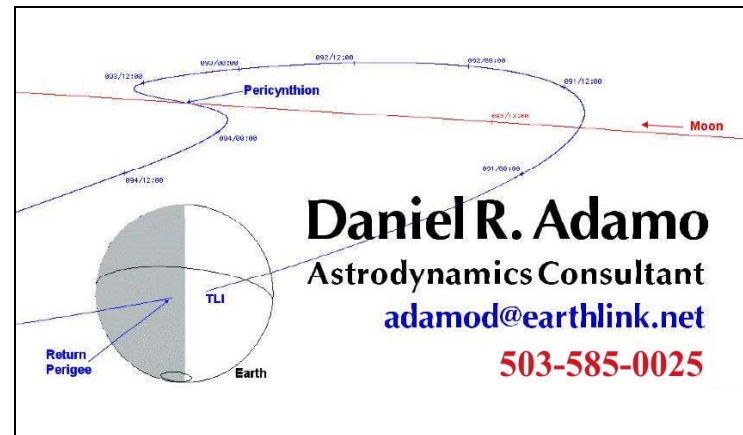


Exploring The Solar System Through Low-Latency Telepresence (LLT)

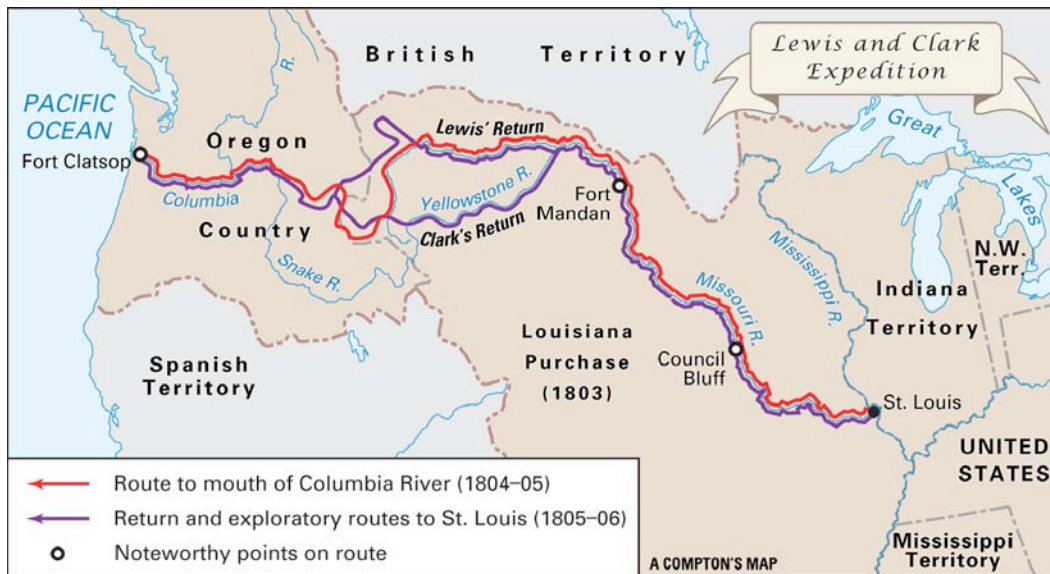


AIAA-Los Angeles/Las Vegas Section
Northrup Grumman Aerospace Systems
Redondo Beach, California
6 September 2018

Exploring The Solar System Through Low-Latency Telepresence (LLT)

What Do We Mean By Off-Earth "Exploration"?

- "Explorers go with the intent of returning to tell their story and point the way for future forays. Pioneers go with the intent to establish a permanent presence."^{*}
 - Meriwether Lewis and William Clark's Corps of Discovery *explored* today's Montana, Idaho, Washington, and Oregon for the U.S. government in 1804-1806
 - Westbound and eastbound, the Corps met trappers who would be among the region's first pioneers and settlers of European descent



- Note "pioneering", "colonizing", and "settling" are not in NASA's charter, even though such enterprises might be enabled by NASA exploration

^{*} NASA, "Pioneering Space: NASA's Next Steps on the Path to Mars", 2014, p. 1. Download available at <http://www.nasa.gov/sites/default/files/files/Pioneering-space-final-052914b.pdf> (accessed 10 June 2018).

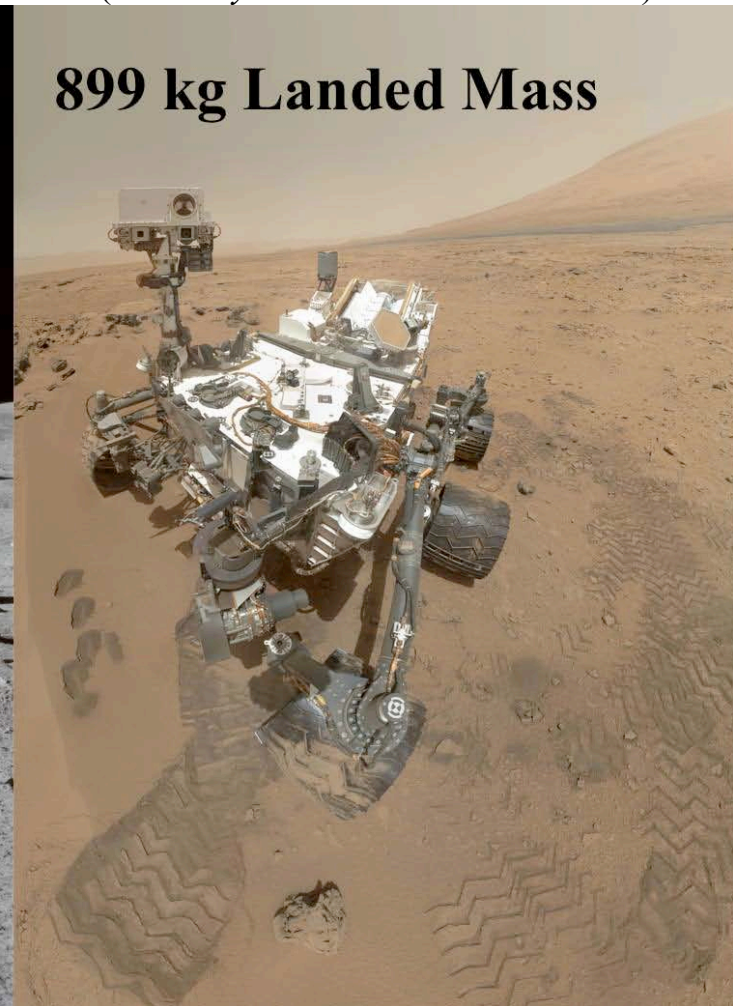
Exploring The Solar System Through Low-Latency Telepresence (LLT)

Up To Now, Humans Have Used Two Modes Of Solar System Exploration

In-Person
(Apollo 16 Photo Credit: NASA)



Telepresence From Earth
(Curiosity Photo Credit: NASA-JPL)

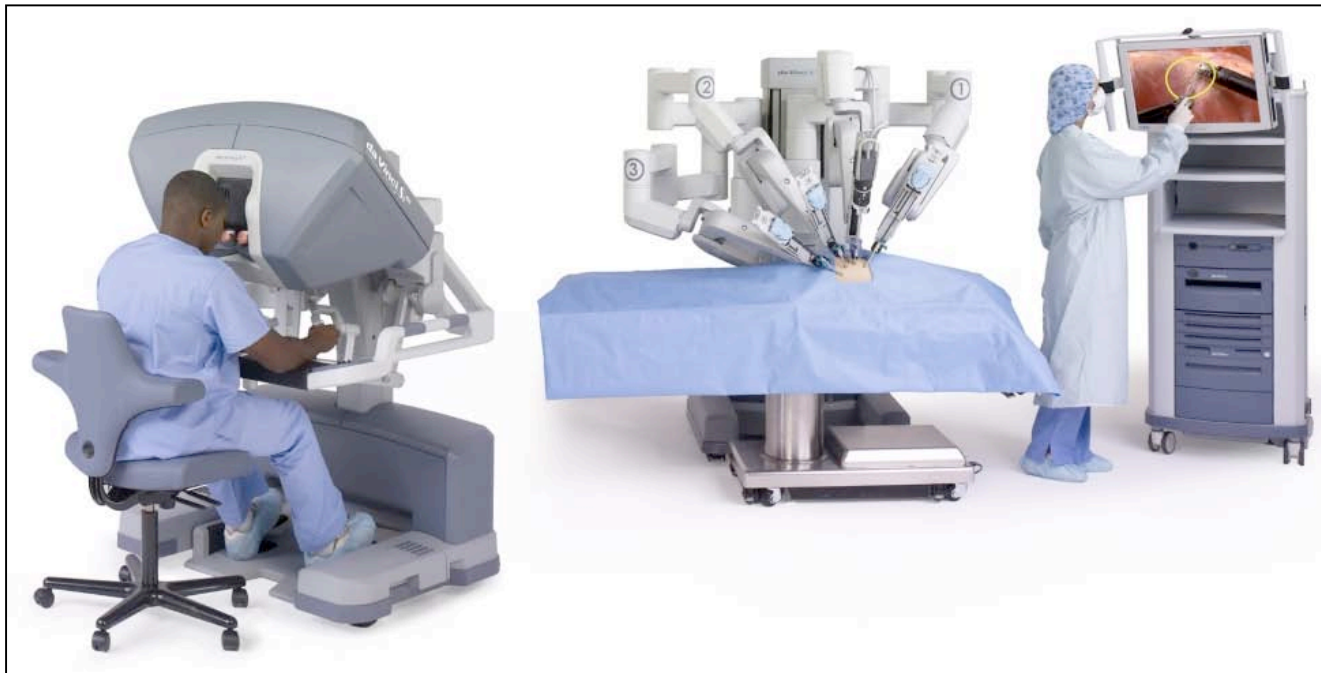


Exploring The Solar System Through Low-Latency Telepresence (LLT)

Telepresence Becomes More Difficult And Restricted As Data Latency Increases

Telepresence Data Latency: the time delay Δt between issuing a command and observing a response

Δt	Associated Telepresence Latency
< 0.2 to 0.5 s	Latency unperceived by humans, depending on task
> 0.5 s	High-dexterity critical tasks like telesurgery (see below) are inadvisable
< 0.9 to 2.6 s	Continuous control possible, depending on task
> 2.3 s	Roundtrip light time (RLT), Moon from Earth
> 0.11 - 0.74 hrs	RLT, Mars from Earth



da Vinci® Telesurgery

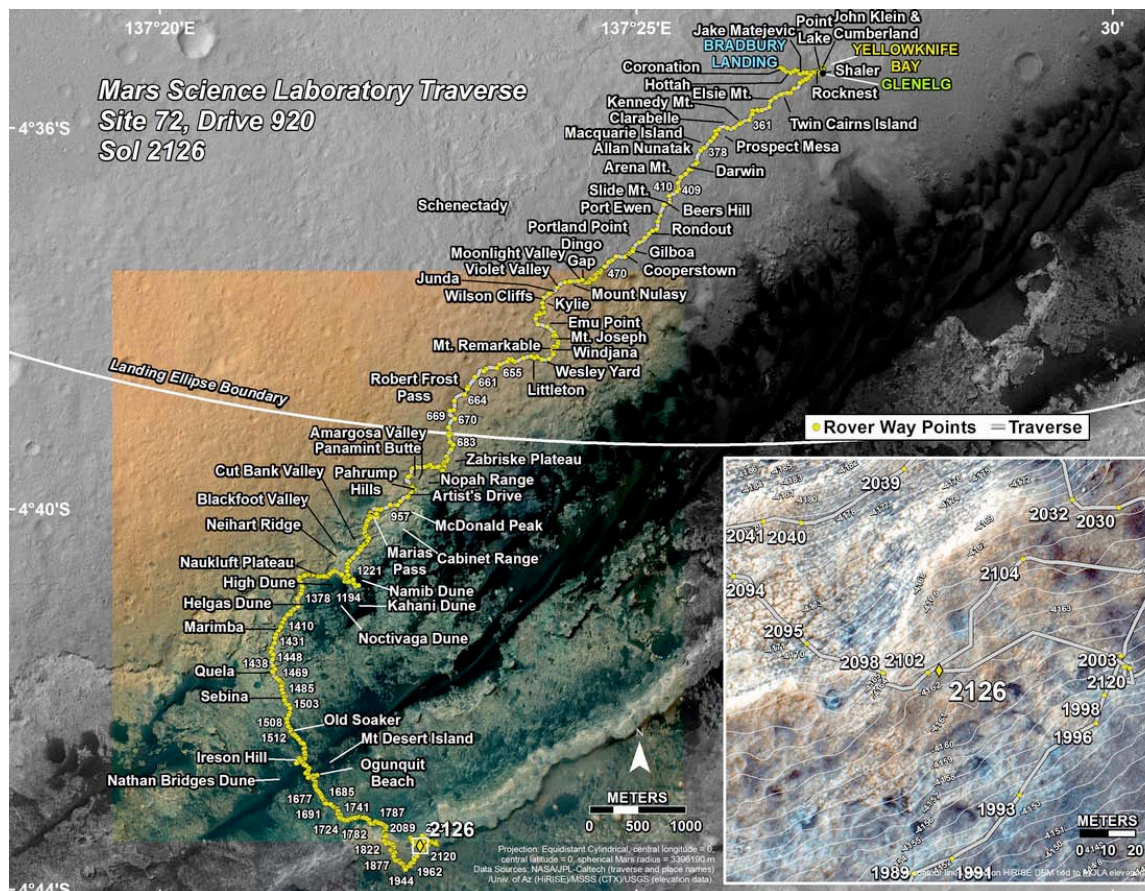
Image Credit: WPI

Automation and
Interventional Medicine
Laboratory

Exploring The Solar System Through Low-Latency Telepresence (LLT)

An Example Of High-Latency Mars Telepresence From Earth: The *Curiosity* Rover

- Drive (up to 150 m semi-autonomously), taking pictures during and afterward
- Wait for communications relay satellite in Mars orbit to overfly and transmit pictures to Earth
- Develop commands for next day's drive based on received pictures analysis at JPL
- Transmit commands directly to *Curiosity*, await local sunrise on Mars, and drive again

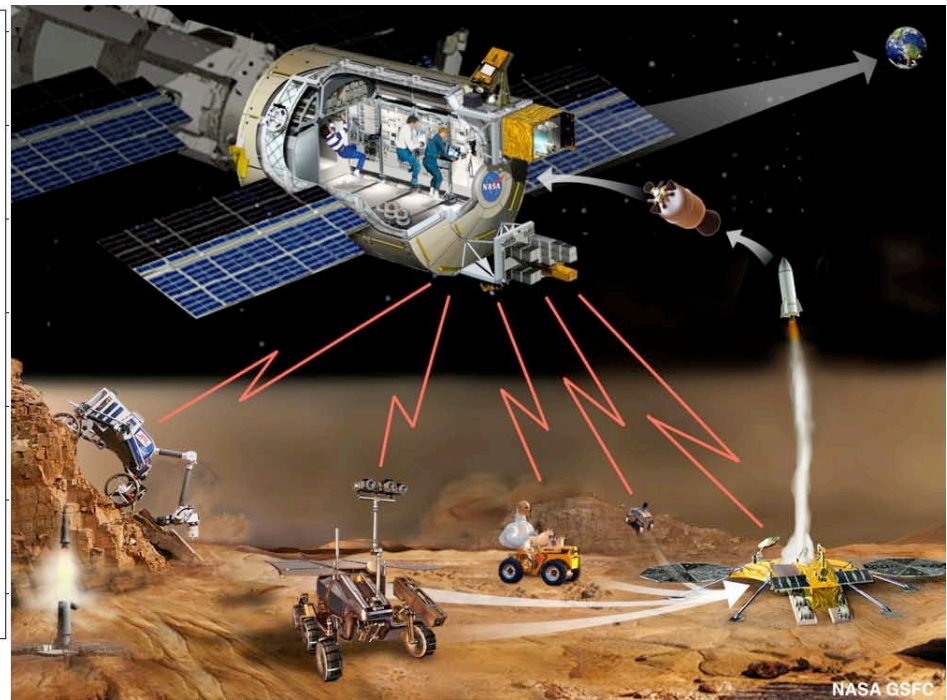
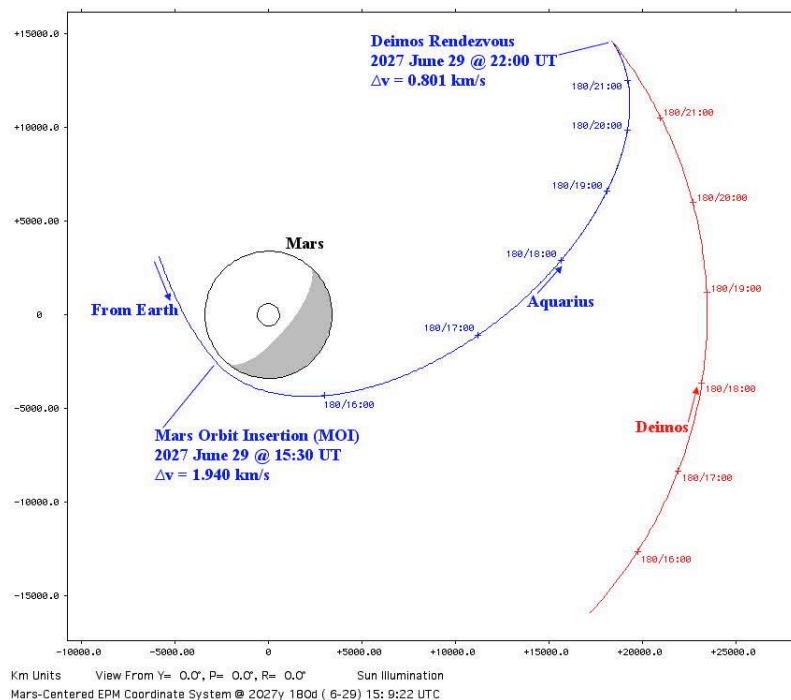


As of 30 July 2018, *Curiosity* had driven 19.54 km since landing 6 August 2012 UT on Mars: average speed = 0.373 m/hour (reference <https://mars.jpl.nasa.gov/msl/mission/whereistherovernow/>)

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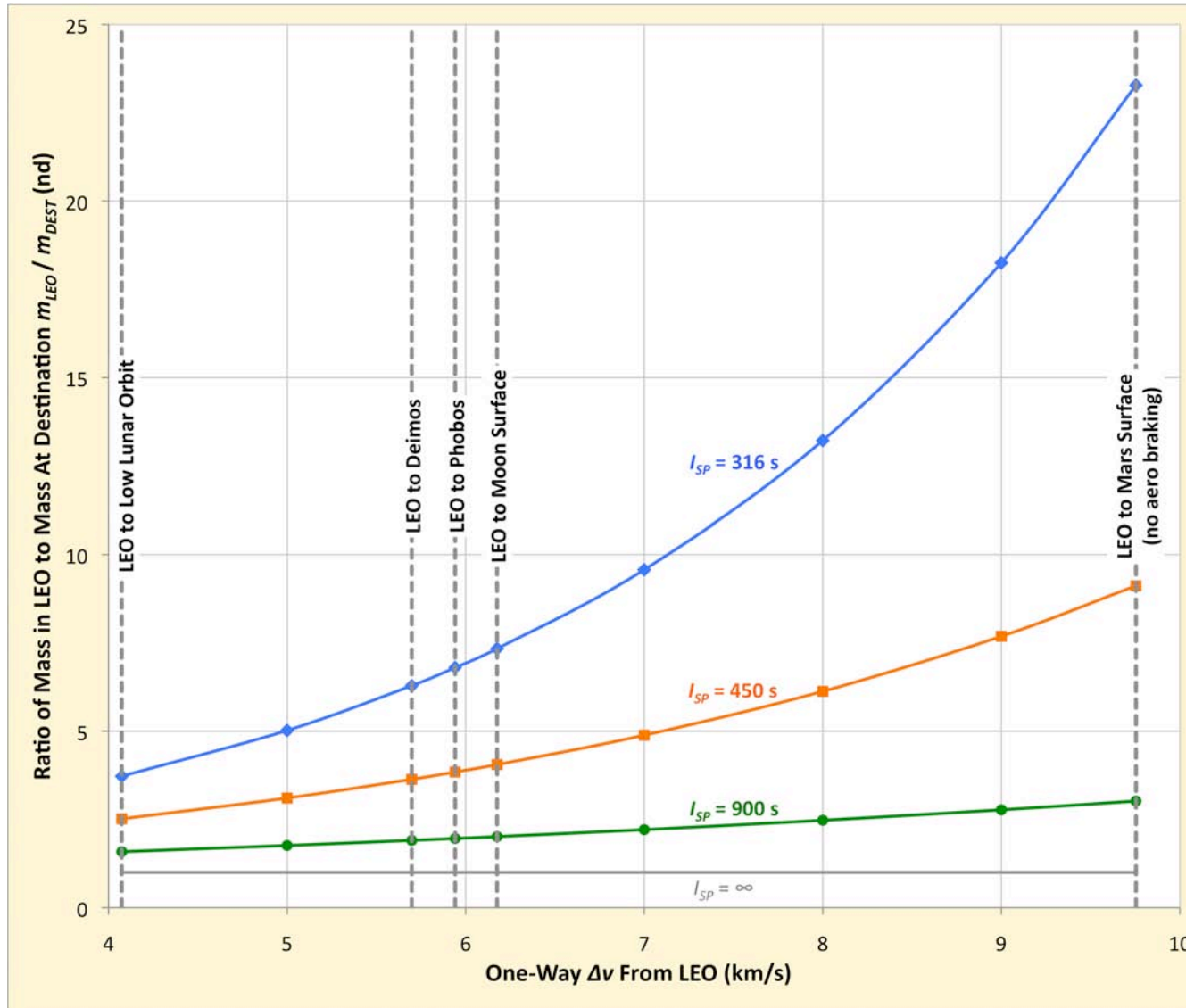
From The Moon Deimos, Mars Surface RLT < 0.16 s: A Whole New Ballgame

- What exploration (besides human adaptation to Mars surface conditions) cannot be conducted?
- Do more exploration sooner, faster, at less expense, and with less risk than in-person mode
- Humans are isolated from contaminating (and being contaminated by) possible native Mars life
- Mars surface hazards will require human telepresence even if humans do land there someday



Exploring The Solar System Through Low-Latency Telepresence (LLT)

Reaching The Martian Surface Is Far More Expensive Than Reaching Mars Orbit



- Velocity change Δv required to reach Mars surface from low Earth orbit (LEO) is 71% greater than that to reach Deimos

- At low specific impulse I_{SP} , propellant mass required to reach a destination is a disproportionate *exponential* function of Δv :

$$\frac{m_{LEO}}{m_{DEST}} = \exp\left\{\frac{\Delta v}{g I_{SP}}\right\}$$

Exploring The Solar System Through Low-Latency Telepresence (LLT)

Low-Latency Telepresence (LLT) ⇒ Enhanced Exploration Productivity

- Extra-vehicular activity (EVA = "spacewalks") only necessary in emergencies
 - Humans nominally remain in a habitat well shielded from vacuum and radiation. Work breaks and handovers are performed in a shirtsleeve/office environment with little overhead.
 - No need to remain close to a habitat or rover to replenish EVA consumables every few hours. Unless samples are to be returned, exploration routes can be roughly linear instead of "loopy".
 - Greater dexterity, mobility, and situation awareness than in pressurized EVA garb
 - Risk-taking in a hostile environment is easier to justify with a robotic proxy than with a human

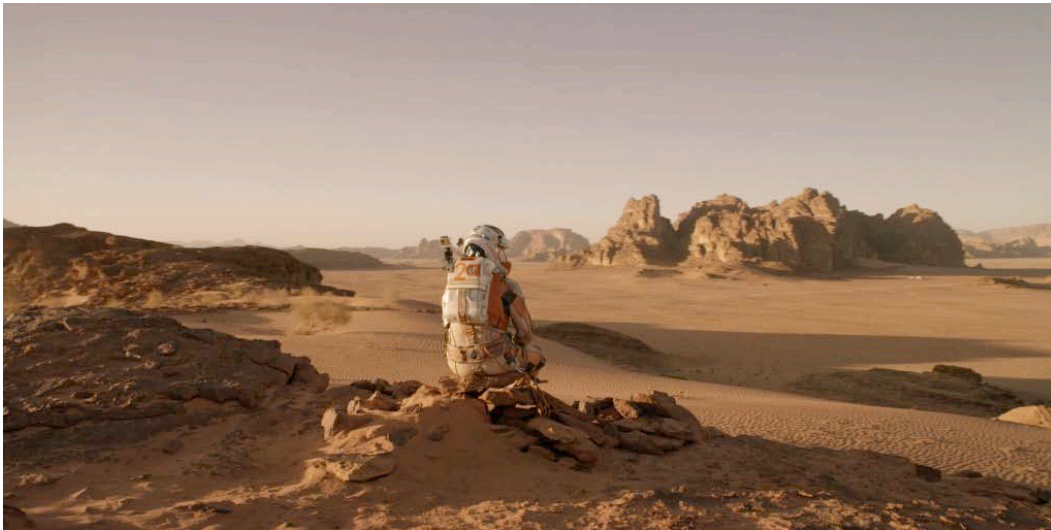


Image credit: 20th Century Fox, *The Martian*

- Exploration by itself cannot justify protracted daily EVAs
- Transient phenomena (dust devils, landslides, eruptions, impacts, ALF?) are far easier to detect and observe throughout each appearance than at high latencies

Exploring The Solar System Through Low-Latency Telepresence (LLT)

Conclusion: we can explore more off-Earth destinations sooner, at less risk, and at less expense with LLT than in-person

- Two Keck Institute for Space Studies (KISS) workshops support this finding
 - <http://kiss.caltech.edu/workshops/telepresence/telepresence.html> (held October 2016)
 - <http://kiss.caltech.edu/workshops/telepresence/telepresence2.html> (held July 2017)
- Study report authored by workshop participants to be published circa early 2019

