$
$D(EF) = ((38-37)^2 + (43-58)^2)^{1/2} = 15$
$D(FB) = ((50-38)^2 + (35-43)^2)^{1/2} = 14$
$D(BG) = ((17-50)^2 + (30-35)^2)^{1/2} = 33$
$D(GH) = ((17-17)^2 + (19-30)^2)^{1/2} = 11$
$D(HI) = ((5-17)^2 + (10-19)^2)^{1/2} = 15$

Total distance traveled = **183 km**. Time = 183,000/300 = 610 hours = **25.4 days**

The Curiosity Rover on the Move!



The Curiosity Rover on Mars landed at Bradbury Station on Day 0 (Called Sol 0) and is headed for an important geological site called Glenelg. This map shows the location of the Rover until Sol 29. Also shown on the map is a coordinate grid marked in intervals of 50-meters. Bradbury Station is located at approximately (+100, +230). The table below gives the location of Curiosity for the period from Sol 29 to Sol 56. Students should use the distance formula to determine interval lengths: $d^2 = (x2-x1)^2 + (y2-y1)^2$ but they may also use millimeter rulers and the image scale to determine the distances between the points.

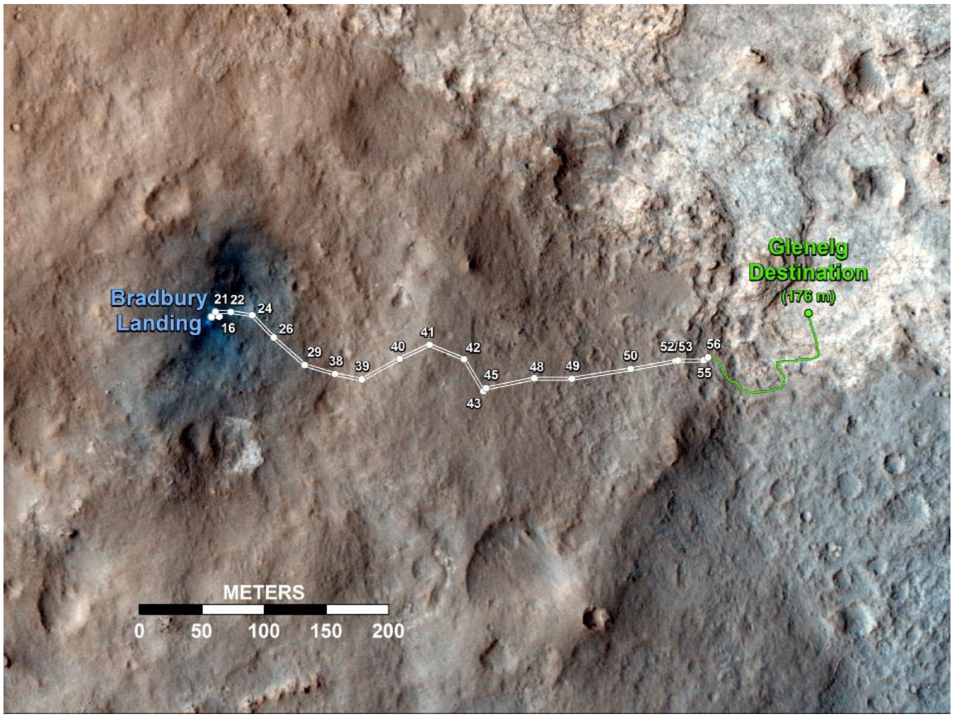
Day	X	Y	Day	X	Y
39	+210	+180	48	+360	+175
41	+270	+210	49	+390	+180
42	+300	+200	52	+470	+200
45	+315	+165	56	+500	+205

Problem 1 – Graph the additional points and connect them with line segments to show Curiosity's path across the martian landscape.

Problem 2 – During which segment was Curiosity traveling the fastest?

Problem 3 – During which segment was Curiosity traveling the slowest?

Problem 4 – What has been the average speed of Curiosity between Sol 39 and Sol 56?



Problem 1 – Graph the additional points and connect them with line segments to show Curiosity's path across the martian landscape. Answer: **See actual course above**.

Day	X	Y	Segment Time (days)	Segment Distance (m)	Segment Speed (m/d)
39	+210	+180			
41	+270	+210	2	67	34
42	+300	+200	1	32	32
45	+315	+165	3	38	13
48	+360	+175	3	46	15
49	+390	+180	1	30	30
52	+470	+200	3	82	27
56	+500	+205	4	30	8

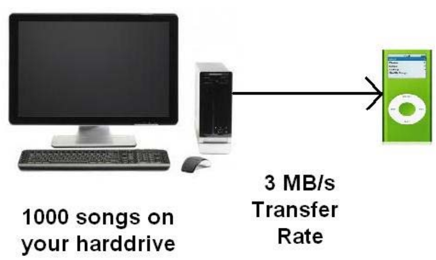
Example: Day 45 - Day 42 = 3 days. $D^2 = (315-300)^2 + (165-200)^2 = 1450$ so d = 38 meters and speed = 38meters/3days = 13 meters/day.

Problem 2 – During which segment was Curiosity traveling the fastest? **Between Sol 41 and Sol 42 at a speed of 34 meters per day.**

Problem 3 – During which segment was Curiosity traveling the slowest? **Between Sol 52 and Sol 56.**

Problem 4 – What has been the average speed of Curiosity between Sol 39 and Sol 56?
Total segment distance traveled = (67+32+38+46+30+82+30)=325 meters in 17 days
So **average speed = 19 meters/day.**

Exploring the InSight Lander Telemetry Data Flow



Transferring digital data from place to place takes time. Like water flowing into a lake, the faster it flows the more rapidly the lake fills up and overflows. With computer data, we have a similar problem. You have probably had to do this yourself many times. Each time you copy your playlist from your PC to your portable music player, you will have to wait a certain length of time. The transfer rate is fixed, so the more songs you want to transfer the longer you have to wait. Here’s how this works!

Problem 1 - Suppose you want to transfer 1000 songs from your PC collection to your music Player. Each 4-minute song takes up 4 megabytes on the PC, and the cable link from your computer to your Player can handle a transfer rate of 3 million bytes/second. How many minutes does it take to transfer all your songs to the Player?

Imagine a lake fed by one large slow-moving river that brings water to it, and a second small, fast-moving river that takes water from the lake. If the rates at which the water enters and leaves the lake are not in step, the lake’s water level will overflow. The InSight lander has a similar problem. It is gathering data at one rate, but transmitting it to Earth at another rate. We don’t want to lose any of the data, so the data has to be stored in a memory device called a buffer.

InSight has two instruments that generate constant streams of digital data. The SEIS seismometer produces 48 megabytes/hr and the HP3 produces 2 megabytes/hr. This data is stored in a 500 megabyte buffer. Every 2 hours, the data in the buffer is transmitted to Earth at a rate of 4 megabytes/sec.

Problem 2 - How long will it take to fill up the buffer with data?

Problem 3 - How long will be required to transmit the buffer data to Earth during each 2-hour transmission cycle?

Problem 4 – The receiver on Earth can be scheduled to contact the Lander as often as once every 2 hours. How large a buffer would you need so that you could gather as much data as 4 megabytes/sec over 2 hours? How long does it take the instruments to gather this much data?

Problem 1 - You want to transfer 1000 songs from your PC collection to your music Player. Each 4-minute song takes up 4 megabytes, and the cable link from your computer to your Player can handle a transfer rate of 3 million bytes/second. How many minutes does it take to transfer all your songs?

Answer: 4000 megabytes x (1 second/ 3 megabytes) = 1333 seconds or about **22 minutes**.

The InSight lander has two instruments that generate constant streams of digital data. The SEIS seismometer produces 48 megabytes/hr and the HP3 produces 2 megabytes/hr which is stored in a 500 megabyte digital memory called a buffer. Every 2 hours, the data in the buffer is transmitted to Earth at a rate of 4 megabytes/sec.

Problem 2 - How long will it take to fill up the buffer with data?

Answer: The data enters the buffer at 50 megabytes/hr and the buffer contains 500 megabytes, so it can store data for 500 MBytes/(50Mbytes/hr) = **10 hours**.

Problem 3 - How long will be required to transmit the buffer data to Earth during each 2-hour transmission cycle?

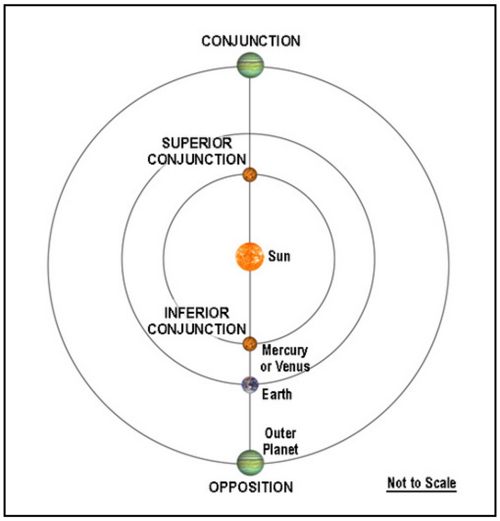
Answer: In 2 hours at a data rate of 50 megabytes/hr you have 100 megabytes stored in the buffer. At a transmission rate of 4 megabytes/sec it takes 100 Mbytes/(4 Mbytes/sec) = **25 seconds** to transmit the100 megabytes from the buffer to Earth.

Problem 4 – The receiver on Earth can be scheduled to contact the Lander as often as once every 2 hours. How large a buffer would you need so that you could gather as much data as 4 megabytes/sec over 2 hours? How long does it take the instruments to gather this much data?

Answer: 2 hours equals 2 x 3600 = 7200 seconds. At a transmission rate of 4 Mbytes/sec, this equals 7200 sec x 4 Mbytes/sec = 28,800 Megabytes or **28.8 Gigabytes.**

The instruments gather 50 Megabytes/hour, so it would take them 28,800 Megabytes/(50 MB/hr) = 576 hours or 24 days to gather this much data.

What this says is that if you had a buffer this large (28.8 gigabytes) it could store 24 days of data from InSight and only take 2 hours to transmit to Earth. The danger of waiting so long to transmit data (every 24 days) is that something could happen to the lander and you would lose all this data! That's why scientists try to download their data as often as possible.



The InSight Lander needs to be in constant communication with Earth every day the data it gathers can be sent back to Earth. As viewed from the surface of Mars, Earth never gets very far from the sun. Over the course of about 780 days, Earth travels from its farthest westward position in the sky (morning star) of 46^{o} W, to its farthest eastward position (evening star) of 41^{o} E and back in about 780 days.

When the Earth-Sun angle is near zero as viewed from Mars, Earth can either be between Mars and the sun (called Inferior Conjunction) or Earth can be on the opposite side of the sun as viewed from Mars (called Superior Conjunction).

When Mars and Earth are in inferior conjunction, Earth can receive signals from the Lander, but the Lander will have to broadcast its data almost directly at the sun, which is a hazard for the transmitter. When Earth and Mars are in superior conjunction, Neither InSight nor the Earth radar can transmit or receive data with Earth behind the sun.

Problem 1 – The following table gives the Earth-Sun angle viewed from Mars during the time InSight is operating on the martian surface. During this time, inferior conjunction occurred on May 22, 2016 and July 26, 2018, with superior conjunction on July 27, 2017. When will the next inferior conjunction occur after July 26, 2018?

Month	Angle	Month	Angle	Month	Angle	Month	Angle
9/16	+46	3/17	+24	9/17	-10	3/18	-40
10/16	+45	4/17	+18	10/17	-17	4/18	-41
11/16	+42	5/17	+13	11/17	-23	5/18	-37
12/16	+38	6/17	+7	12/17	-28	6/18	-27
1/17	+34	7/17	+1	1/18	-33	7/18	-7
2/17	+29	8/17	-5	2/18	-38		

Angular data obtained from *Eyes on the Solar System* (February 28, 2013).

Problem 2 – InSight will end its operations after one full martian year (687 days). If it lands on September 20, 2016, during which months of operation will Earth be within 10 degrees of the sun at conjunction, and unable to communicate with Earth?

Problem 3 - Graph the data in the table. During which months will the Earth-Mars angle A) be changing the most rapidly? B) the slowest?

Problem 1 – When will the next superior conjunction occur after July 26, 2018?

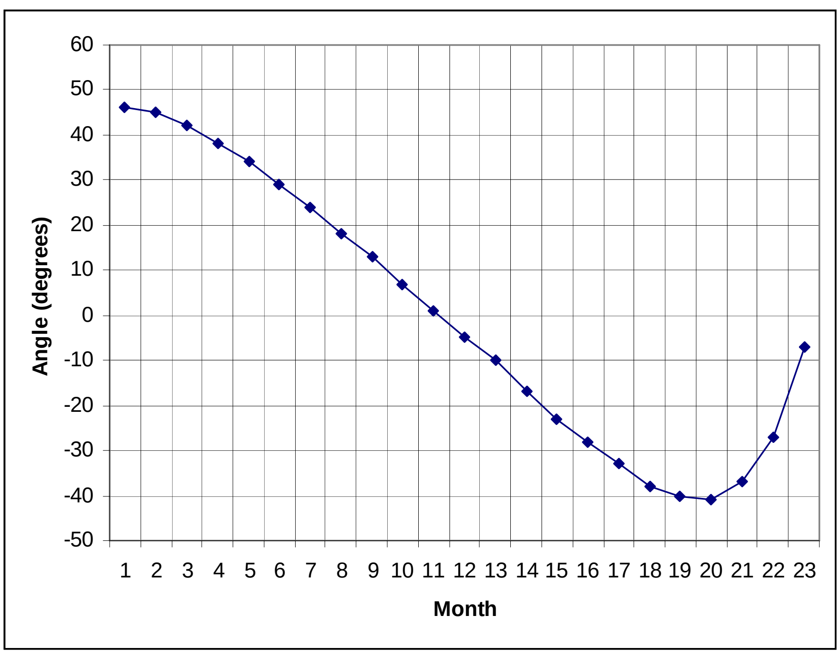
Answer: Each pair of superior and inferior conjunctions happen in cycles. The time for one cycle can be found by the time between the dates of the two listed inferior conjunctions on 5/22/2016 and 7/26/2018. Students can find the number of days between these dates manually (hard), or they can use an online calculator (fun!) like http://www.timeanddate.com/date/duration.html to get 796 days. To find the next superior conjunction, add 796 days to July 27, 2017 (eg. http://www.timeanddate.com/date/dateadd.html) to get **May 4, 2019**.

Problem 2 – InSight will end its operations after one full martian year (687 days). If it lands on September 20, 2016, during which months of operation will Earth be within 10 degrees of the sun at conjunction, and unable to communicate with Earth?

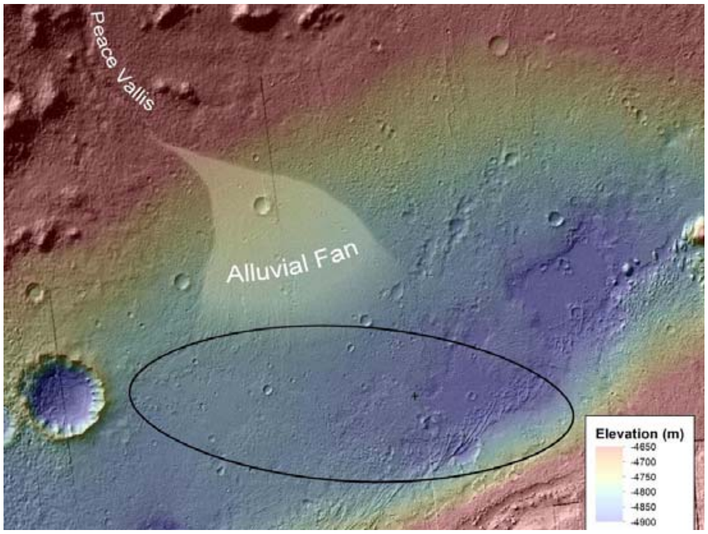
Answer: Conjunction occurs on July 27, 2017. From the table, Earth is within 10 degrees of the sun during the months of **June 2017 to August 2017** so it will be difficult to directly transmit or receive data during this time.

Problem 3 - Graph the data in the table. During which months will the Earth-Mars angle A) be changing the most rapidly? B) the slowest?

Answer: Students may use Microsoft Excel. X-axis may be the month number.
A) June-July, 2018.
B) During September-November, 2016 and February-April, 2018. Slow changes correspond to a nearly flat 'slope' while fast changes correspond to the steepest slope.



Curiosity Discovers Ancient Mars River !



The Curiosity Rover discovered rounded pebbles near its original landing site marked with the ‘X’ in the figure. The figure also shows the elevation changes in this area. Here is what the pebbles looked like ! The white bar is 1 cm long.

Geologists studying the pebbles and the landscape believe that the water flow that moved and rounded the pebbles was at least ankle deep and perhaps waist deep. As on Earth, the pebbles were carried by fast moving water and over time became rounded by the constant scraping and bouncing. How fast was the water moving?

Calculating the stream gradient:

Problem 1 – The landing ellipse is 18 km wide. To the nearest kilometer, how far is the Curiosity ‘X’ from the apex of the alluvial fan near Peace Valllia?

Problem 2 – What is the change in elevation, h, between the alluvial fan vertex and the ‘X’.?

Problem 3 – The stream gradient is defined as the elevation difference divided by the distance traveled. What is the stream gradient, SG, in units of meters/meters, for the water which left Peace Vallis and flowed down the alluvial fan?

Calculating the stream flow speed:

Problem 4 – On Mars, the stream flow can be approximated by $V = (2gh)^{1/2} \sin(\theta)$ where $\tan(\theta) = SG$, $g = 3.8$ meters/sec^2 is the acceleration of gravity on Mars, and h is the difference in elevation of the top and bottom of the stream. About how fast was the water flowing past the Curiosity landing area to create the pebbles?

Calculating the stream gradient:

Problem 1 – The landing ellipse is 18 km wide. To the nearest kilometer, how far is the Curiosity 'X' from the apex of the alluvial fan near Peace Valllia? Answer: **About 15 km**.

Problem 2 – What is the change in elevation, h, between the alluvial fan vertex and the 'X'.? Answer: -4650 m – (-4900 m) so h = **250 meters.**

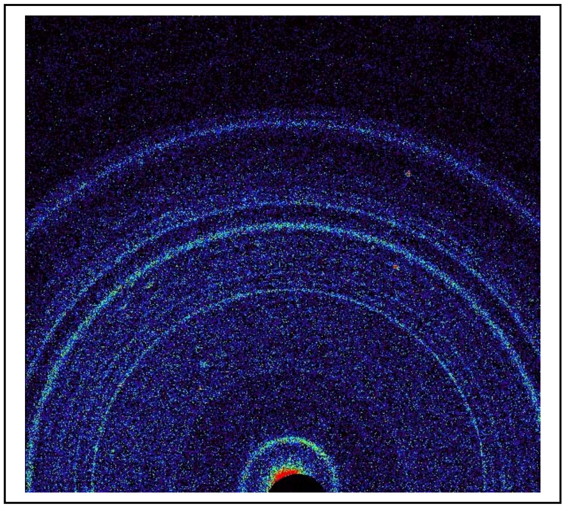
Problem 3 – The stream gradient is defined as the elevation difference divided by the distance traveled. What is the stream gradient, SG, in units of meters/meters, for the water which left Peace Vallis and flowed down the alluvial fan? 250 meters / 15 km = **17 meters/kilometer or SG=0.017 meters/meter.**

Calculating the stream flow speed:

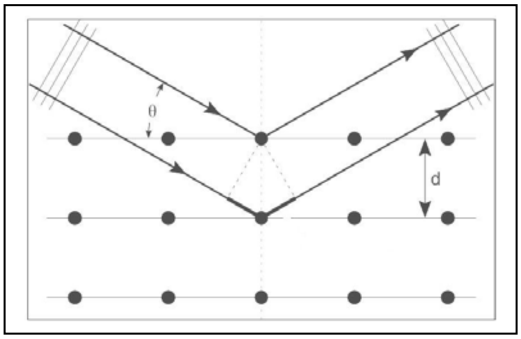
Problem 4 – On Mars, the stream flow can be approximated by $V = (2gh)^{1/2} \sin(\theta)$ where $\tan(\theta)$ = SG, and g = 3.8 meters/sec^2 is the acceleration of gravity on Mars. About how fast was the water flowing past the Curiosity landing area to create the pebbles?

Answer: h = 650 meters, SG=0.017, g = 3.8 meters/sec^2 . then q = 1.0 degrees.
$V = (2 \times 3.8 \times 650)^{1/2} \sin(1.0)$
V = 1.2 meters/sec.

This is about as fast as a human walking very slowly (about 0.3 miles/hr or 4.3 km/hr).



The Curiosity Rover recently use a technique called X-ray Diffraction Crystallography to determine the identity of compounds found in a rock sample on the surface of Mars. The image to the left shows what this data looks like. The exact radii of these rings, and the locations of spots along these rings, serve as a fingerprint of the shape of the mineral compound in space. We all know how human fingerprints work, and even 'DNA' fingerprinting is commonly mentioned in TV programs like NCIS or CSI. But how does this technique work?



The figure to the left shows a beam of light striking the surface of a crystal with 15 atoms arranged into three parallel planes. The light strikes the atoms and is 'defracted' into a new direction defined by the angle θ.

If two beams of light are out-of-phase by 90 degrees, when they are added together, the crests of one wave interfere with the troughs of the other wave and you end up with no light. If they are in-phase, they will add together, you get the light intensified and you also get a ring of light!

The diagram shows the added distance that the lower ray gains by being diffracted through the angle θ.

Problem 1 – From the information in the diagram, what is the extra distance, s, traveled by the x-ray light in a crystal lattice where the planes are separated by a distance d?

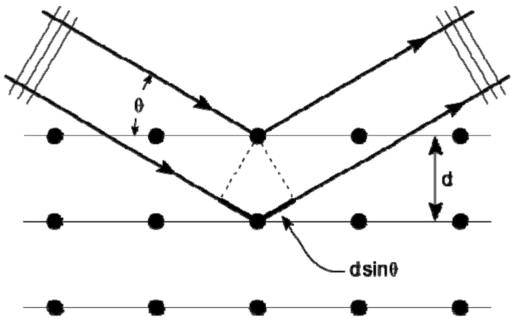
Problem 2 - If the light struck the crystal exactly face-on ($\theta=90^{O}$) how much extra distance would the second beam travel compared to the first beam that was reflected only from the top surface?

Problem 3 – If the wavelength of the x-ray light is L, what is the relationship between L and s so that the wave crests exactly match up?

Problem 4 – Suppose that in the Curiosity data, a diffraction ring is detected at an angle of incidence $\theta=2^{O}$. The Curiosity instrument uses X-rays with an energy of 6.929 keV, which have a wavelength of $1.79\text{x}10^{-10}$ meters. What is the separation, d, of the crystal planes in the mineral sample?

Problem 1 – From the information in the diagram, what is the extra distance, L, traveled by the x-ray light in a crystal lattice where the planes are separated by a distance d?

Answer: From the diagram below, **s = 2d sin** θ



Problem 2 - If the light struck the crystal exactly face-on ($\theta=90^{o}$) how much extra distance would the second beam travel compared to the first beam that was reflected from the top surface?

Answer: **s = 2d**

Problem 3 – If the wavelength of the x-ray light is L, what is the relationship between L and s so that the wave crests exactly match up?

Answer: The wavelength is L and for the waves to exactly match up, the two waves can either be shifted by s=0, or by **one full wavelength** s = L. So the first non-zero condition is that L = 2 d sinθ and so

$$d = \frac{L}{2\sin\theta}$$

Problem 4 – Suppose that in the Curiosity data, a diffraction ring is detected at an angle of incidence $\theta=2^{o}$. The Curiosity instrument uses x-rays with an energy of 6.929 keV, which have a wavelength of 1.79×10^{-10} meters. What is the separation, d, of the crystal planes in the mineral sample?

Answer: d = 1.79×10^{-10} meters/($2\sin2^{o}$) so d = **2.56×10^{-9} meters**.