Sensory robotics

Lecture 08.

i) Sensors and measurement methods of
Curiosity Rover on MARS

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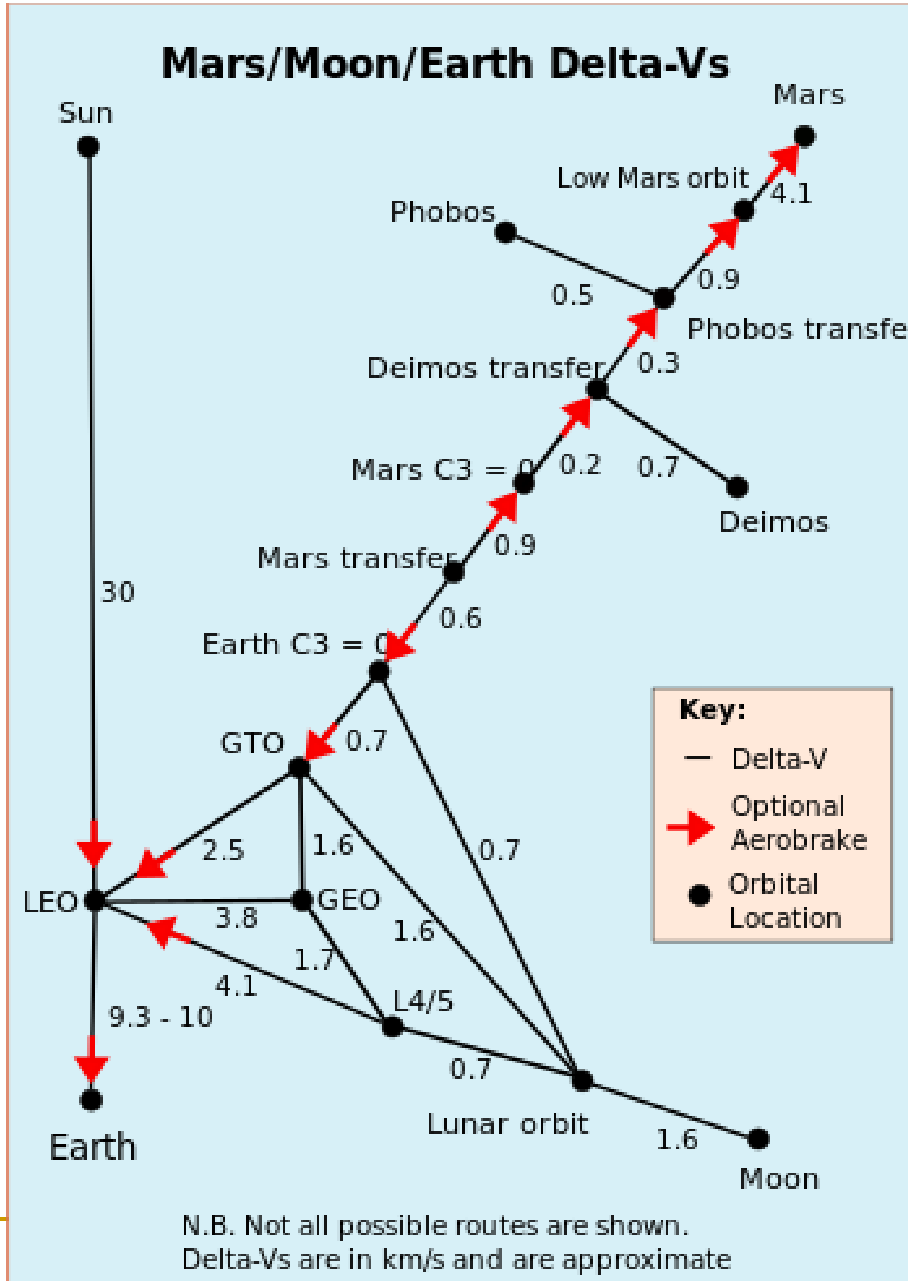
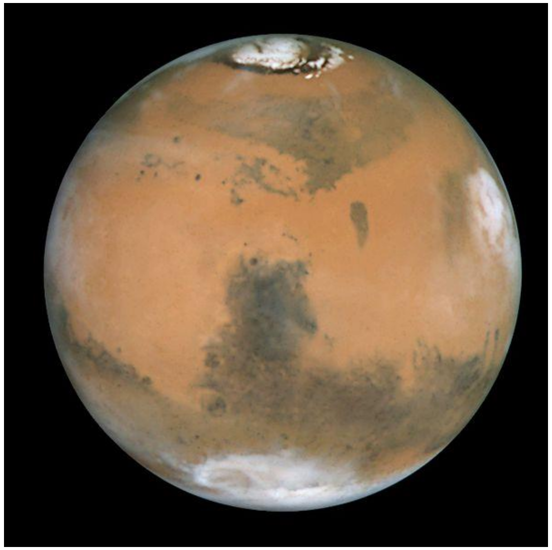
Sensors and measurement methods of Curiosity Rover on MARS

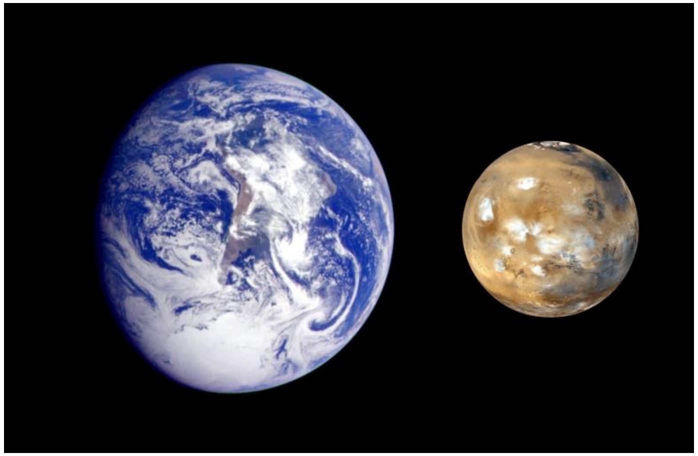
- *Source: Jet Propulsion Laboratory webpage http://msl-scicorner.jpl.nasa.gov/*
- *Source: NASA webpage* https://mars.nasa.gov/
- ChemCam (Chemistry and Camera complex); APXS (Alpha-particle X-ray spectrometer); CheMin (“Chemistry and Mineralogy”); SAM (Sample Analysis at Mars); RAD (Radiation Assessment Detector); DAN (Dynamic Albedo of Neutrons); REMS (Rover Environmental Monitoring Station); 17 cameras; MAHLI (Mars Hand Lens Imager); MARDI (Mars Descent Imager); MastCam;
- Youtube videos



- Source: wikipedia

MARS

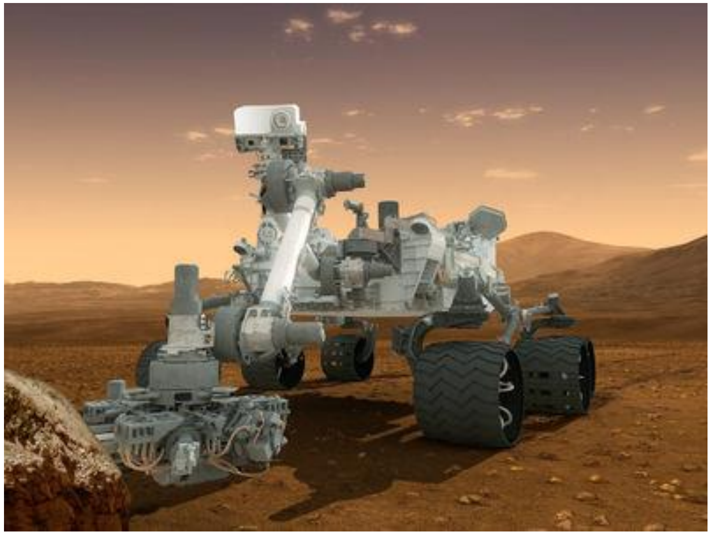


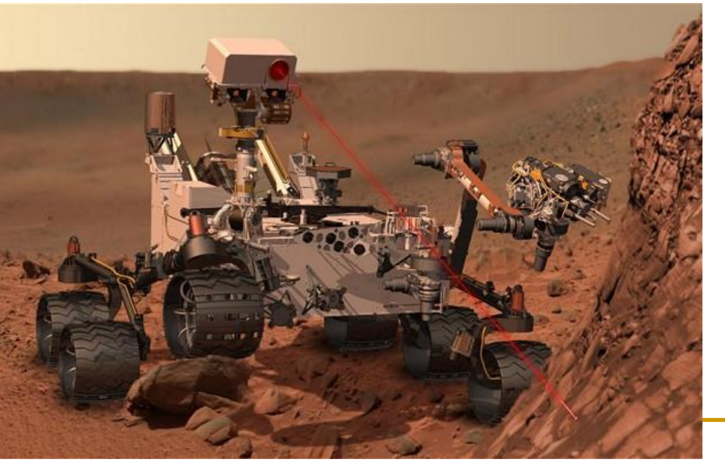


- **Mars** is the fourth planet from the Sun and the second smallest planet in the Solar System
- It is often described as the "Red Planet", as the iron oxide prevalent on its surface gives it a reddish appearance
- Mars is a terrestrial planet with a thin atmosphere
- Mars has two moons, which are small and irregularly shaped
- Mars can easily be seen from Earth with the naked eye

WHY EXPLORING MARS ?

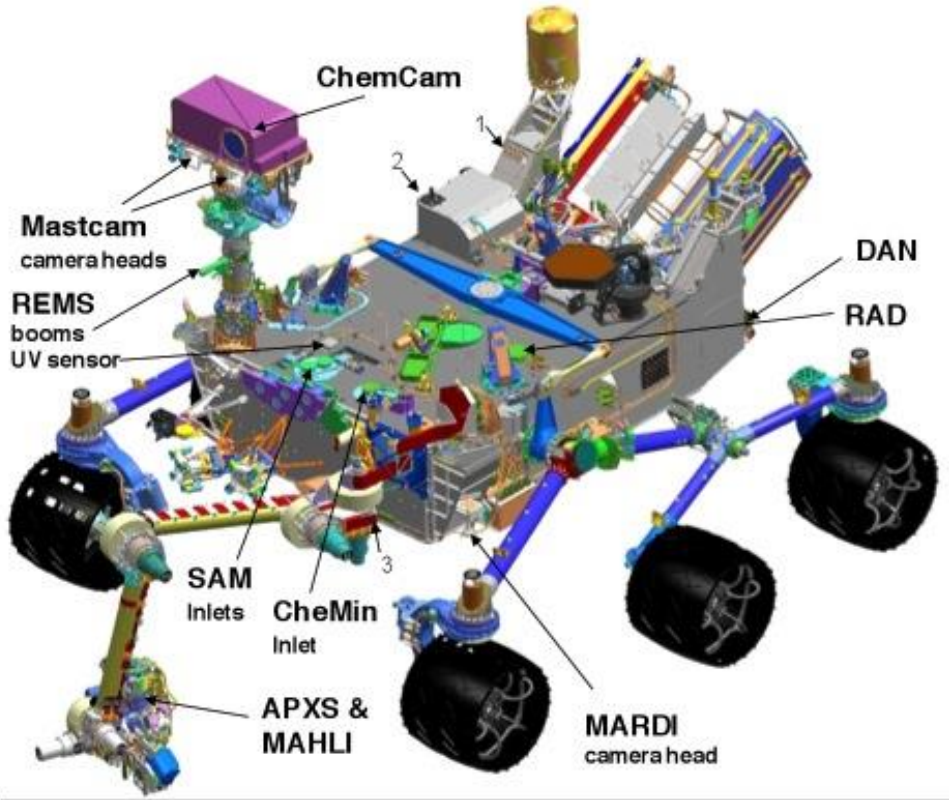
- The rotational period and seasonal cycles of Mars are likewise similar to those of Earth (Martian day about 24 hour and 35 min)
- Exploring existence of life and it's constituents, which include:
  - Searching of Water
  - Study Martian's chemical elements and geology
  - Study the weather and radiation
- Huge business …





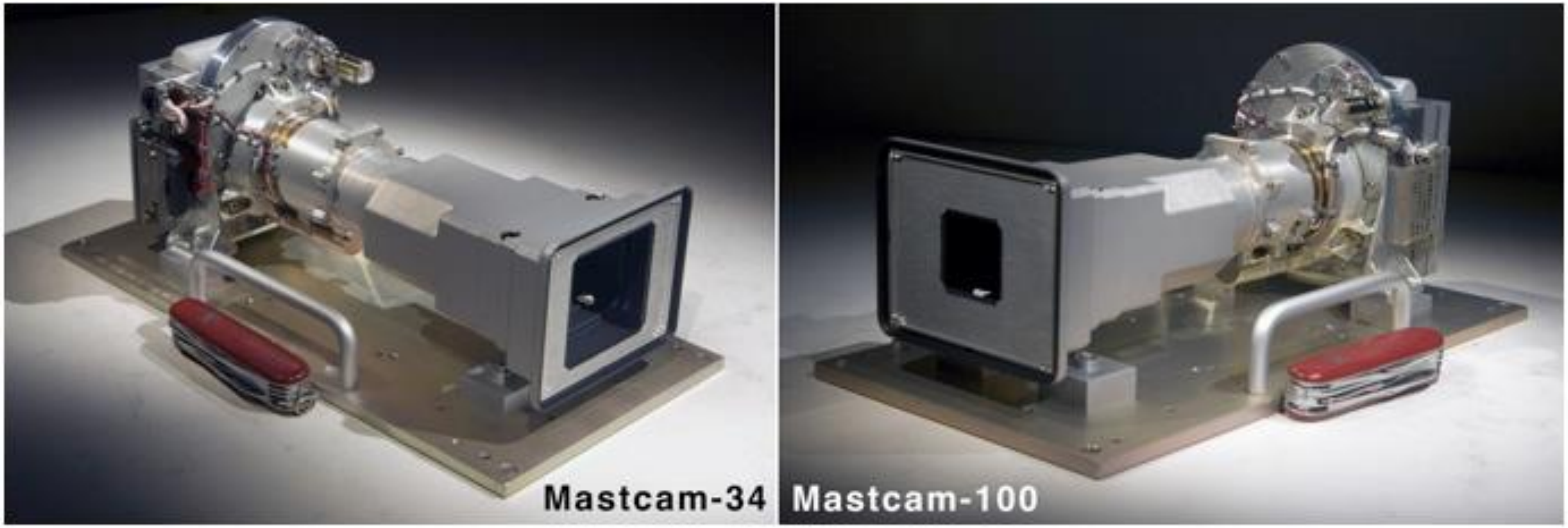
NASA's Mars Rover Curiosity - Landing

Sensors of Curiosity Rover



- **REMOTE SENSING**
- **Mastcam** (M. Malin, MSSS) - Color and telephoto imaging, video, atmospheric opacity
- **ChemCam** (R. Wiens, LANL/CNES) – Chemicacomposition; remote micro-imagingl
- **CONTACT INSTRUMENTS (ARM)**
- **MAHLI** (K. Edgett, MSSS) –Han-lens color imagingd
- **APXS** (R. Gellert, U. Guelph, Canada) - Chemical composition
- **ANALYTICAL LABORATORY (ROVER BODY)**
- **SAM** (P. Mahaffy, GSFC/CNES) - Chemical and isotopic composition, including organics
- **CheMin** (D. Blake, ARC) - Mineralogy
- **ENVIRONMENTAL CHARACTERIZATION**
- **MARDI** (M. Malin, MSSS) - Descent imaging
- **REMS** (J. Gómez-Elvira, CAB, Spain) - Meteorology / UV
- **RAD** (D. Hassler, SwRI) - High-energy radiation
- **DAN** (I. Mitrofanov, IKI, Russia) - Subsurface hydrogen

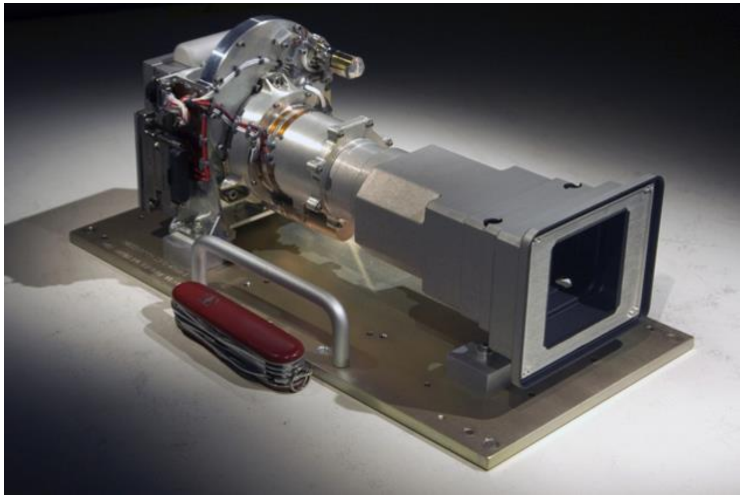
Mast kamera (Mastcam)

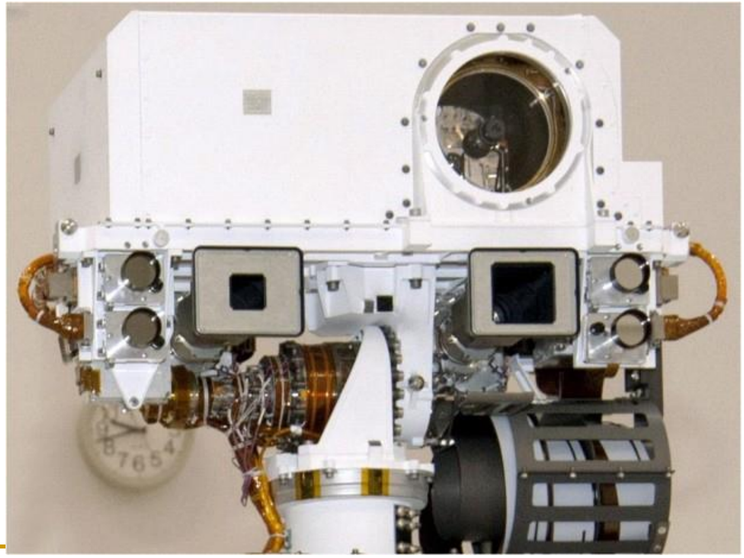


- Fixed-focal length (FFL) Mastcams. The only distinguishing difference in outward appearance between the cameras is the aperture size in the front baffle.

Mast Camera (MastCam)

- The MastCam system provides multiple spectra and true-color imaging with two cameras
- The cameras can take true-color images at 1600×1200 pixels and up to 10 fps and video at 720p (1280×720)
- Each camera has 8 GB of flash memory, which is capable of storing over 5,500 raw images, and can apply real time lossless data compression
- The cameras have an autofocus capability that allows them to focus on objects from 2.1 m (6 ft 11 in) to infinity





Mast Camera (Mastcam)

- The Mast Camera is a two-instrument suite of imaging systems mounted on the MSL rover's Remote Sensing Mast (RSM), with the boresight **~1.97 m** above the bottom of the wheels when the rover is on a flat surface.
- The Mastcam consisted of two identical area-array digital cameras each with a **6.5-100 mm** (15:1) variable-focal length (VFL) (zoom telephoto**) lens**, whose electronics were identical to the electronics of the MARDI and MAHLI cameras, also provided by Malin Space Science Systems.
- These cameras would have provided same focal length binocular vision for stereoscopic studies at all focal lengths as well as **14 filter** positions for scientific multispectral studies.

Mast Camera (Mastcam)

- The FFL Mastcams (we use the plural here because the “eyes” of the FFL Mastcam investigation are not identical) as built and delivered consist of **two cameras** with different focal lengths and different science color filters. The stereo baseline of the pair is ~24.5 cm.
- One camera, referred to as the Mastcam-34 (M-34), has a ~**34 mm focal length**, f/8 lens that illuminates a 15° square field-of-view (FOV), 1200 × 1200 pixels on the 1600 × 1200 pixel detector.
- The other camera, the Mastcam-100 (M-100), has a ~**100 mm focal length**, f/10 lens that illuminates a 5.1° square, 1200 × 1200 pixel FOV. Both cameras can focus between 2.1 m (nearest view to the surface) and infinity. The M-100 IFOV is 7.4×10^{-5} radians, yielding 7.4 cm/pixel scale at 1 km distance and ~150 μm/pixel scale at 2 m distance. The M-34 IFOV is 2.2×10^{-4} radians, which yields a pixel scale of 450 μm at 2 m distance and 22 cm at 1 km.
- A strict definition of “in focus” is used for these cameras wherein the optical blur circle is equal to or less than one pixel across.

Mast Camera (Mastcam)

- Each camera has an **8 gigabyte internal buffer** that permits it to store over 5,500 raw frames.
- Each camera is capable of losslessly compressing the images, or applying lossy JPEG compression, in realtime during acquisition and storage, although it is more likely that images will be acquired raw and compressed just prior to downlink to Earth. The 8 gigabytes is equivalent to a full-scale mosaic of **360° × 80° imaged** in 3 science color filters with >= 20% overlap between adjacent images. With minimally lossy JPEG compression (e.g., a factor of 2), a mosaic including all science filters could be acquired.
- **This is much more than can be transmitted back to Earth** under normal communication limitations. Subframing of images is only available at acquisition, not during later processing.
- **Color thumbnail images of 150 × 150 pixels** can be created simultaneously with the acquisition of full scale images, or during processing just prior to downlink.

Mast Camera (Mastcam)

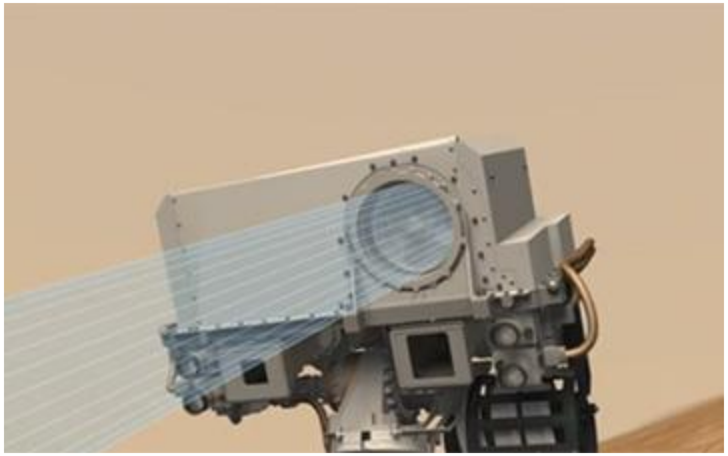
- The primary objectives of the Mastcam investigation are to characterize and determine **details of the history and processes recorded in geologic material at the MSL landing site**. Both Mastcams can acquire panoramic, color, multispectral images and together are able to acquire stereoscopic observations to address the following specific objectives:
- Observe landscape physiography and processes in order to provide a full description of the topography, geomorphology, and geologic setting of the MSL **landing site** and the nature of past and present geologic processes at the site
- **Examine the properties of rocks** (i.e., outcrops down to clasts as small as 0.15 mm) and the results of interaction of rover hardware with rocks to help determine morphology, texture, structure, mineralogy, stratigraphy, rock type, history/sequence, and depositional, diagenetic, and weathering processes for these materials
- Study the **properties of disaggregated materials** (fines as small as 0.15 mm) to determine the processes that acted on these materials and individual grains within them, including physical and mechanical properties, the results of interaction of rover hardware with fines, plus stratigraphy, texture, mineralogy, and depositional processes

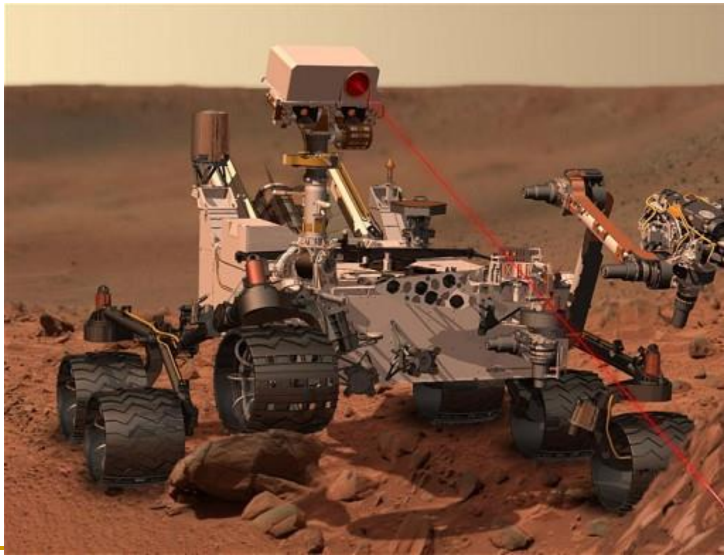
Mast Camera (Mastcam)

- **View frost, ice, and related processes**, if present, to determine texture, morphology, thickness, stratigraphic position, and relation to regolith and, if possible, observe changes over time; also examine ice-related (e.g., periglacial) geomorphic features
- Document atmospheric and **meteorological events** and processes by observing clouds, dust-raising events, properties of suspended aerosols (dust, ice crystals), and (using the video capability) eolian transport of fines
- **Support/facilitate rover operations**, analytical laboratory sampling, contact instrument science, and other MSL science by assisting rover navigation, acquiring images that help determine the location of the Sun, horizon features, and provide information pertinent to rover trafficability (e.g., hazards at hundreds of meters distance), and for other MSL science instruments, provide data that helps the MSL science team identify and characterize materials to be collected or studied in situ.

Chemistry and Camera complex

- ChemCam is a suite of remote sensing instruments, it's actually two different instruments combined as one: **a laser-induced breakdown spectroscopy (LIBS) and a Remote Micro Imager (RMI) telescope**.
- The purpose of the LIBS instrument is to provide **elemental compositions of rock and soil**, while the RMI will give ChemCam scientists **high-resolution images** of the sampling areas of the rocks and soil that LIBS targets
- The LIBS instrument can target a rock or soil sample from **up to 7 meters away**





LIBS instrument

- The LIBS instrument uses **powerful laser pulses**, focused on a small spot on target rock and soil samples within 7 m of the rover, to ablate atoms and ions in electronically excited states from which they decay, producing light-emitting plasma.
- The power density needed for LIBS is > **10 MW/mm^2**, which is produced on a spot in the range of **0.3 to 0.6** mm diameter using focused, ~14 mJ laser pulses of 5 nanoseconds duration.
- The plasma light is collected by a **110 mm diameter** telescope and focused onto the end of a fiber optic cable. The fiber carries the light to three dispersive spectrometers which record the spectra over a range of 240 - 850 nm at resolutions from 0.09 to 0.30 nm in 6144 channels.
- The **spectra consist of emission lines of elements** present in the samples. Typical rock and soil analyses yield detectable quantities of Na, Mg, Al, Si, Ca, K, Ti, Mn, Fe, H, C, O, Li, Sr, and Ba. Other elements often seen in soils and rocks on Earth include S, N, P, Be, Ni, Zr, Zn, Cu, Rb, and Cs.
- It is anticipated that **50-75 laser pulses will be required** achieve the desired 10% accuracy for major elements at 7 m distance.

LIBS instrument

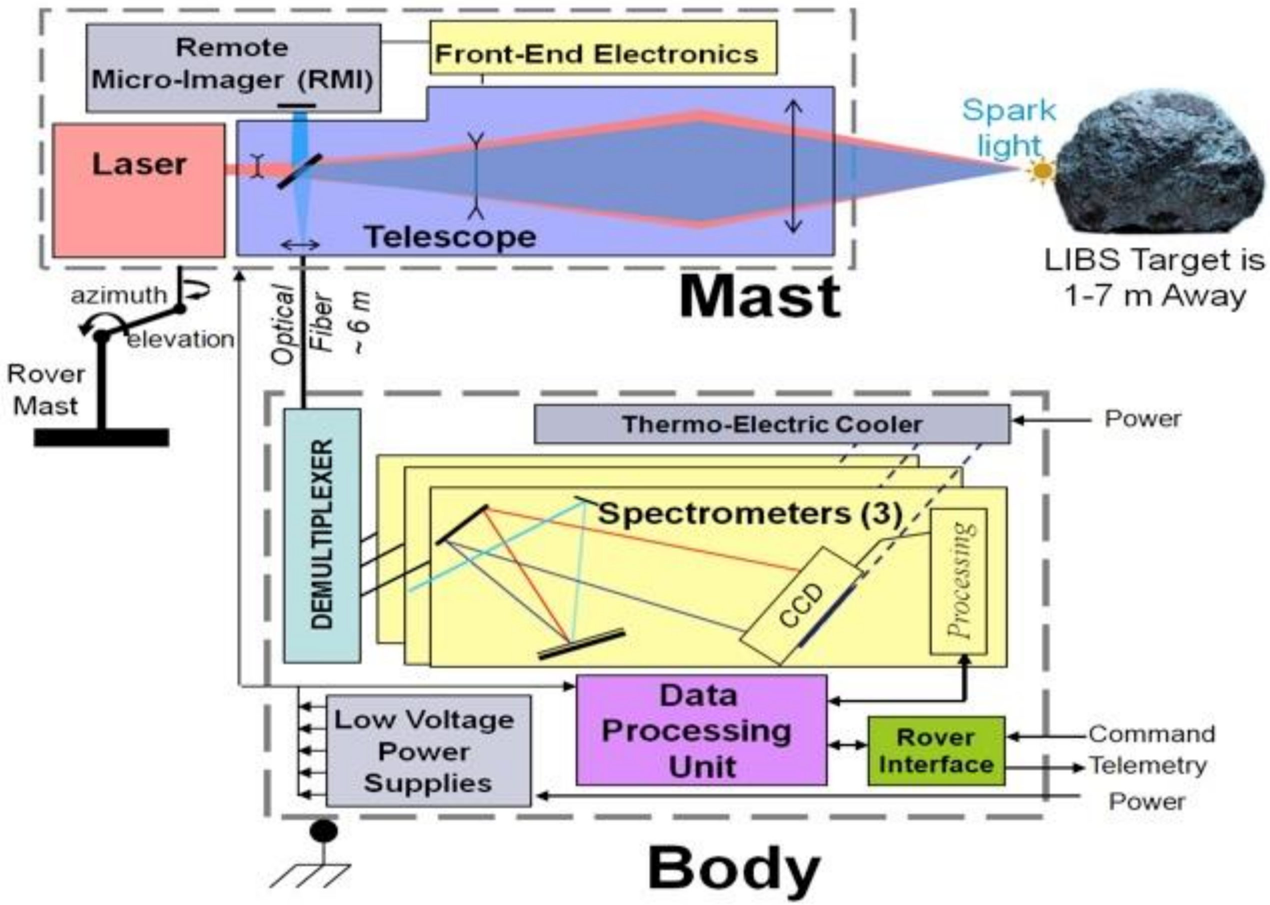
- The advantages of the LIBS instrument are:

- **Remote elemental analysis** with no sample preparation
- Ability **to remove dust and weathering layers** with repeated laser pulses trained on the same spot
- **Simultaneous analysis** of many elements
- Low detection limits for a number of minor and trace elements, including Li, Sr, and Ba
- **Rapid analysis**; one laser shot can constitute an analysis, though many spectra are often averaged for better statistics, still only taking a few seconds
- Small **analysis spot size of < 0.6 mm diameter**
- Ability to **identify water and/or hydrated minerals**
- **Low power consumption** resulting from very short analysis times

RMI instrument

- The Remote Micro-Imager (RMI) is intended as a context imager for the LIBS, though unlike LIBS, it has **no restrictions on the distance** to the targets it images.
- It images through the same telescope as the LIBS, with the camera wavelength response shown in the figure at right. The detector is a 1024 x 1024 pixel CCD. The RMI has a field of view of 19 milliradians.
- Due to optimization of the telescope for LIBS, the **RMI resolution is not pixel-limited**. The RMI can clearly distinguish the s**ubmillimeter** LIBS spot on a metal plate at any distance within range of the LIBS.

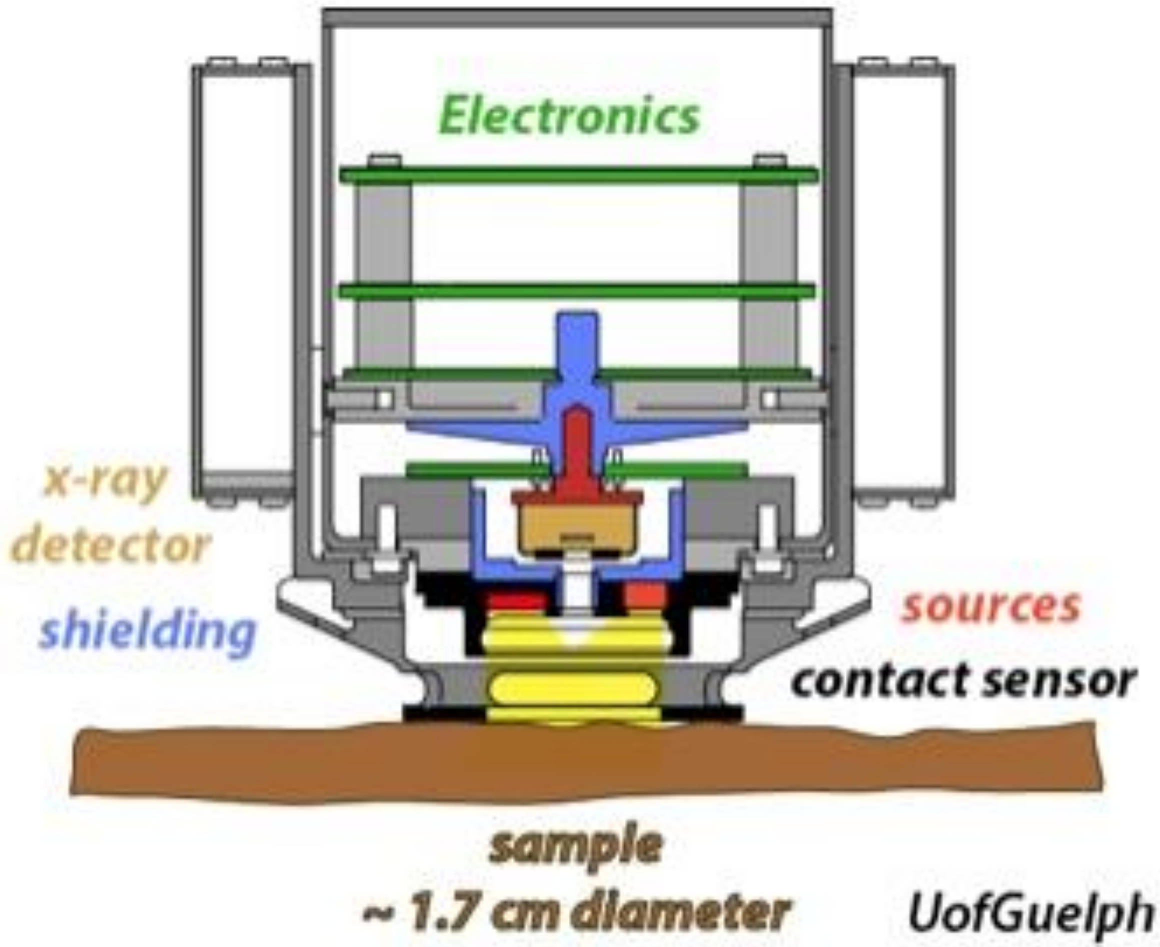
Instrument description



Alpha Particle X-ray Spectrometer (APXS)

- This tool helps **identify the chemical elements** in rocks and soil and tells us how much of each is present
- Identifying the elemental composition of lighter elements (**sodium, magnesium or aluminum**) and heavier elements (**iron, nickel or zinc**) helps scientists identify main materials in the Martian crust
- This information helps scientists select rock and "soil" samples, characterize **the interiors of the rocks** following brushing, and then **determine how the material formed long ago** and if it was later altered by wind, water, or ice. All previous rovers have carried a tool like this one, so comparisons of landing sites can be made to understand the history of Mars even better.
- The sampled area is about **1.7 cm in diameter** when the instrument is in contact with the sample.

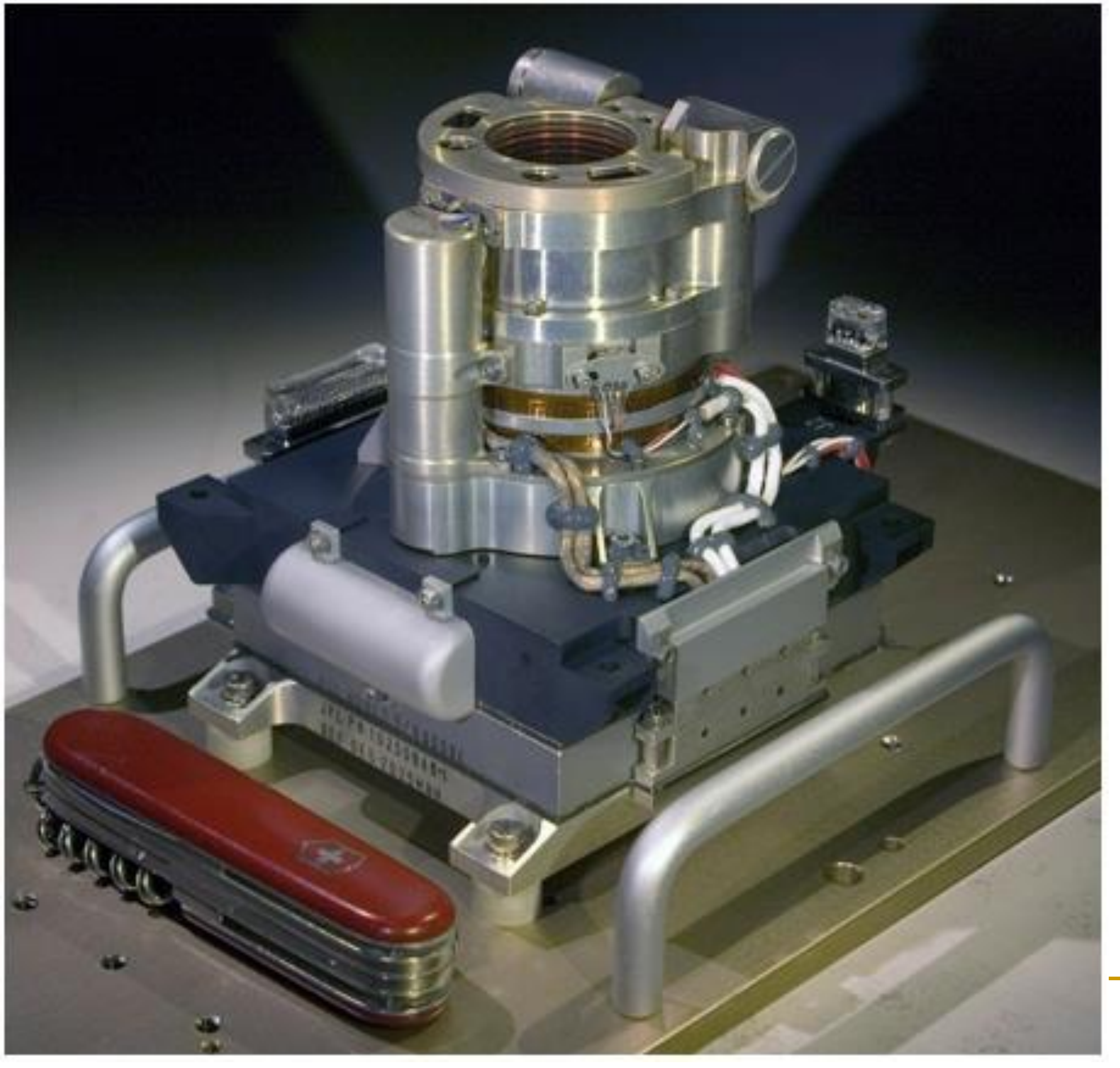
APXS instrument



Mars Hand Lens Imager (MAHLI)

- "Magnifying Eye“, much like a geologist's hand lens, **this camera provides close-up views of minerals**, textures, and structures in Martian rocks at scales smaller than the diameter of a human hair
- **That information will help us understand if any rocks formed in water**, which is necessary to life as we know it. It will help scientists select which rocks may be the best to study further--that is, rocks and minerals that may contain signs of organics, the chemical building blocks of life.
- **With two white LED lights**, it can take pictures at night, and with ultraviolet (UV) LEDs, can look for minerals that fluoresce
- It can also send high-definition video back to Earth and even be used to look back to take a self-portrait of Curiosity.

Mars Hand Lens Imager (MAHLI)



Mars Hand Lens Imager (MAHLI)

- The Mars Hand Lens Imager (MAHLI) is a focusable color camera located on the turret at the end of the MSL robotic arm. The instrument acquires images of up to 1600 by 1200 pixels with a color quality equivalent to that of consumer digital cameras. The table below summarizes the basic characteristics of the instrument.

Parameter	Value/Description	
Focus	Adjustable; working distances 20.4 mm to ∞	
Focus group range of motion	11.44 mm	
Bandpass	380–680 nm	
Pixel scale	Variable from 13.9 μm/pixel to >>> 13.9 μm/pixel	
Focus-Position Dependent Parameters	25 mm working distance, 15 μm/pixel	∞ working distance
Depth of field	1.6 mm	> 4800 mm
Field of view	34.0° diagonal	39.4° diagonal
Focal ratio	f/9.8	f/8.5
Effective focal length	18.3 mm	21.3 mm
Back focal length	19.8 mm	8.4 mm

Examples of How MAHLI is Used

- **Closeup imaging of rocks** and fine regolith targets from a near-normal (i.e., along z-axis of the camera lens) viewing position.
- **Night imaging**.
- Searching for **fluorescent materials** using the UV LEDs.
- Observing **seasonal frost**; monitoring changes in frost over night.
- **Drill hole imaging** (might involve shining LED illumination into the hole).
- **Periscope Imaging—**robotic arm is extended upward to allow MAHLI to look over the top of something that the other cameras cannot reach (the robotic arm can place MAHLI higher above the ground than the top of the Remote Sensing Mast).
- Acquiring public outreach or **documentary video sequences** (e.g., opening of a sample inlet cover; viewing landscape go by as rover drives and MAHLI is stowed; moving rover a very short distance while arm is deployed such that MAHLI can observe wheels rolling over the surface; movement of Remote Sensing Mast).
- **Rover problem diagnosis** (view under the rover as done with on Spirit, only this time in focus and in color; view wheels from the side).
- **Rover self portraits** (for education/public outreach) by holding camera head up above the rover or out at some distance from the rover.

Chemistry and Mineralogy (CheMin)

- **Finding minerals** that either formed in water or were altered by water in the past helps us understand if Mars **ever could have been a habitat for microbes**
- This tool is one of two instruments that **studies powdered rock and soil samples** scooped up by the robotic arm
- Curiosity uses it to tell us **what kinds of minerals are in samples and how much** of them are there
- Minerals provide a record of **what happened in the past**
- Different minerals are linked to certain kinds of environments

CheMin Instrument Description

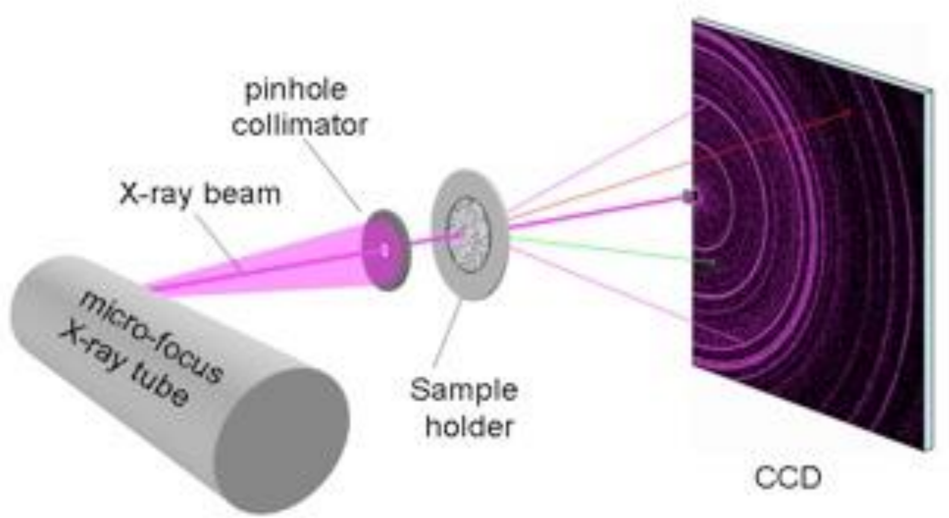
- CheMin, short for “Chemistry and Mineralogy,” is a powder **X-ray Diffraction** (XRD) instrument that also has **X-ray Fluorescence** (XRF) capabilities. CheMin is part of the Analytical Laboratory of the MSL rover, which is located inside the main body of the rover.
- CheMin will analyze as many as **74 samples** delivered by the SA/SPaH system during the nominal prime mission, but is capable of analyzing many more because its **sample cells can be reused** for additional analyses.
- Each analysis may **take up to 10 hours of analysis time**, spread out over two or more Martian nights, although some samples may provide acceptable results in a single sol.
- CheMin utilizes a microfocus **cobalt X-ray source**, a transmission sample cell, and an energy-discriminating X-ray sensitive CCD to produce simultaneous 2-D X-ray diffraction patterns and energy-dispersive histograms from powdered samples.
- Raw CCD frames are **processed into data products onboard the rover** to reduce the data volume. These data products are **transmitted to Earth** for further processing and analyses.

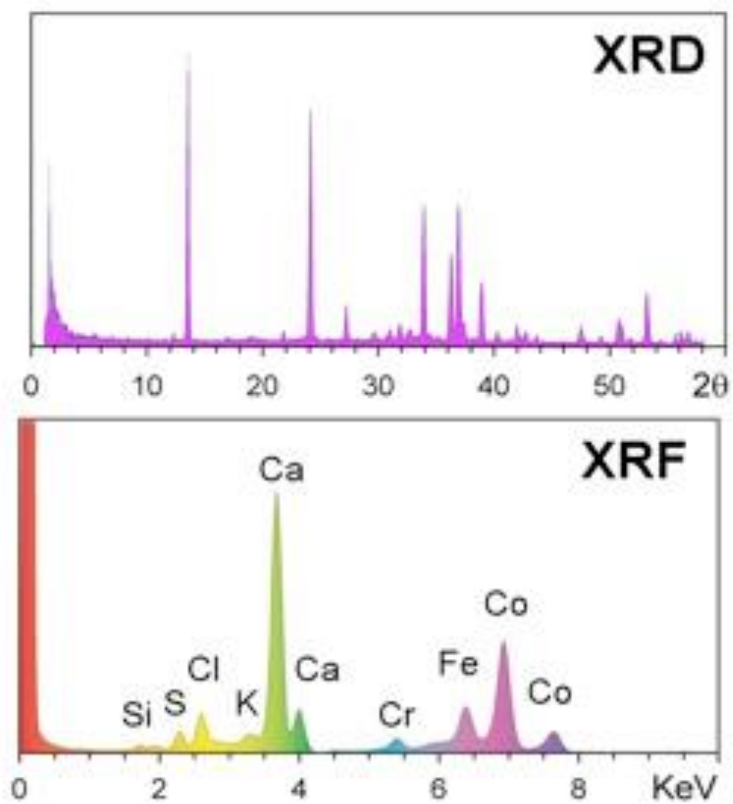
CheMin Measurement Description

- In operation, a **collimated X-ray beam** from the X-ray tube **is directed through a transmission sample cel**l containing powdered material prepared and delivered by the SA/SPaH system.
- An X-ray sensitive **CCD imager is positioned on the opposite side** of the sample from the source and directly detects X-rays diffracted or fluoresced by the sample.
- The CCD detector is operated in **single-photon counting mode**. The CCD detector is exposed to the X-ray flux, read out and erased a large number of times for each analysis (1000 or more exposures).
- When operated in this manner**, the CCD can be used to measure the charge generated by each photon**. Diffracted X-rays strike the detector and are identified by their energy, producing a two-dimensional image that constitutes the diffraction pattern. All of the X-rays detected by the CCD are summed into a histogram of number of photons vs. photon energy that constitutes an energy-dispersive X-ray histogram of the sample.
- At incremental radii the two-dimensional pattern is summed circumferentially about the central undiffracted beam (ground processing) to yield a one-dimensional 2-theta plot comparable to conventional diffractometer data.

Geometry of the CheMin instrument.

- **(left) Overall geometry of CheMin; (above right) XRD 2-theta plot obtained by summing diffracted photons from either of the characteristic lines of the X-ray source (Co K-alpha is colored magenta); (below right) X-ray energy-dispersive histogram obtained by summing all of the X-ray photons detected by the CCD (fluoresced photons from the sample shown schematically for elements Fe and lighter).**





Sample Analysis at Mars (SAM)

- The Sample Analysis at Mars (SAM) Suite Investigation in the MSL Analytical Laboratory is designed to address the present and **past habitability of Mars by exploring molecular and elemental chemistry relevant to life**. SAM addresses **carbon chemistry** through a search for organic compounds, the chemical state of light elements other than carbon, and isotopic tracers of planetary change.
- SAM is a suite of **three instruments**, a Quadrupole Mass Spectrometer (QMS), a Gas Chromatograph (GC), and a Tunable Laser Spectrometer (TLS). The QMS and the GC can operate together in a GCMS mode for separation (GC) and definitive identification (QMS) of organic compounds. The TLS obtains precise isotope ratios for C and O in carbon dioxide and measures trace levels of methane and its carbon isotope.

Sample Analysis at Mars (SAM)

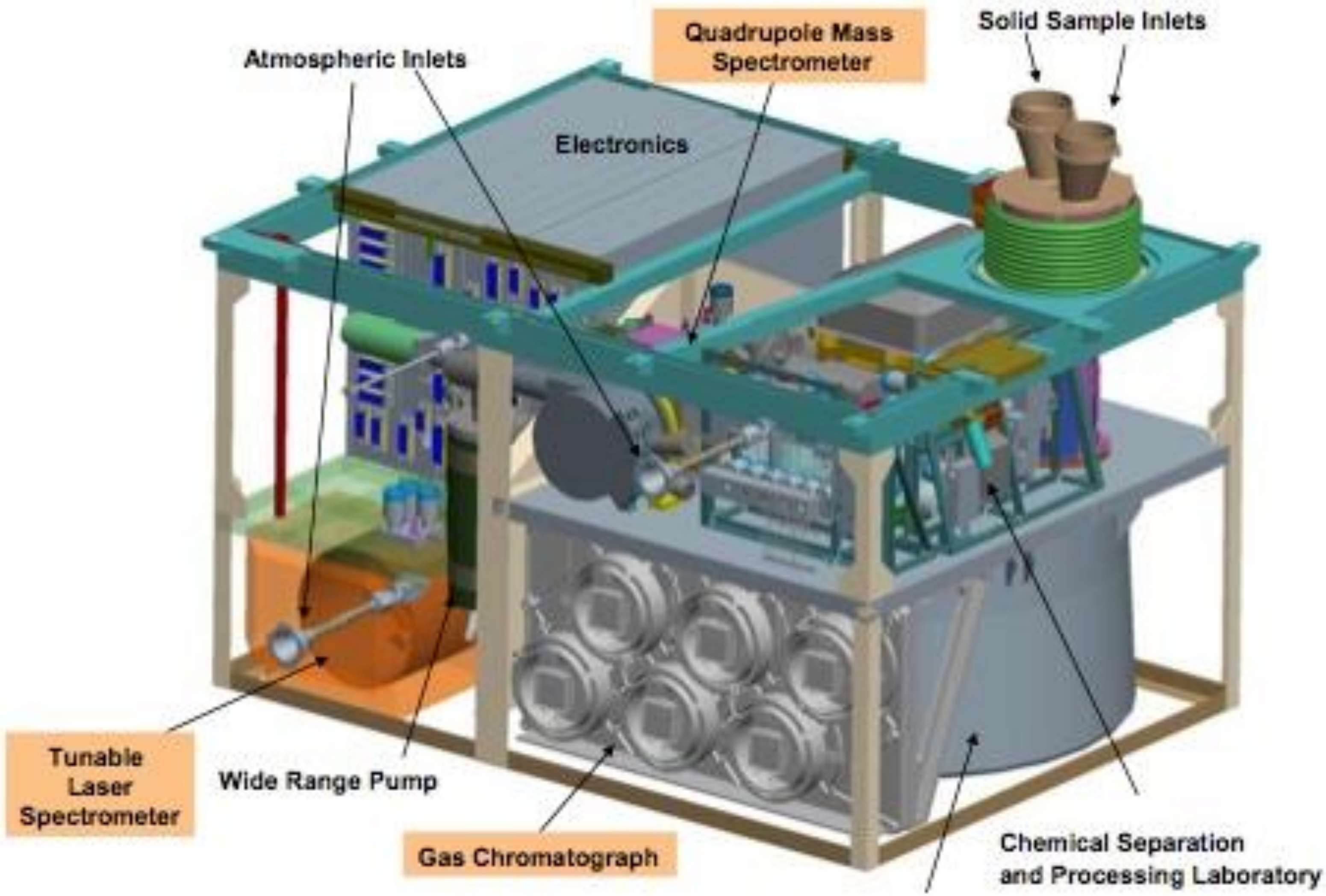
- Curiosity uses this tool to search for organics, **carbon-based molecules** that are the chemical building blocks of life
- **Finding organics is important** in the search for Martian environments capable of supporting microbes, because life as we know it cannot exist without them (though they can exist without life)
- This tool allows Curiosity to **detect lower concentrations of a wider variety of organic molecules** than any other instrument yet sent to Mars.
- Curiosity will **deliver powdered samples** to one of two funnels on the rover deck ("back") and then to small cups for processing inside the rover's "body." Finding evidence that Gale Crater had both past water and organics would suggest it might have been hospitable to life

SAM's science goals

- Three questions about the ability of Mars to support past, present, or future life are addressed by SAM's five science goals as stated in the table below.

Science and Measurement Goal	Habitability Question
1) Survey carbon compound sources and evaluate their possible mechanisms of formation and destruction 2) Search for organic compounds of biotic and prebiotic importance, including methane	What does the inventory or lack of carbon compounds near the surface of Mars tell us about its potential habitability?
3) Reveal the chemical and isotopic state of elements (i.e. N, H, O, S and others) that are important for life as we know it. 4) Determine atmospheric composition including trace species that are evidence of interactions between the atmosphere and soil.	What are the chemical and isotopic states of the lighter elements in the solids and in the atmosphere of Mars and what do they tell us about its potential habitability?
5) Better constrain models of atmospheric and climatic evolution through measurements of noble gas and light element isotopes.	Were past habitability conditions different from today's?

Sample Analysis at Mars (SAM)



Radiation Assessment Detector (RAD)

- This instrument was the first of ten instruments to be turned on. Its first role was to **characterize** the broad spectrum of **radiation environment**
- RAD main purpose is to **determine the viability and shielding needs** for potential human explorers. Its second role is to characterize the radiation environment on the surface of Mars, which it started doing immediately after landing.

Radiation Assessment Detector (RAD)

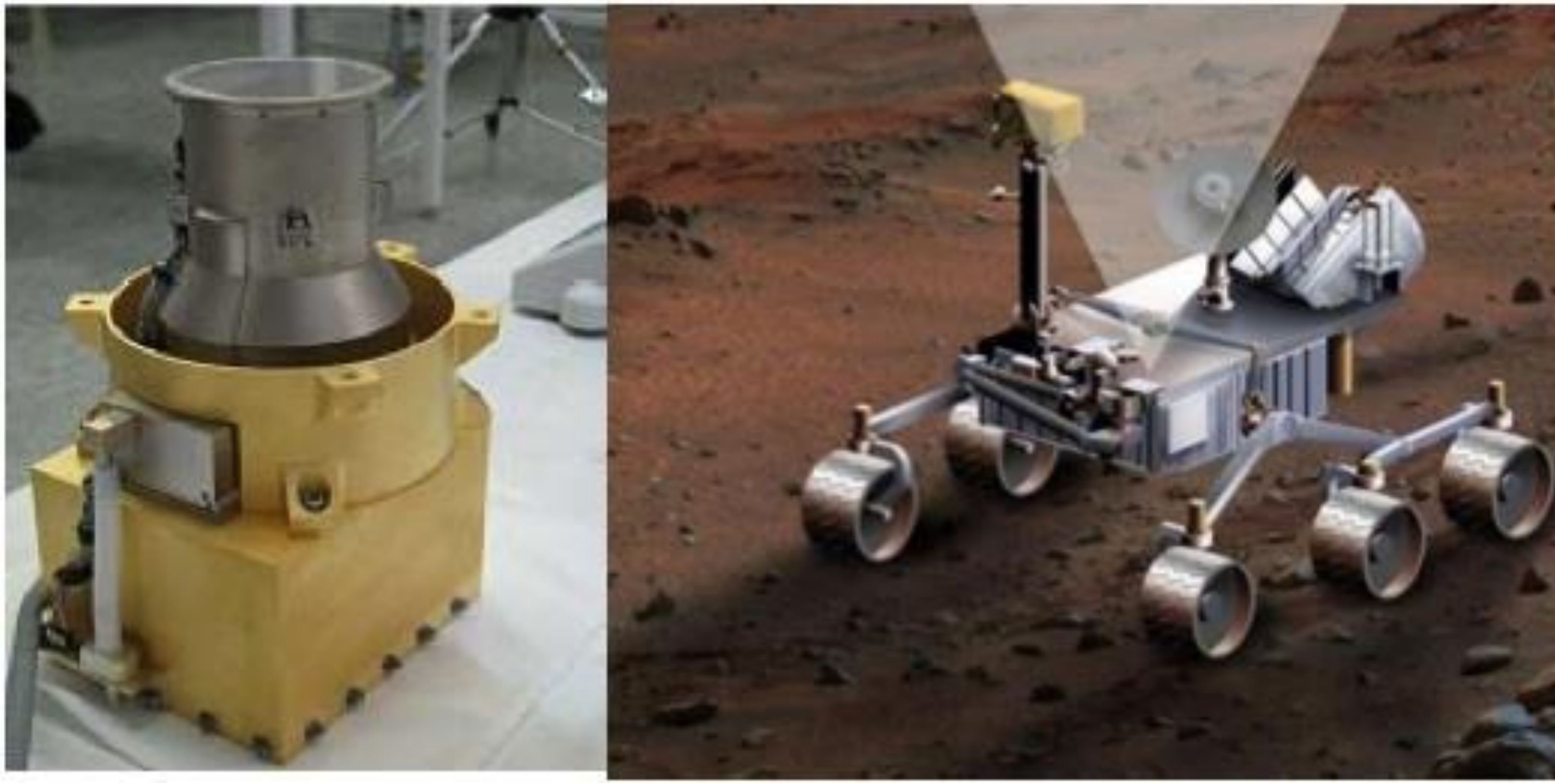


Photo of RAD flight model in the lab (left) and artwork of an older MSL rover design, showing RAD charged particle channel 65-degree field-of-view pointing towards the zenith.

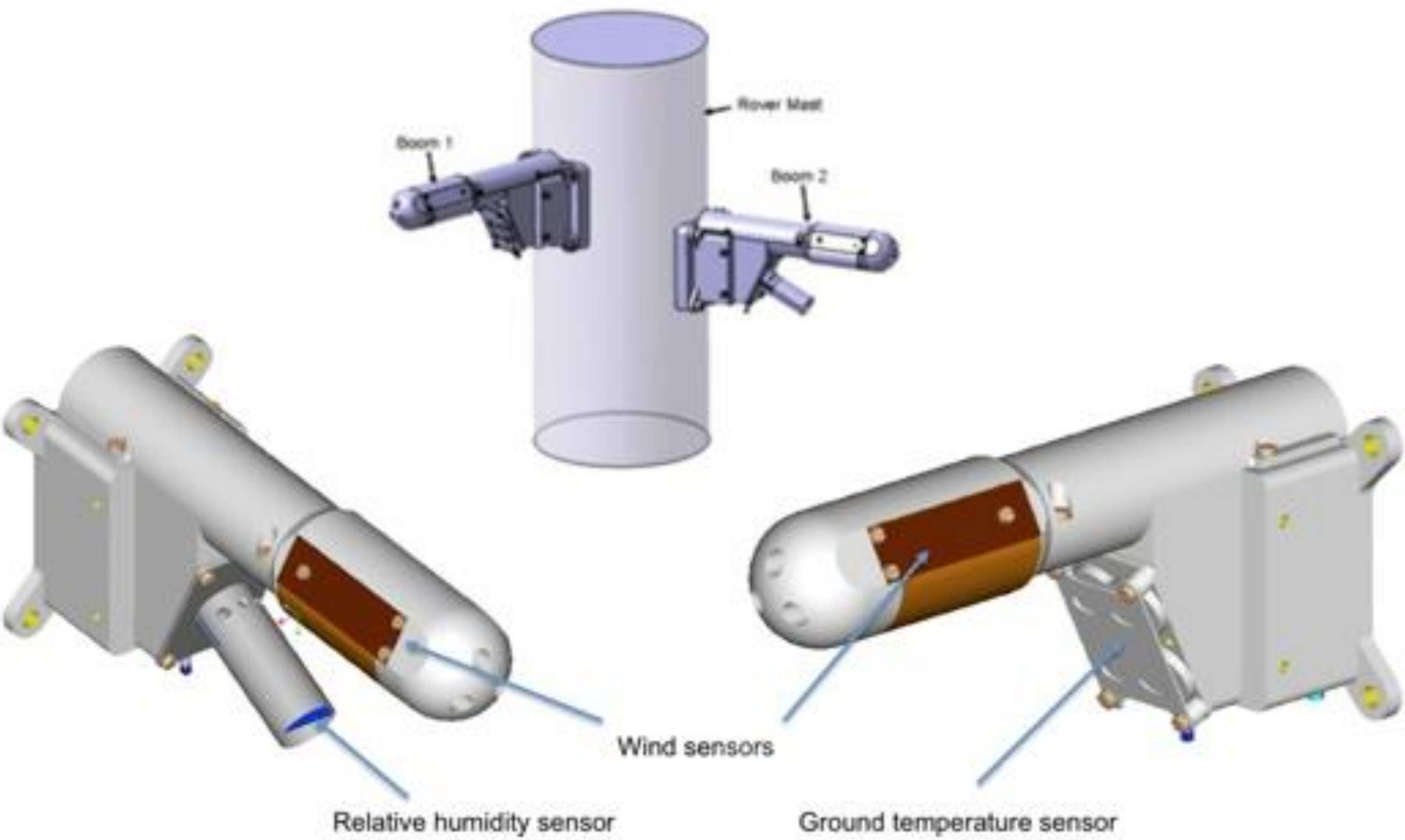
Radiation Assessment Detector (RAD)

- Because of rover energy constraints, the present plan is to acquire roughly 15-minute observations every hour throughout each sol.
- RAD's primary science objectives are to:
  - Characterize the energetic particle spectrum at the surface of Mars
  - Determine the radiation dose for humans on the surface of Mars
  - Enable validation of Mars atmospheric transmission models and radiation transport codes
  - Provide input to the determination of the radiation hazard and mutagenic influences to life, past and present, at and beneath the Martian surface
  - Provide input to the determination of the chemical and isotopic effects of energetic particles on the Martian surface and atmosphere

Rover Environmental Monitoring Station (REMS)

- REMS has been designed to **record six atmospheric parameters: wind speed/direction, pressure, relative humidity, air temperature, ground temperature, and ultraviolet radiation**. All sensors are located around three elements: **two booms** attached to the rover Remote Sensing Mast (RSM), the Ultraviolet Sensor (UVS) assembly located on the rover top deck, and the Instrument Control Unit (ICU) inside the rover body.
- The booms are approximately **1.5 m above ground level**. The two booms are separated in azimuth by **120 degrees** to help insure that at least one of them will record clean wind data for any given wind direction. The figure below shows the booms' relative position. There is a 50 mm height difference to minimize mutual wind perturbation.
- Boom 2, which points in the driving direction of the rover, has wind sensors and the relative humidity sensor. Boom 1, which looks to the side and slightly to the rear of the rover, hosts another set of wind sensors and the ground temperature sensor. Both booms have an air temperature sensor.

Rover Environmental Monitoring Station (REMS)



Rover Environmental Monitoring Station (REMS)

- Each hour, every sol, REMS will record 5 minutes of data at 1 Hz for all sensors. REMS will record data whether the rover is awake or not, and both day and night.
- REMS operation is designed assuming an integrated total of three hours of operation each day, primarily constrained by power availability.
- The main science objectives that the science team will focus on are:
  - Signature of the Martian general circulation and mesoscale phenomena near the surface (e.g., fronts, jets)
  - Microscale weather systems (e.g., boundary layer turbulence, heat fluxes, dust devils)
  - Local hydrological cycle (e.g., spatial and temporal variability, diffusive transport from regolith)
  - Destructive potential of UV radiation, dust UV optical properties, photolysis rates, and oxidant production
  - Subsurface habitability based on ground-atmosphere interaction

Dynamic Albedo of Neutrons (DAN)

- The Dynamic Albedo of Neutrons (DAN) is an active/passive neutron spectrometer that measures the abundance and depth distribution of H- and OH-bearing materials (e.g., adsorbed water, hydrated minerals) in a shallow layer (~1 m) of Mars' subsurface along the path of the MSL rover.
- The science objectives of the DAN instrument are as follows:
  - 1) Detect and provide a quantitative estimation of the hydrogen in the subsurface throughout the surface mission;
  - 2) Investigate the upper <0.5 m of the subsurface and determine the possible layering structure of hydrogen-bearing materials in the subsurface;
  - 3) Track the variability of hydrogen content in the upper soil layer (~1 m) during the mission by periodic analysis; and
  - 4) Track the variability of neutron radiation background (neutrons with energy < 100 keV) during the mission by periodic analysis.
- The DAN instrument is expected to be used during rover traverses (e.g., during short stops at ~1 m intervals) and while the rover is parked. Short-duration (< 2 min) measurements will provide a rough estimate of the water-equivalent hydrogen distribution with an accuracy of ~1% by weight.

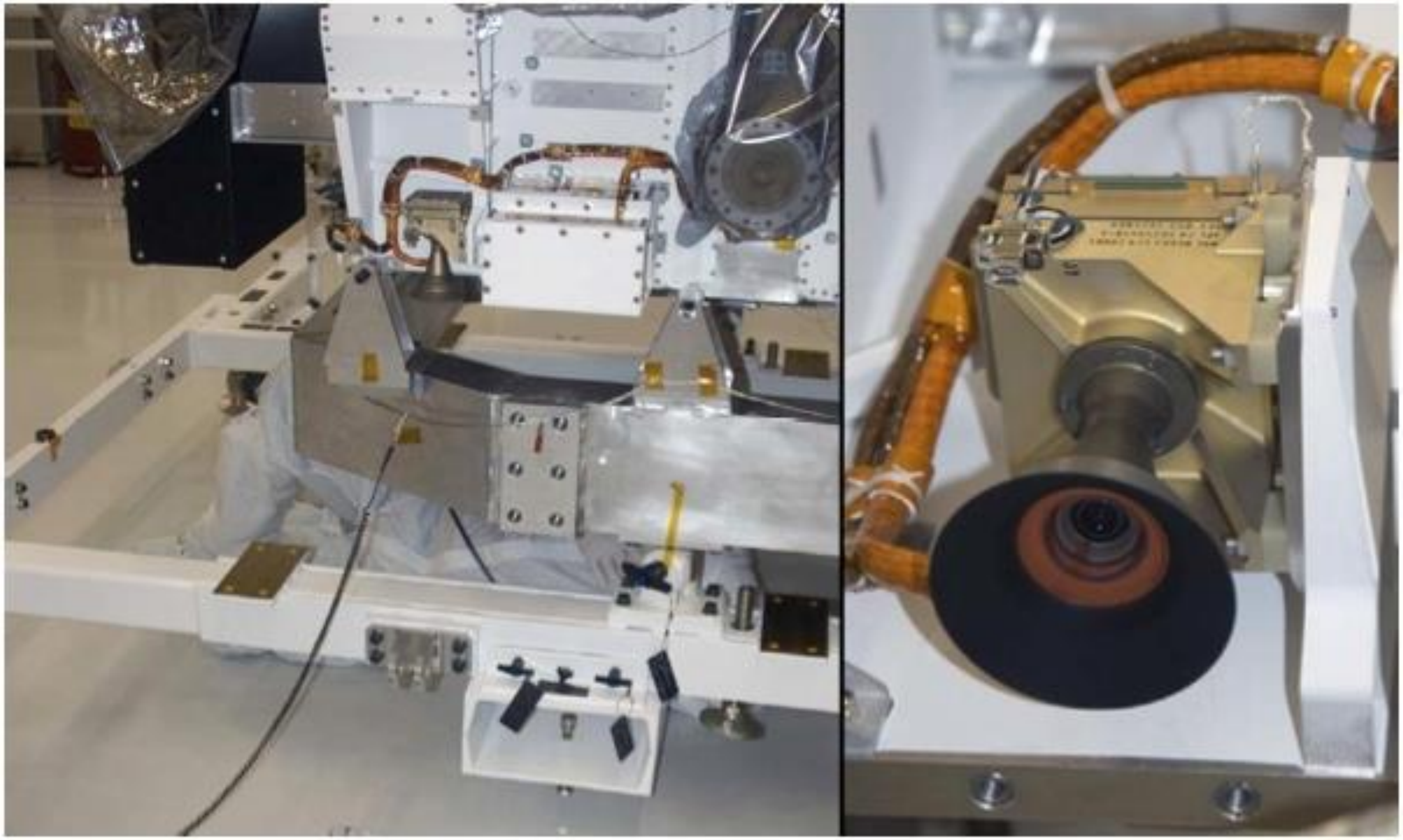
Mars Descent Imager (MARDI)

- Ever wonder what it would be like to have an "astronauts" view of landing on Mars? Finishing its job in **the seconds before landing, this camera shoots full-color video** of Curiosity's journey **through the atmosphere** all the way down to the Martian surface.
- This camera may give the science team and rover drivers a glimpse of the **landing site** to aid them in accurately **identifying Curiosity's landing spot** and in **planning the rover's first drives**
- One of its main jobs is helping the mission team **locate loose debris, boulders, cliffs, and other features in the terrain** that pose potential hazards to the rover and should be avoided.

Mars Descent Imager (MARDI)

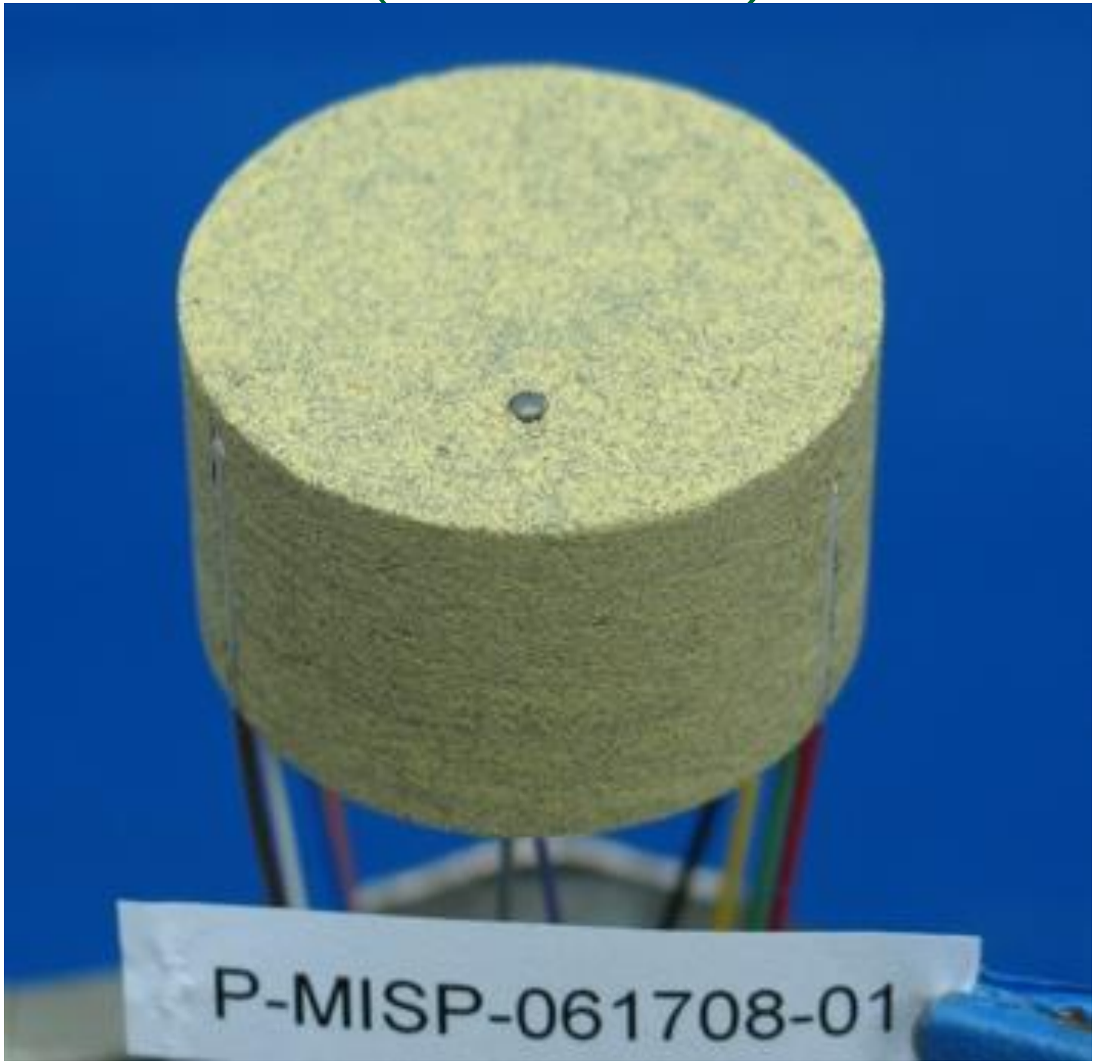
- The Mars Descent Imager (MARDI) is a **fixed-focus color camera fixed-body-mounted** to the fore-port-side of the MSL rover, even with the bottom of the rover chassis. The optical axis points in the +Z direction (toward the ground in the rover coordinate system). The camera will take **1600 × 1200 pixel images at ~5 frames per second** throughout the period of time between **heatshield separation and touchdown** plus a few seconds (a period of about two minutes). **The rover software issues a “start imaging” command and the camera operates autonomously until the rover software determines that landing has succeeded and issues a “stop imaging” command.** The data are written into permanent flash memory in real time during acquisition for **later transmission.**

Mars Descent Imager (MARDI)



MSL EDL Instrument (MEDLI) Suite

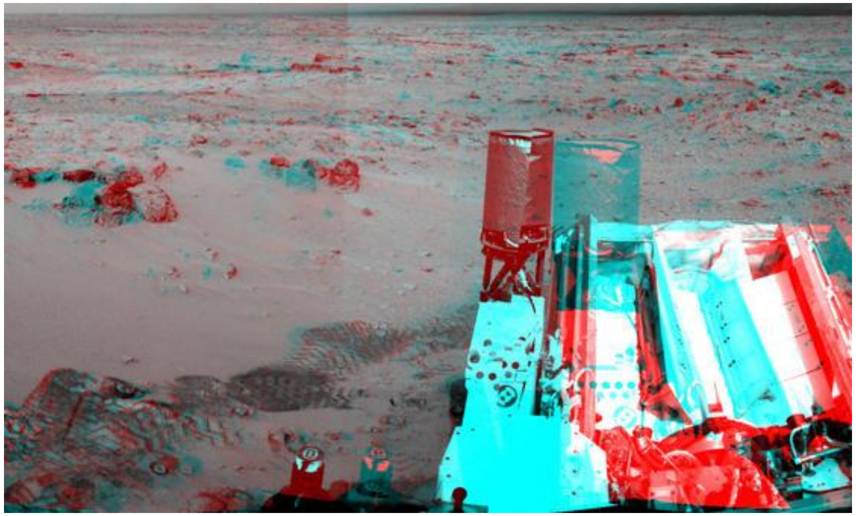
- It used to measure atmospheric data during landing.



Navigation Cameras (Navcams)

- The rover has two pairs of black and white navigation cameras mounted on the mast to support ground navigation
- The cameras have a 45 degree angle of view and use visible light to capture stereoscopic

  3-D imagery
- These cameras support use of the ICER image compression format.



Hazard Avoidance Cameras

- The rover has **four pairs of black and white navigation cameras** called Hazcams—two pairs in the front and two pairs in the back
- They are **used for autonomous hazard avoidance** during rover drives and for safe positioning of the robotic arm on rocks and soils
- The cameras use **visible light to capture stereoscopic** three-dimensional (3-D) imagery
- The cameras have a **120 degree field of view** and map the terrain at up to 3m in front of the rover
- This imagery **safeguards against the rover crashing into unexpected obstacles**, and works in tandem with software that allows the rover to make its own safety choices

Operation on the surface

Results: 1. Curiosity Found Evidence of Persistent Liquid Water in the Past

- Just after landing, Curiosity found smooth, rounded pebbles that likely rolled downstream for at least a few miles in a river that was ankle- to hip-deep. When Curiosity reached Mount Sharp, the team found that over 1,000 vertical feet of rock formed originally as mud at the bottom of a series of shallow lakes. Rivers and lakes persisted in Gale crater for perhaps a million years or longer.

Results: 2. A Suitable Home for Life

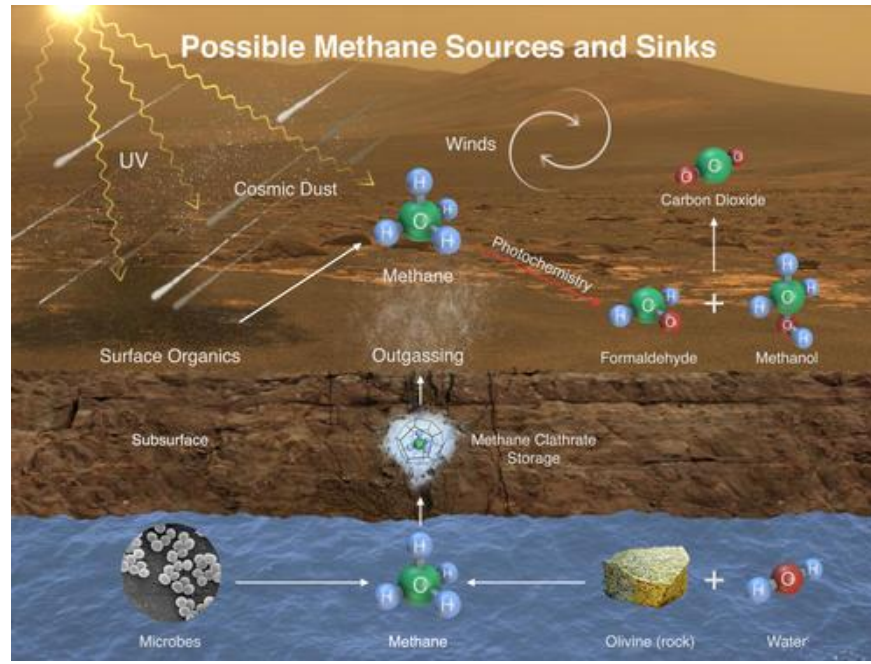
- The Curiosity rover found that ancient Mars had the right chemistry to support living microbes. Curiosity found sulfur, nitrogen, oxygen, phosphorus and carbon-- key ingredients necessary for life--in the powder sample drilled from the "Sheepbed" mudstone in Yellowknife Bay. The sample also reveals clay minerals and not too much salt, which suggests fresh, possibly drinkable water once flowed there.

Results: 3. Organic Carbon Found in Mars Rocks

- Organic molecules are the building blocks of life, and they were discovered on Mars after a long search by the Sample Analysis at Mars (SAM) instrument in several samples drilled from Mount Sharp and the surrounding plains. The finding doesn't necessarily mean there is past or present life on Mars, but it shows that raw ingredients existed for life to get started there at one time. It also means that ancient organic materials can be preserved for us to recognize and study today.

Results: 4. Present and Active Methane in Mars' Atmosphere

- The Tunable Laser Spectrometer within the SAM instrument detected a seasonally varying background level of atmospheric methane and observed a ten-fold increase in methane over a two-month period. The discovery of methane is exciting because methane can be produced by living organisms or by chemical reactions between rock and water, for example. Which process is producing methane on Mars? What caused the brief and sudden increase?



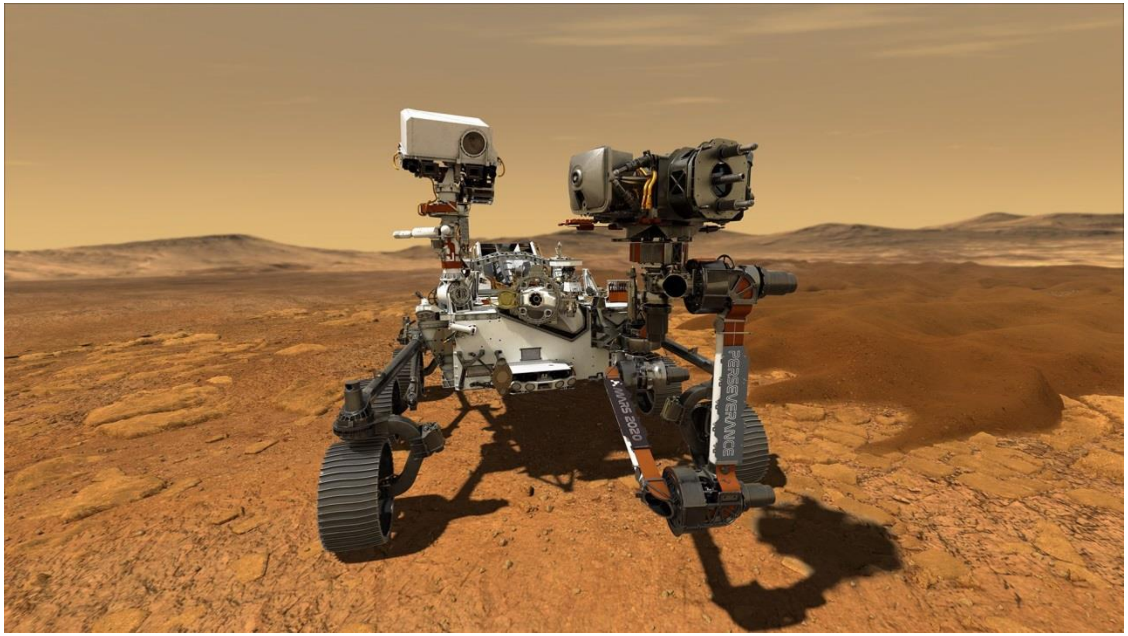
Results: 5. Radiation Could Pose Health Risks for Humans

- Curiosity experienced radiation levels that would exceed NASA's career limit for astronauts, if left unshielded. The Radiation Assessment Detector (RAD) instrument on Curiosity found that two forms of radiation pose potential health risks to astronauts in deep space. One is galactic cosmic rays (GCRs), particles caused by supernova explosions and other high-energy events outside the solar system. The other is solar energetic particles (SEPs) associated with solar flares and coronal mass ejections from the sun.

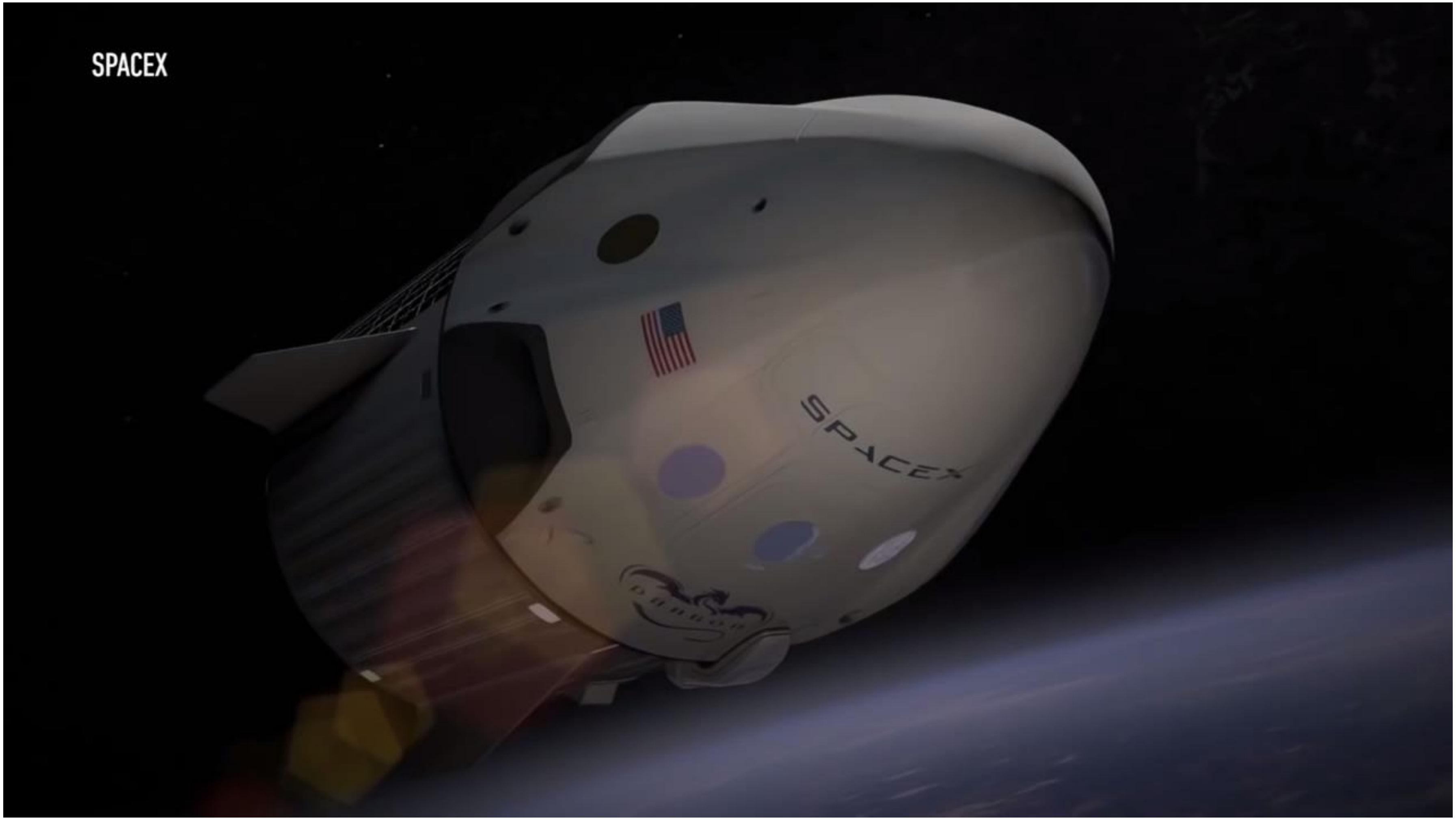
Results: 6. A Thicker Atmosphere and More Water in Mars' Past

- The SAM instrument suite has found Mars' present atmosphere to be enriched in the heavier forms (isotopes) of hydrogen, carbon, and argon. These measurements indicate that Mars has lost much of its original atmosphere and inventory of water. This loss occurred to space through the top of the atmosphere, a process currently being observed by the MAVEN orbiter.

NASA's next Mars rover is named Perseverance



- Once on Mars, the mission is designed to search out possible signs of past life on the planet and cache samples for a future mission to return back to Earth one day.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References

- *Source: Jet Propulsion Laboratory honlap http://msl-scicorner.jpl.nasa.gov/*
- *Youtube videos*

End of lecture 08.

i) Sensors and measurement methods of
Curiosity Rover on MARS

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04. 19. 2021.