Luminary Presentation
2013 PHM Conference, New Orleans, LA

Autonomous Robotic Reconnaissance Missions in Extreme Space Environments

Prof. Dr. Wolfgang Fink[1,2]

Associate Professor

Edward & Maria Keonjian Endowed Chair

AIMBE Fellow

[1]Depts. of Electrical & Computer Engineering, Biomedical Engineering, Systems & Industrial Engineering,
Aerospace & Mechanical Engineering, and Ophthalmology & Vision Science
Visual and Autonomous Exploration Systems Research Laboratory, University of Arizona, Tucson, AZ
[2]California Institute of Technology, Visual and Autonomous Exploration Systems Research Laboratory,
Division of Physics, Mathematics and Astronomy, Mail Code 103-33, Pasadena, CA

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Indranil Roychoudhury

Yvonne Lopez

Roxane Rose

et al.

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Collaborators:

Mark A. Tarbell

Visiting Scientist and Senior Research Scientist

Visual and Autonomous Exploration Systems Research Laboratory

Caltech/University of Arizona

Wayne Waller

Former Director

Digital Media Center

Caltech

Colleagues at various Institutions

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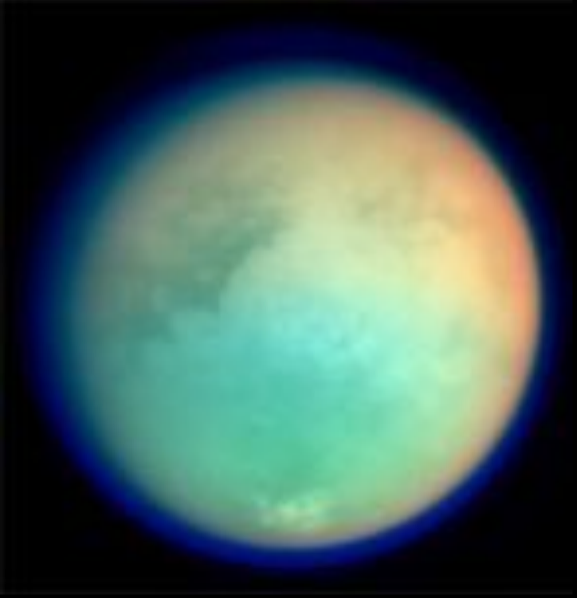
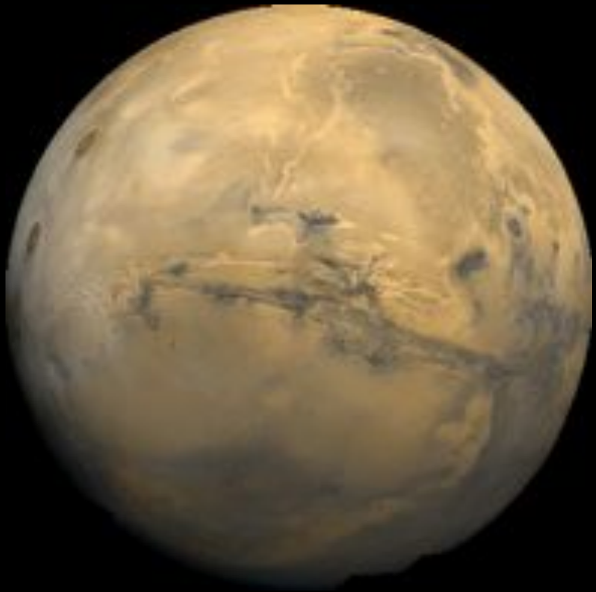
Motivation

Planetary Bodies of High Interest





[Images Courtesy NASA]

OSIRIS-REx: Asteroid Sample Return Mission 2016

Global Scale:
Vast Canyon Systems such as Valles Marineris

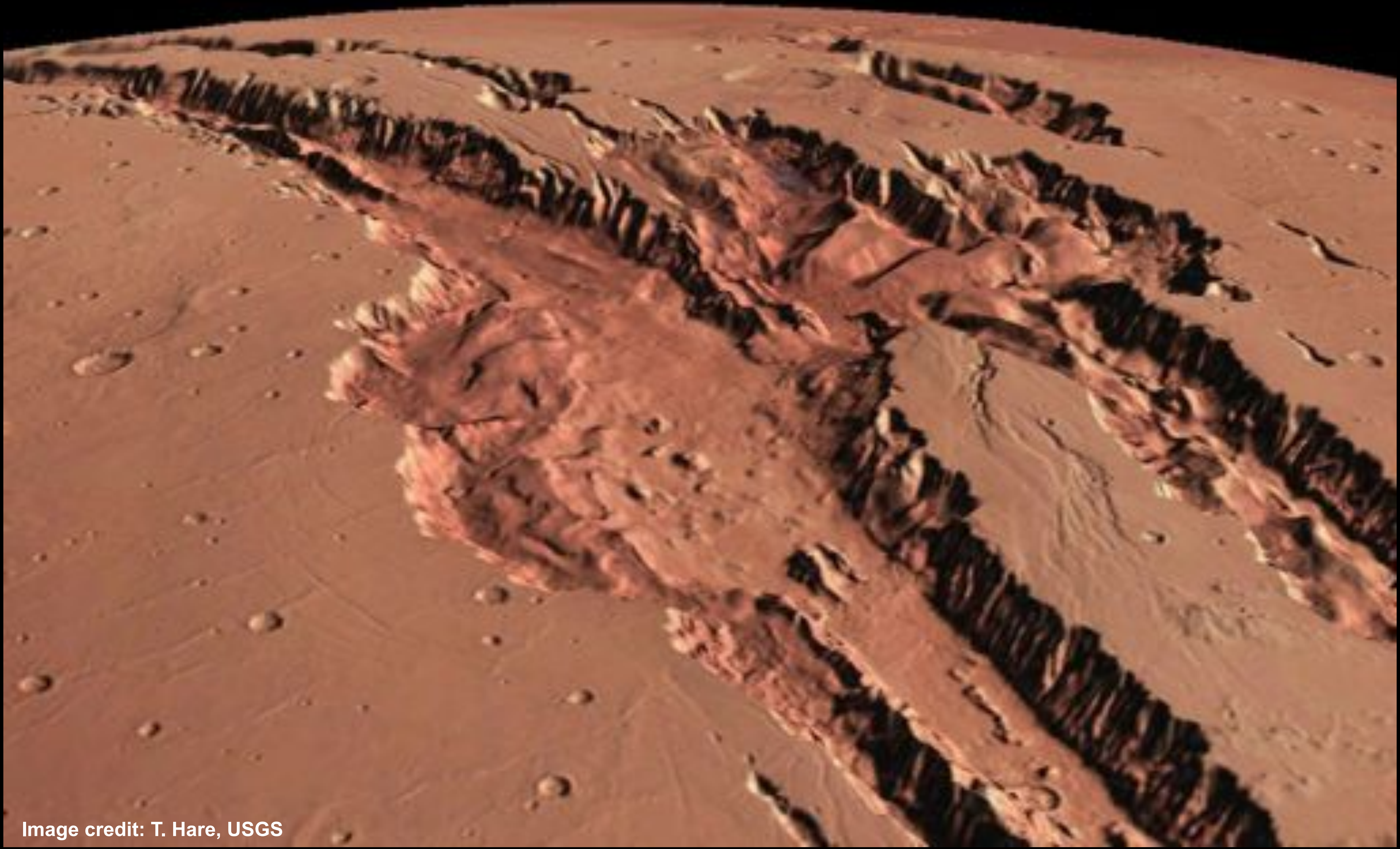


Image credit: T. Hare, USGS

Global to Regional Scale:
Central Valles Marineris

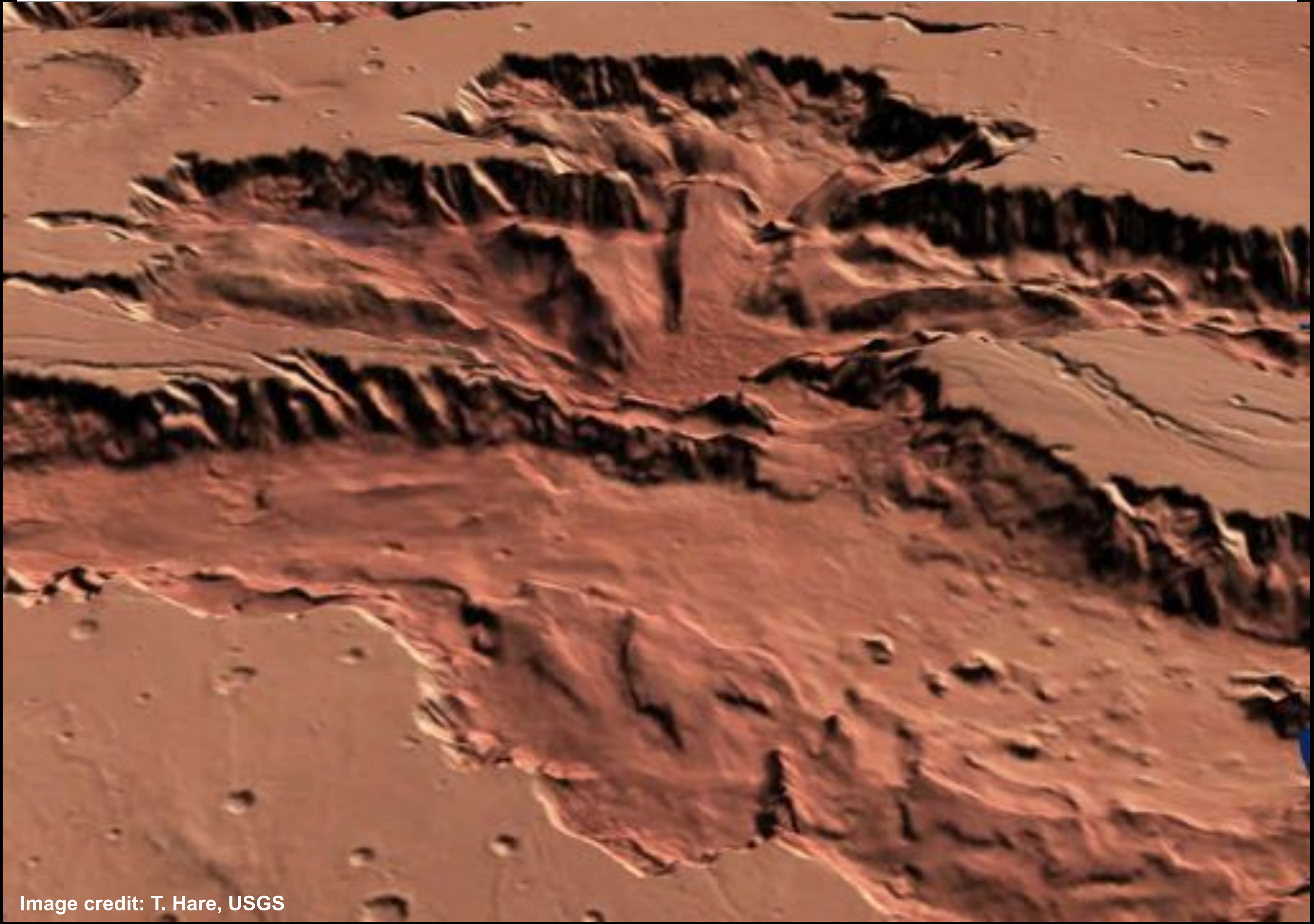


Image credit: T. Hare, USGS

Regional Scale:
Melas Chasma

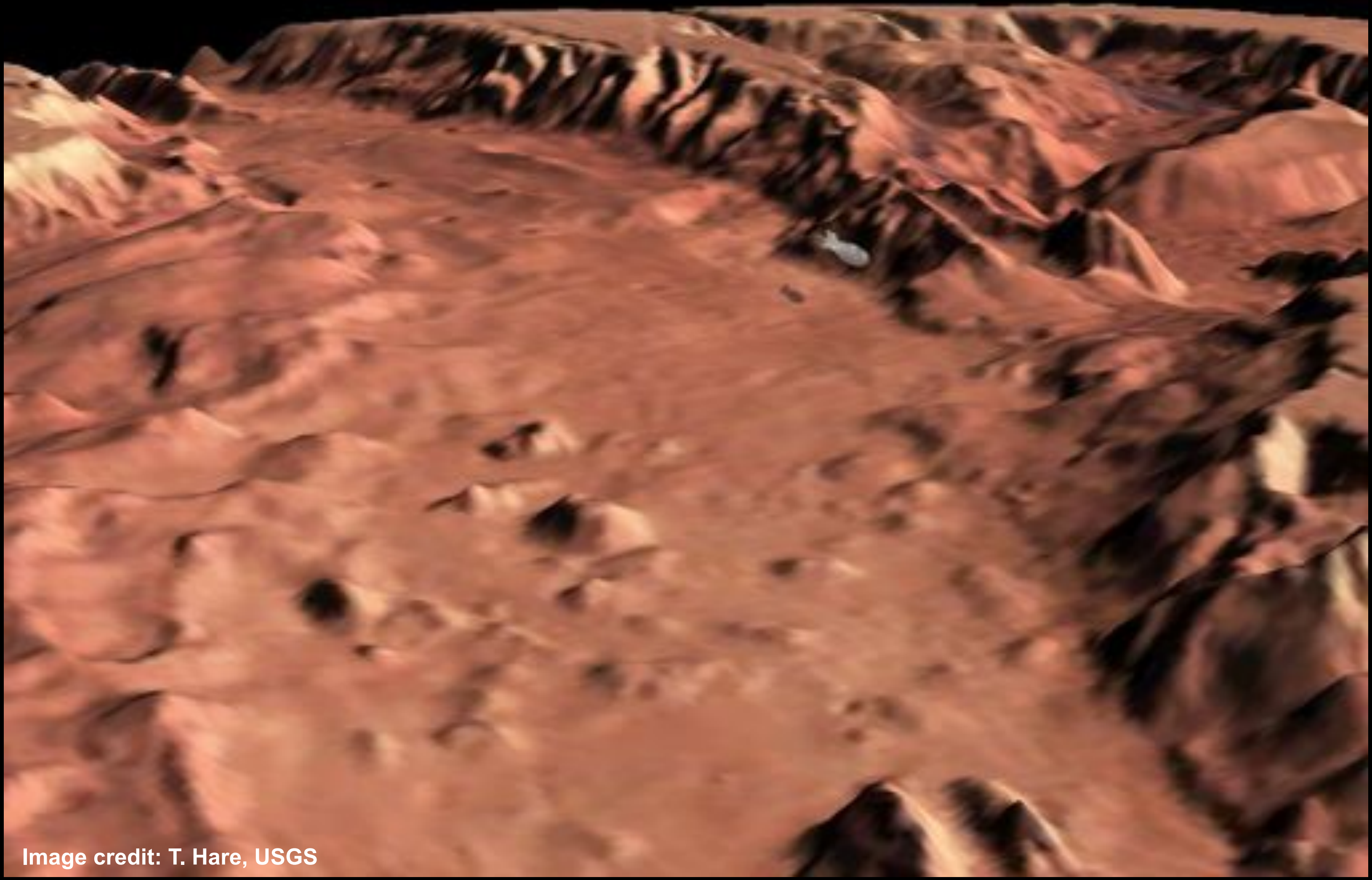
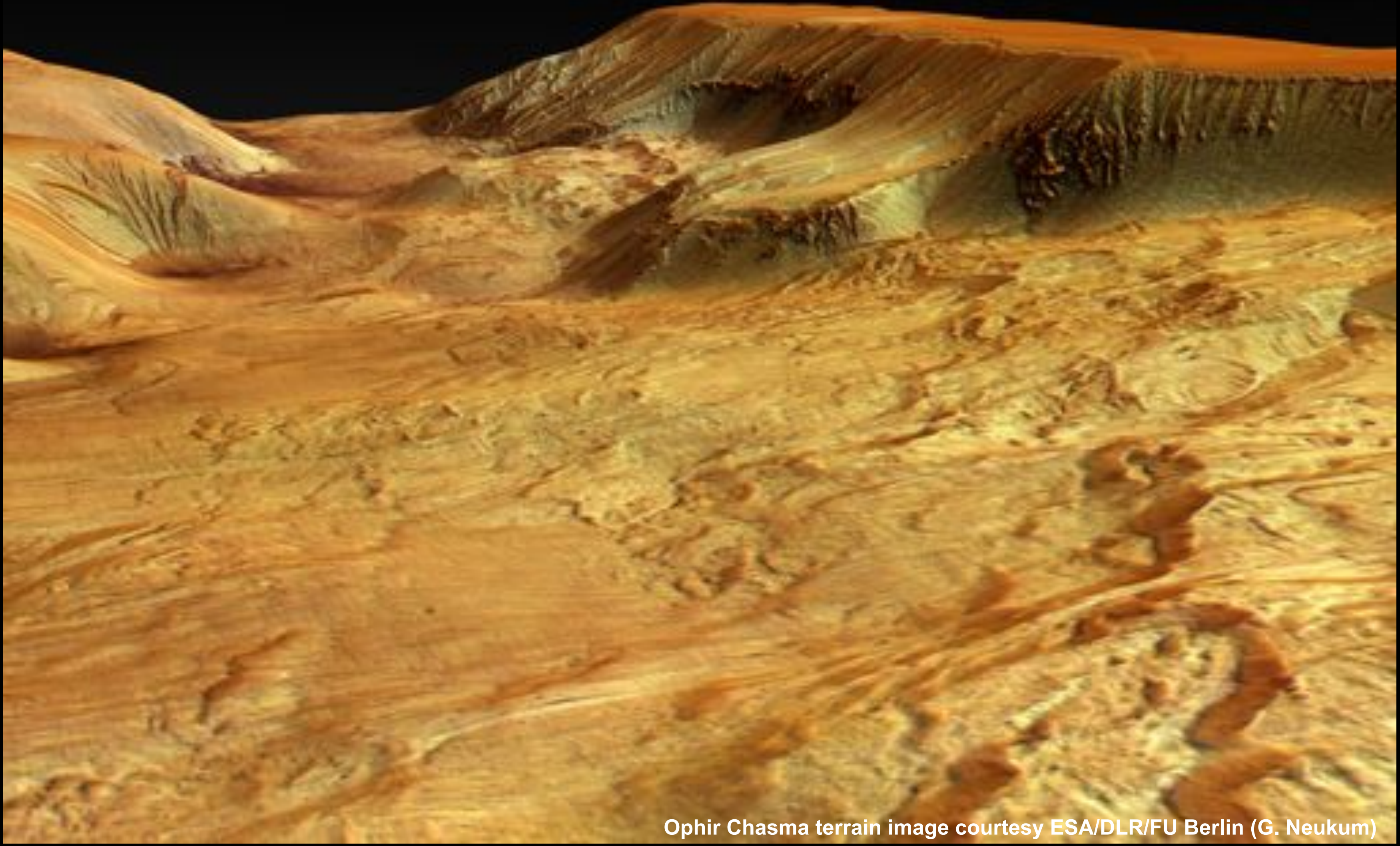


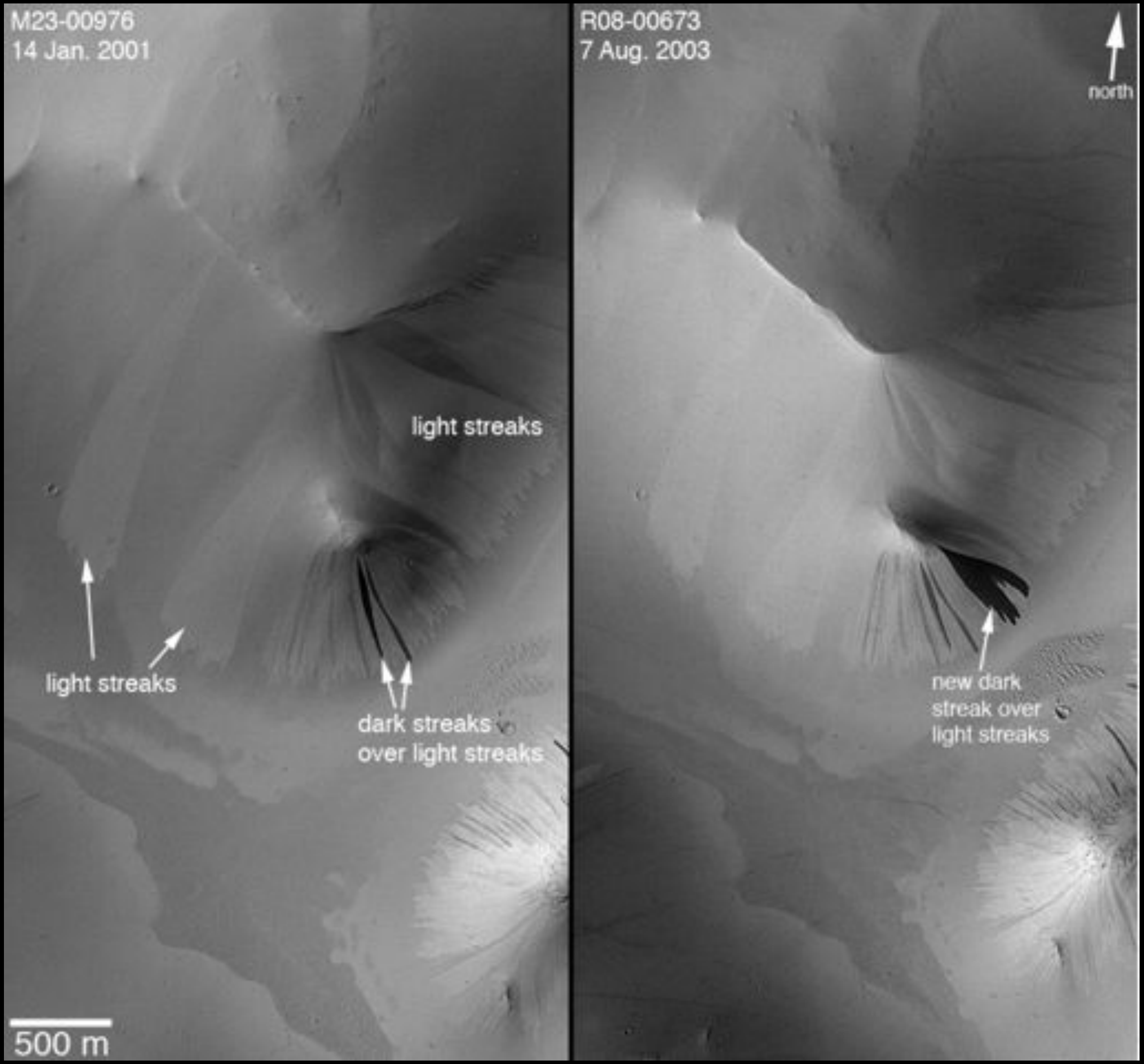
Image credit: T. Hare, USGS

Regional to Local Scale:
Ophir Chasma



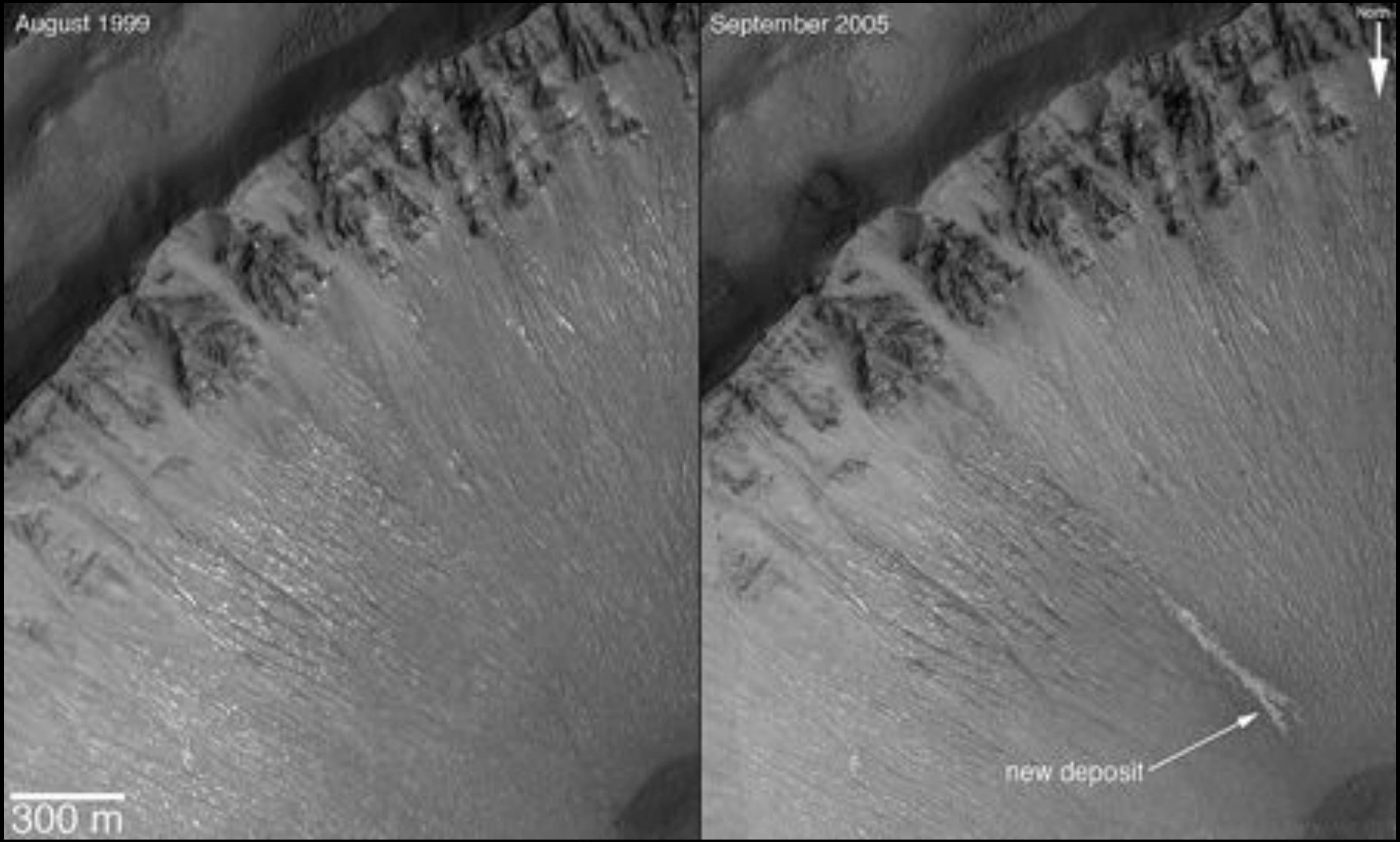
Ophir Chasma terrain image courtesy ESA/DLR/FU Berlin (G. Neukum)

Example of Recent/Transient Events:
Dark Slope Streaks



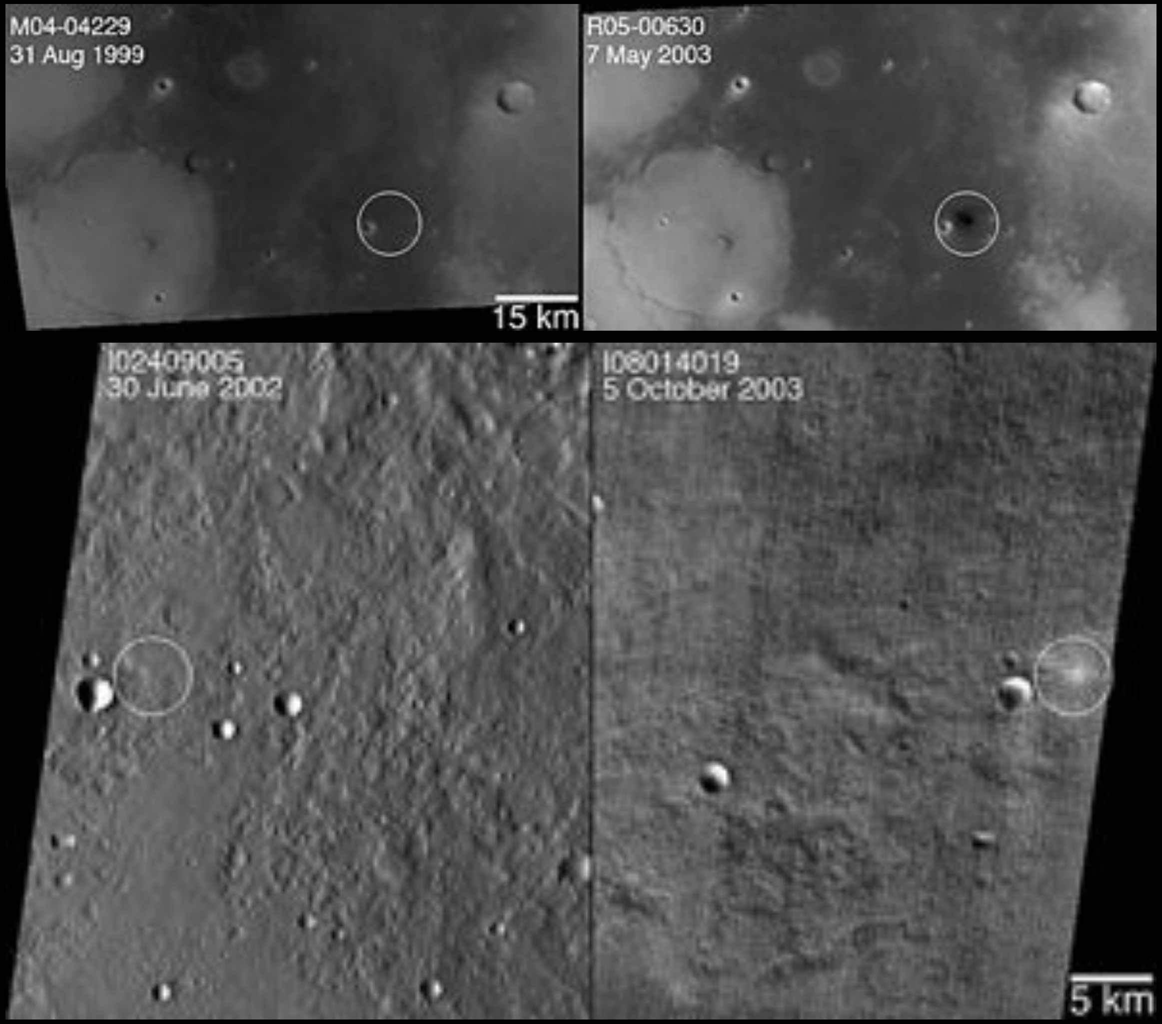
[Images courtesy of NASA/JPL/MSSS]

Example of Recent/Transient Events:
Light-toned Gully Deposit



[Images courtesy of NASA/JPL/MSSS]

Example of Recent/Transient Events:
New Impact Crater (also: Volcanoes, Fires, Floods)



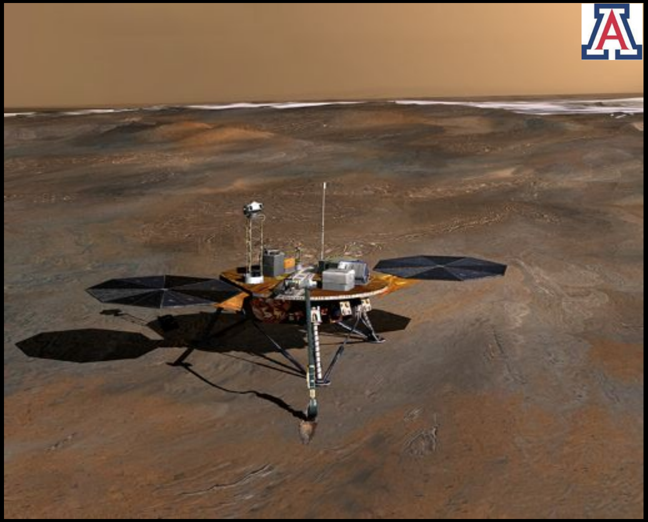
[Images courtesy of NASA/JPL/MSSS]

Tier-Scalable Reconnaissance
&
Autonomous Robotic (Space) Exploration

Traditional Mission Architectures

Mars Reconnaissance Orbiter (courtesy of NASA)

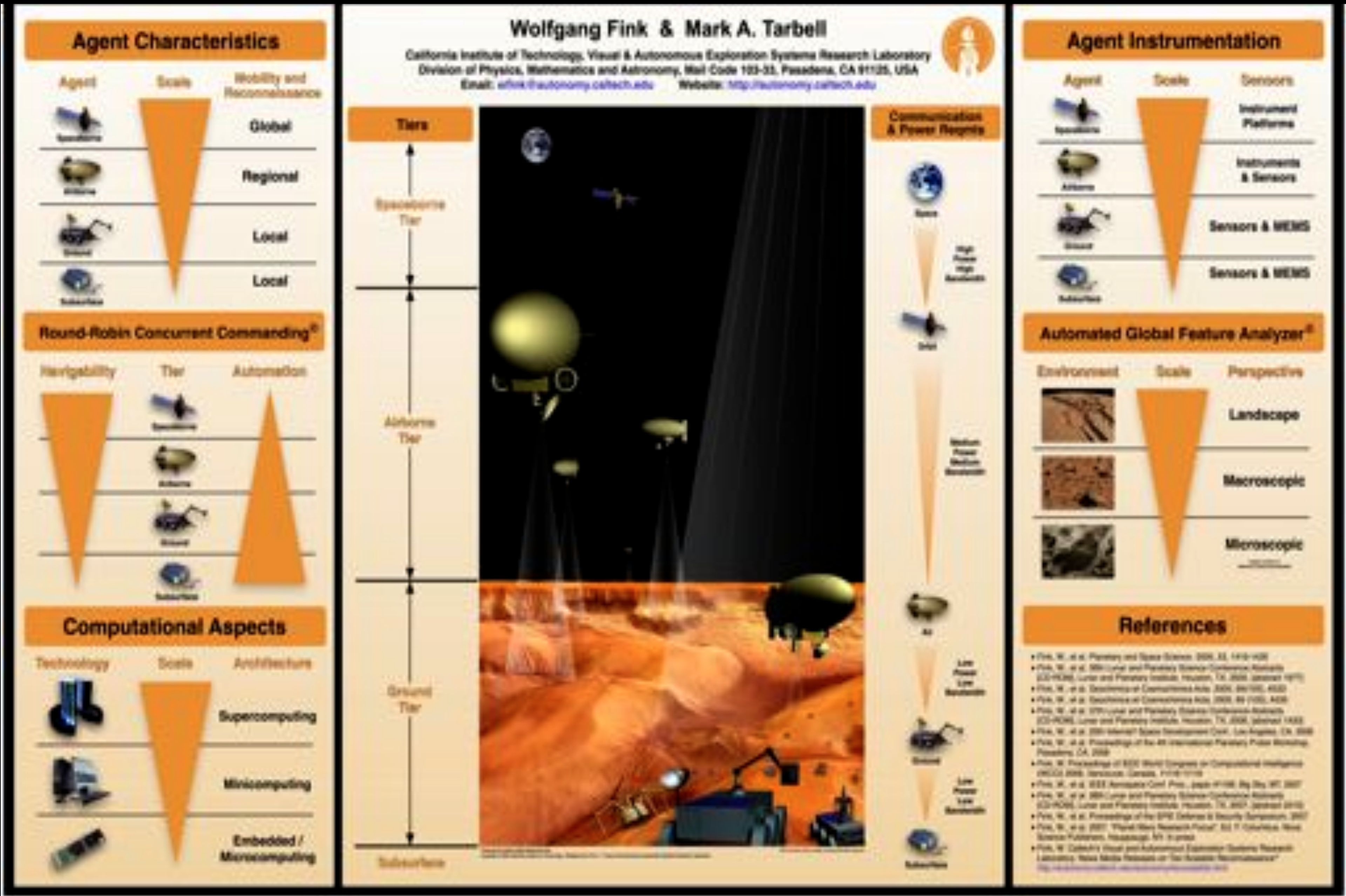
Mars Science Laboratory Rover Mission (courtesy of NASA)



Phoenix Lander Mission (courtesy of NASA)

Tier-Scalable Reconnaissance:
Autonomous C^4ISR Architecture

Fink et al., PSS 2005



Wolfgang Fink & Mark A. Tarbell

California Institute of Technology, Visual & Autonomous Exploration Systems Research Laboratory
Division of Physics, Mathematics and Astronomy, Mail Code 103-33, Pasadena, CA 91125, USA
Email: wfink@autonomy.caltech.edu Website: http://autonomy.caltech.edu

Agent Characteristics

Agent	Scale	Mobility and Reconnaissance
Spaceborne		Global
Airborne		Regional
Ground		Local
Subsurface		Local

Round-Robin Concurrent Commanding©

Navigability	Tier	Automation
	Spaceborne	
	Airborne	
	Ground	
	Subsurface	

Computational Aspects

Technology	Scale	Architecture
		Supercomputing
		Minicomputing
		Embedded / Microcomputing

Tiers

Spaceborne Tier
Airborne Tier
Ground Tier
Subsurface

Communication & Power Regime

Space
High Power High Bandwidth
Orbit
Medium Power Medium Bandwidth
Air
Low Power Low Bandwidth
Ground
Low Power Low Bandwidth
Subsurface

Agent Instrumentation

Agent	Scale	Sensors
Spaceborne		Instrument Platforms
Airborne		Instruments & Sensors
Ground		Sensors & MEMS
Subsurface		Sensors & MEMS

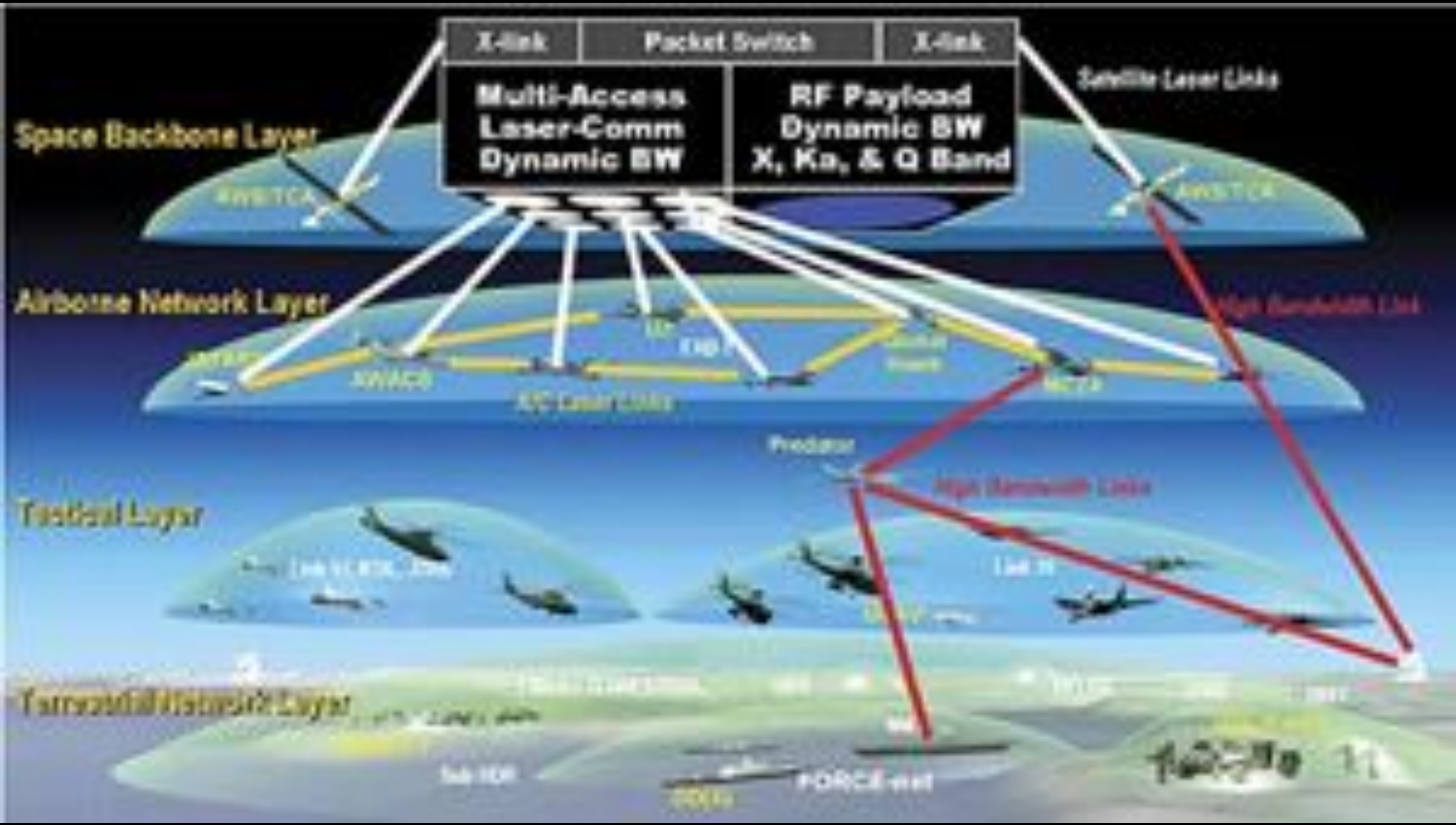
Automated Global Feature Analyzer©

Environment	Scale	Perspective
		Landscape
		Macroscopic
		Microscopic

References

Raytheon

Future C⁴ISR Architecture (TSAT)



Financial Disclosure:
Existing Caltech Intellectual Property (IP)

Patent number: US 6,990,406
Title: “MULTI-AGENT AUTONOMOUS SYSTEM”
Authors: Wolfgang Fink et al.

Patent number: US 7,734,063
Title: “MULTI-AGENT AUTONOMOUS SYSTEM”
Authors: Wolfgang Fink et al.

Patent number: US 7,742,845
Title: “MULTI-AGENT AUTONOMOUS SYSTEM AND METHOD”
Authors: Wolfgang Fink et al.

Tier-Scalable Reconnaissance Paradigm and Robotic Test Bed
Featured in SCIENCE 30 July 2010 Vol 329

EXPLORATION

Making Smarter, Savvier Robots

What machines of the future really need to learn, say experts who plan to have them explore the far reaches of the solar system, is more independent behavior

Which rock? On Mars, the robot Opportunity needed some human help to spot this meteorite.

On 18 July 2009, the Mars rover Opportunity was scooting toward a distant martian crater when it spied an anomaly amid the ripples of red soil: a bruise-colored rock the size of a watermelon. It looked like a meteorite—potential evidence that the ancient atmosphere of Mars, like today's, was thin enough for such rocks to pass through without exploding.

The strange rock was exactly the kind of thing NASA sent Opportunity to find. But because Mars and Earth are millions of kilometers apart and rotate out of sync, NASA scientists didn't see it until Opportunity had driven 200 meters beyond it. They hit reverse but had to wait three full days for Opportunity to backtrack to the spot.

The researchers got their meteorite. But the near miss—and the frustrating delay—underscored a defect of current exploration technology: Basically, robots are pretty dumb. Now scientists across the world are striving to change that by developing intelligent robots that can circumvent danger and spot enticing features on their own.

Hundreds of scientists, mostly at NASA and at universities, are working on improving robot explorers. But only a few dozen specialize in developing robots with true, high-level independence. The main NASA lab, at the Jet Propulsion Laboratory (JPL) in Pasadena, California, has a dozen people and a budget of about $4 million—a lower figure than in the past. But scientists there see promising signs. For one, NASA chief technologist Robert Braun has begun a new, general Space Technology Program that lists "machine intelligence" as one thrust.

"There are compelling reasons to send humans into deep space," says Steve Chien, who develops autonomous space systems for JPL. "A smart scientist can do much better experiments. But it's very expensive. By making the spacecraft much smarter, we can reduce the gap between human exploration and robotic exploration."

Where to go

Robots with an IQ boost will be essential for fully exploring some locations in the solar system—including hostile spots. On Venus, for example, 450°C surface temperatures and pressures comparable to those a kilometer deep in the ocean will destroy the onboard computers of any lander within 5 hours, tops. To get anything done, the lander will need to perform experiments, such as sampling soil, without human input.

Rendezvous missions with comets or asteroids and landings on distant moons would also benefit from more autonomous robots, researchers say. On Saturn's moon Titan, radio waves carrying scientists' instructions take 90 minutes to arrive from Earth. Yet a probe flying through Titan's atmosphere would have to negotiate hazards in real time, notes Wolfgang Fink, a computer scientist working at the California Institute of Technology and the University of Arizona. "If it's about to fly into a mountain range, it can't say, 'I'm flying into a mountain range. Please advise,' and wait 1½ hours."

Scientists also hope that greater intelligence will make robots more efficient, improving their "energy storage, memory, computational throughput, communication downlink bandwidth, and heating and cooling capability," says Larry Matthies, a computer scientist at JPL. Opportunity (and its companion on Mars, Spirit) travel at such pokey paces—28 kilometers total in 6 years—partly because they rely on humans to spot dangerously loose sand or steep slopes. A smarter robot could zip around obstacles by itself and travel up to 10 times as far each day, Matthies estimates. And the more work the rover can do alone, the more time it will have to collect good samples.

Recipes for "eureka"

In December and January, NASA took the first steps toward making a spacecraft autonomous when it uploaded four pieces of software to Opportunity. Tara Estlin, a senior engineer at JPL, explains that, with the new software, "scientists can give us a single property or combination of properties—the largest rock you can find, or the darkest rock," and Opportunity will zero in on them. In March, the software passed its first test by discovering, all on its own, an angular, football-size rock—ejected from a nearby impact crater—in a field of rounder boulders. (Paradoxically, though, Estlin's team still has to tell the rover a day in advance when to be autonomous and when not to.)

Earth-based systems have already demonstrated significant independence, within limits. Chien works on the Earth Observing Sensorweb, a group of half a dozen NASA satellites that monitor Earth's atmosphere. Some scan large sections of Earth's surface and pick out a flood or a volcanic plume from space. They beam the data to ground-based computers, which in turn direct higher-resolution satellites to focus on the event—all without human input. Chien hopes to expand the work to other planets. But the instruments can spot only a short list of predefined events; they cannot find anything interesting or new on their own. Asked whether the system could shift its attention on its own between the two most notable geological events of the past few months, the Eyjafjallajökull volcano eruption in March and the BP oil slick in the Gulf of Mexico in April, Chien groans: "I wish, I wish."

CREDITS: (MAIN) NASA/JPL-CALTECH; NASA/JPL

To solve problems of data filtering and interpretation, some researchers are working to cultivate a robot's taste for the unusual. Sometimes scientists want to study the most representative feature around, but more often they are intrigued by anomalies. "If the whole desert is smooth and one area is rough, that's interesting," says Chien. "If the whole desert is rough and one area is smooth, that's interesting. If you really don't know about the environment, you have to fall back on something like outliers."

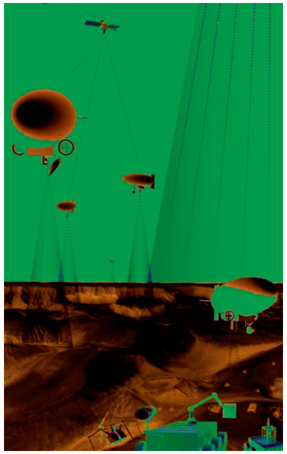
Patrick McGuire, a computer scientist and geologist at the University of Chicago in Illinois, has developed a simple setup that can detect novel features in a landscape. A netbook laptop hooked up to a cell phone with a camera snaps a picture and compares its colors, textures, and shapes with other pictures in its memory. The computer then compresses the image with an algorithm. If the compression process is very similar to that of an earlier image, the computer concludes that the new image doesn't contain much novel information and throws it out.

McGuire has tested this system at rock outcrops in Utah and Spain that resemble the barren landscape a probe might encounter on a distant planet. He reported late last year that the software performed equally well in both locations. In one case, the software immediately recognized a patch of lichen as novel—and then, with the next picture, threw out an image of lichen on another rock as too similar to bother remembering, demonstrating that it is a quick study.

Curious future

Some scientists, including Fink, say better programming alone won't turn robots into independent explorers. "In planetary exploration, you're in for surprises," Fink argues, "and you will not always have a rule" on how to proceed. He dreams of robots that can experiment with their own "neural networks"—their internal architectures for taking inputs, processing information, and producing outputs—and can, like humans, form their own rules for exploring.

McGuire says certain architectures have advantages in different applications. With a so-called Hopfield neural network, for example, a computer can recognize an entire picture stored in memory after seeing only a fraction. Many robots come equipped with multiple lenses and cameras that take pictures on different scales, so the capability to tag small snippets as familiar would help make the robot more efficient in selecting which scenes to shoot or not shoot.



Mechanized teamwork. Caltech's Wolfgang Fink foresees robots exploring in tiered ranks.

CREDIT: DR. WOLFGANG FINK AND WAYNE WALLER, VISUAL AND AUTONOMOUS EXPLORATION SYSTEMS RESEARCH LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY

Even more ambitiously, Fink is developing systems to give robots freedom to change their logical architecture—essentially to "rewire" their brains. A robot might make a rule more complicated or simpler by adding or cutting steps, or combining the binary code of two rules and trying out their "offspring." If the new rules worked well, it adds them to its problem-solving repertoire.

Fink published a paper last year on a self-configuring neural network to sort odd numbers from even numbers. Working with numbers 24 bits long—in the tens of millions in decimal notation—the network hit upon the solution (look at the final digit) with no guidance. And by focusing on one bit, the computer freed 23 other bits for different tasks. In other contexts, such self-configuring networks have helped scientists design circuits and new drugs.

Ultimately, Fink says, he hopes to instill something like curiosity in robots. That kind of programming would go far beyond algorithms his team has developed to help robots calculate the best angle to stretch out an arm to grasp an object or scoop soil. "We're after the *intent* to deploy the arm. How does the spacecraft know where it wants to dig? This is of interest to me."

The first test?

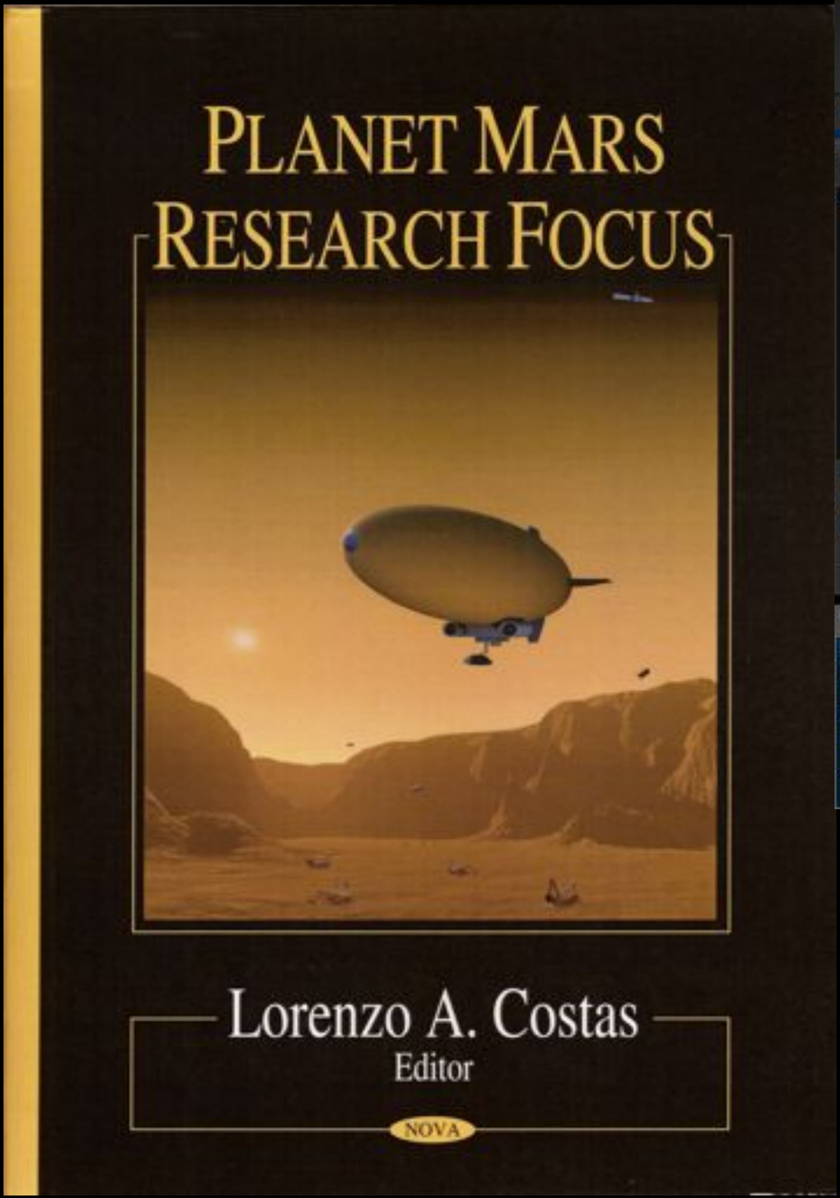
Smart, curious robot explorers wouldn't have to work alone. Fink envisions a multitier scheme of robots with satellites, blimps or balloons, and platoons of ground rovers. An intelligent satellite would direct the blimps to canvass certain areas. The blimps, in turn, would direct surface rovers to scout hydrothermal vents or rappel down cliff faces with a cable. Based on feedback between each tier, the satellite would decide which sites to concentrate on and how best to deploy the other machines. It would judge when to risk sending rovers into dangerous areas like active volcanoes, and when to stop collecting data, Fink says. "A spacecraft could even leave a place and tell you, 'There's nothing interesting here. I'll go somewhere else and I'll tell you when I get there.' " Fink and his team have started building a test site in Arizona with rovers, boats, and blimps for field experiments with rudimentary versions of such robotic expeditions.

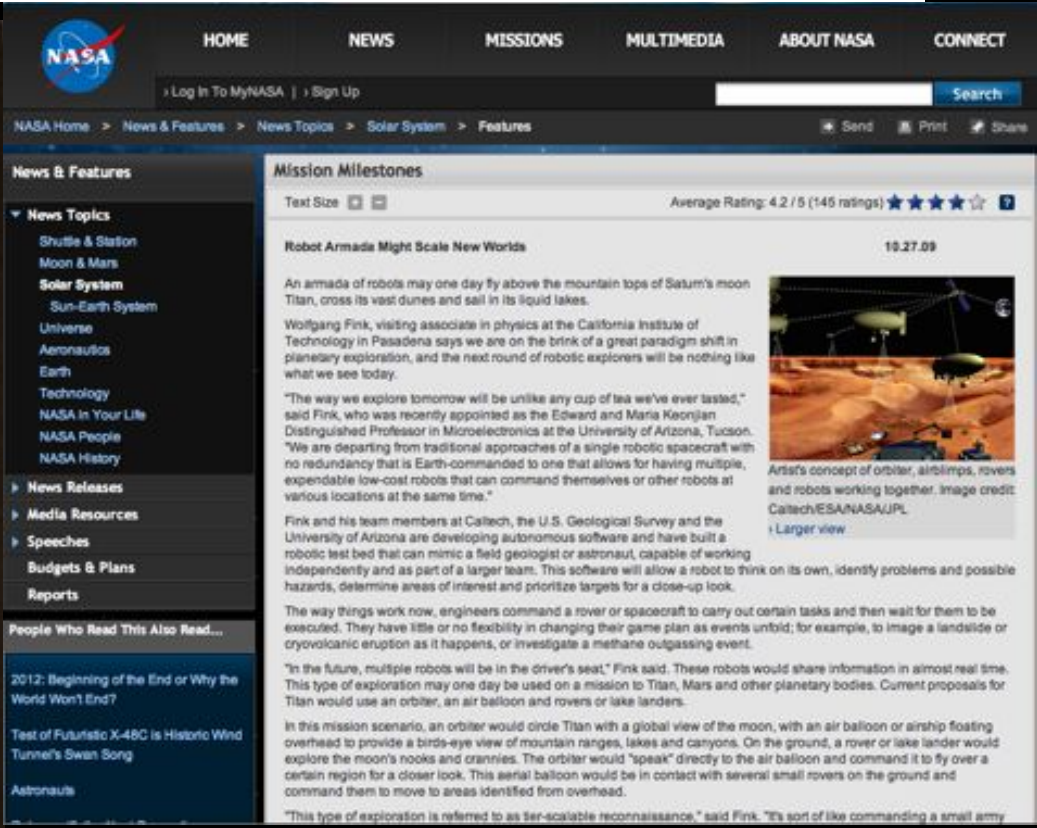
Chien imagines a different sort of teamwork: human explorers with fast-learning robot assistants. A group led by David Akin at the University of Maryland, College Park, is testing a golf cart–size three-wheeled rover, named Raven, to help astronauts explore planets. On tricky terrain such as loose soil or slopes, Akin says, the astronaut can simply say, "Follow my path," and the robot will.

President Barack Obama's stated goals of sending humans to an asteroid in the 2020s and to Mars in the 2030s could help foster such partnerships. Chien says human-and-robot teams could do a better job together than either could alone. Humans would make plans and be in charge, while robots slogged through the important but routine technician work. "It's the classic apprentice thing," Chien says. "You want the biggest brainpower worrying about the biggest problems."

–SAM KEAN

Public Exposure, Media Releases, and Awards





Robot Armada Might Scale New Worlds 10.27.09

An armada of robots may one day fly above the mountain tops of Saturn's moon Titan, cross its vast dunes and sail in its liquid lakes.

Wolfgang Fink, visiting associate in physics at the California Institute of Technology in Pasadena says we are on the brink of a great paradigm shift in planetary exploration, and the next round of robotic explorers will be nothing like what we see today.

"The way we explore tomorrow will be unlike any cup of tea we've ever tasted," said Fink, who was recently appointed as the Edward and Maria Keonjian Distinguished Professor in Microelectronics at the University of Arizona, Tucson. "We are departing from traditional approaches of a single robotic spacecraft with no redundancy that is Earth-commanded to one that allows for having multiple, expendable low-cost robots that can command themselves or other robots at various locations at the same time."

Artist's concept of orbiter, airblimps, rovers and robots working together. Image credit: Caltech/ESA/NASA/JPL

Fink and his team members at Caltech, the U.S. Geological Survey and the University of Arizona are developing autonomous software and have built a robotic test bed that can mimic a field geologist or astronaut, capable of working independently and as part of a larger team. This software will allow a robot to think on its own, identify problems and possible hazards, determine areas of interest and prioritize targets for a close-up look.

The way things work now, engineers command a rover or spacecraft to carry out certain tasks and then wait for them to be executed. They have little or no flexibility in changing their game plan as events unfold; for example, to image a landslide or cryovolcanic eruption as it happens, or investigate a methane outgassing event.

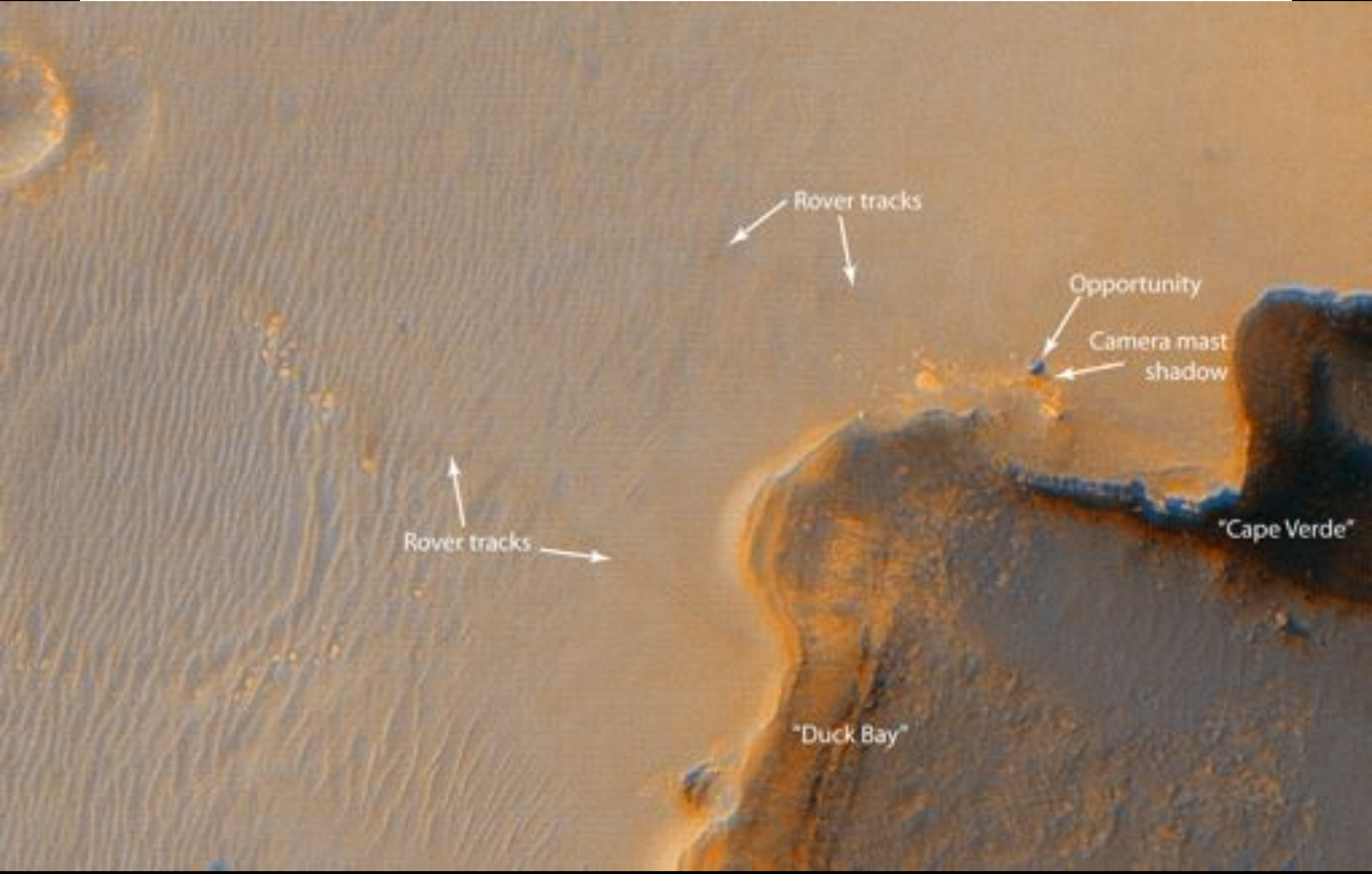
"In the future, multiple robots will be in the driver's seat," Fink said. These robots would share information in almost real time. This type of exploration may one day be used on a mission to Titan, Mars and other planetary bodies. Current proposals for Titan would use an orbiter, an air balloon and rovers or lake landers.

In this mission scenario, an orbiter would circle Titan with a global view of the moon, with an air balloon or airship floating overhead to provide a birds-eye view of mountain ranges, lakes and canyons. On the ground, a rover or lake lander would explore the moon's nooks and crannies. The orbiter would "speak" directly to the air balloon and command it to fly over a certain region for a closer look. This aerial balloon would be in contact with several small rovers on the ground and command them to move to areas identified from overhead.

"This type of exploration is referred to as tier-scalable reconnaissance," said Fink. "It's sort of like commanding a small army

received
NASA Board Award
November 2009

Example of Space-Ground Collaboration:
Locating MER Opportunity (NASA MRO)



Advantages • Payload • Applications

Advantages of Tier-scalable Reconnaissance Architecture:

- Overhead navigation affords deployment of less smart, therefore less costly, expendable ground agents
- Deploy *multiple expendable ground agents* in target zones – reduced driving requirement
- Mission *safety* and *redundancy*
- Optimized target identification and obstacle avoidance
- Efficient (overhead) commanding of multiple ground agents

Example (onboard) Instruments/Sensors:

- Optical, IR, UV cameras
- Hyperspectral cameras
- Sonar-systems
- Ground penetrating radar (GPR)
- MEMS-based devices and sensors

Application Examples:

- Operations in hazardous environments (incl. military, biochemical, radiation, or natural disasters)
- Reconnaissance operations (incl. planetary, military, civilian)
- Surveillance operations (e.g., Homeland Security), Stand-off Detection (IEDs)

Tier-Scalable Reconnaissance Robotic Test Bed

Tier-Scalable Reconnaissance Mission Test Bed:
Proof-of-Concept Multi-Rover Test Bed

Capabilities:

- Near real-time remote control worldwide
- Autonomous self-commanding
- Autonomous tele-commanding as part of Tier-scalable Reconnaissance© mission architectures
- Capable of complex and numerically intensive onboard calculations
- Hot-swapping of new exploration algorithms while en route
- Emulating realistic space mission communication scenarios
- Cooperative multi-rover operations
- Distributed scientific exploration

Specifications:

- Battery operated
- 4 WD drive
- User-controllable onboard cameras
- Wireless video link (TCP/IP)
- Swappable sensor platform
- Dual core general purpose onboard Unix workstation
- Remote controllable
- TCP/IP enabled (wireless LAN)

Fink & Tarbell, LPSC 2008

~3 kg payload!

Rover “CYCLOPS” featured in Popular Science 2010 and on National Science Foundation 2009 main webpage

AUGUST 10 2010 Volume 277 #2

CYCLOPS

A Legally Blind Robotic Guinea Pig for Testing Artificial Eyes

John B. Carnett

Birthplace
California Institute of Technology --- Dr. Wolfgang Fink, Mark A. Tarbell

Occupation
Simulates the visual experience of a blind person outfitted with a retinal implant

Why We Need It
Most vision implants are still too crude to test on humans.

How It Works
Cyclops, a $20,000, four-wheeled rover, is the world’s first stand-in for the visually impaired, allowing researchers to test and refine image-processing software for prosthetic eyes on a robot instead of a person. Mounted to Cyclops’s head is a remote-controlled camera that can pivot to capture the same view as a patient with that particular prosthesis would. If the robot can’t tell the difference between a stairwell and a fireplace, researchers will know they need to refine their algorithms.

On The Job By
This year.

CYCLOPS

A LEGALLY BLIND ROBOTIC GUINEA PIG FOR TESTING ARTIFICIAL EYES

BIRTHPLACE: California Institute of Technology
OCCUPATION: Simulates the visual experience of a blind person outfitted with a retinal implant
WHY WE NEED IT: Most vision implants are still too crude to test on humans.
HOW IT WORKS: Cyclops, a $20,000, four-wheeled rover, is the world’s first stand-in for the visually impaired, allowing researchers to test and refine image-processing software for prosthetic eyes on a robot instead of a person. Mounted to Cyclops’s head is a remote-controlled camera that can pivot to capture the same view as a patient with that particular prosthesis would. If the robot can’t tell the difference between a stairwell and a fireplace, researchers will know they need to refine their algorithms.
ON THE JOB BY: This year

Robot for Testing Artificial Retina

News From the Field

Caltech Scientists Create Robot Surrogate for Blind Persons in Testing Visual Prostheses

October 19, 2009

Scientists at the California Institute of Technology have created a remote-controlled robot that is able to simulate the "visual" experience of a blind person who has been implanted with a visual prosthesis, such as an artificial retina. An artificial retina consists of a silicon chip studded with a varying number of electrodes that directly stimulate retinal nerve cells. It is hoped that this approach may one day give blind persons the freedom of independent mobility. Full Story

Source
California Institute of Technology

The National Science Foundation (NSF) is an independent federal agency that supports

Tier-Scalable Reconnaissance Mission Test Bed:
Surface Explorers: Rovers

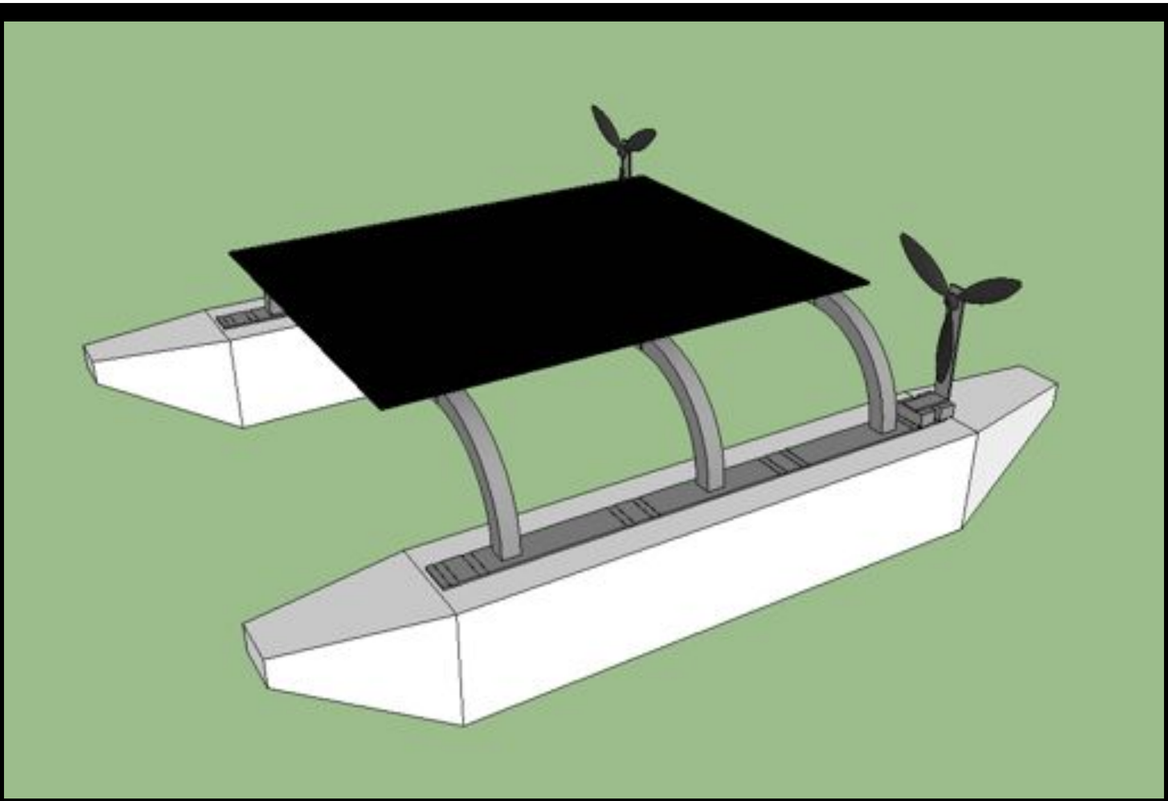
Fink et al., IEEE Aerospace 2011

Rovers:

- Electric motors
- Metal chassis and sensor platform
- General-purpose, high-performance Unix workstation
- Range up to 10 km on one battery charge
- Up to 10 hours onboard computing
- Wireless Internet capability
- > 30 kg payload sustained
- Onboard GPS
- Onboard HD camera

Robotic Lake Lander/Sea-Rover Test Bed:

Design Specifications



Fink et al., IEEE Aerospace 2012

- Catamaran design
- Very stable
- 1.8 m long by 1.5 m wide by 0.5 m tall
- Mass: ~45 kg without sensor payload
- > 68 kg payload capability
- Highly modular design

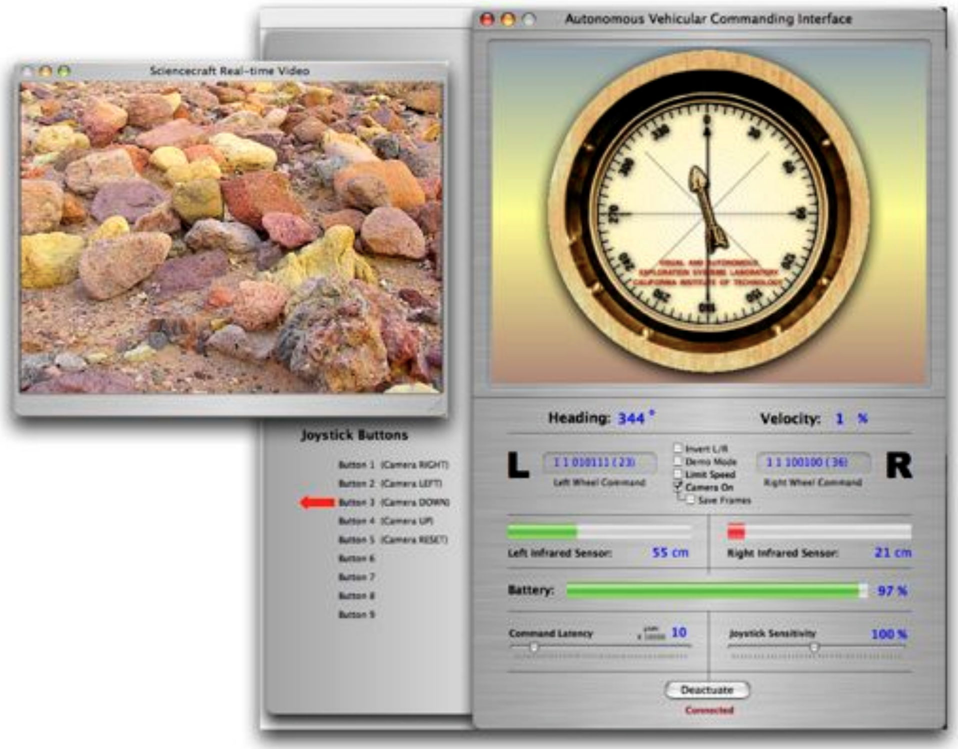
- Electric motors
- Air-based propulsion system
- General-purpose, high-performance Unix workstation
- Onboard HD cameras
- Onboard side-scanning sonar
- Wireless Internet capability (Earth applications)
- Onboard GPS (Earth applications)

Robotic Lake Lander/Sea-Rover Test Bed:

The REAL Thing

Fink et al., IEEE Aerospace 2012

World-wide Commanding & Sensor Data Transmission Infrastructures



Heading: 344°

Velocity: 1 %

L: 1 1 010111 (23) Left Wheel Command

☐ Invert L/R
☐ Demo Mode
☐ Limit Speed
☑ Camera On
☐ Save Frames

R: 1 1 100100 (36) Right Wheel Command

Left Infrared Sensor: 55 cm

Right Infrared Sensor: 21 cm

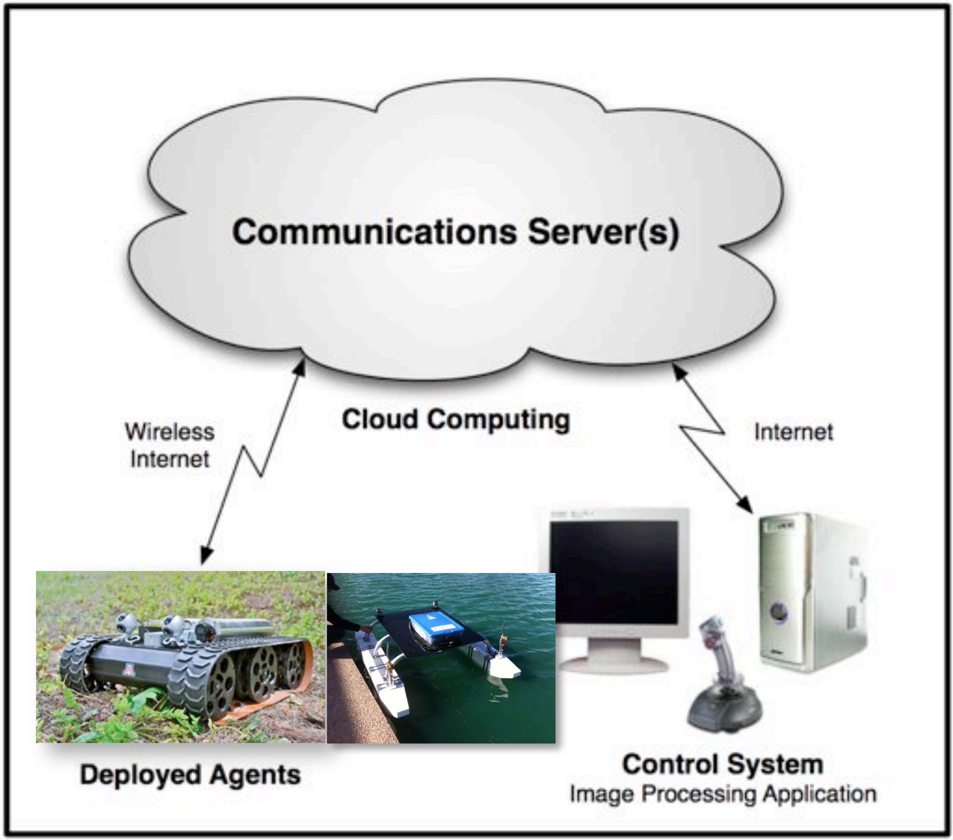
Battery: 97 %

Command Latency 10

Joystick Sensitivity 100 %

Worldwide Control via Cloud Computing!

Fink et al., CMPB 2009; SPIE 2009



Controllable worldwide via iPhone (demonstrated at MacTech 2010 Conference)

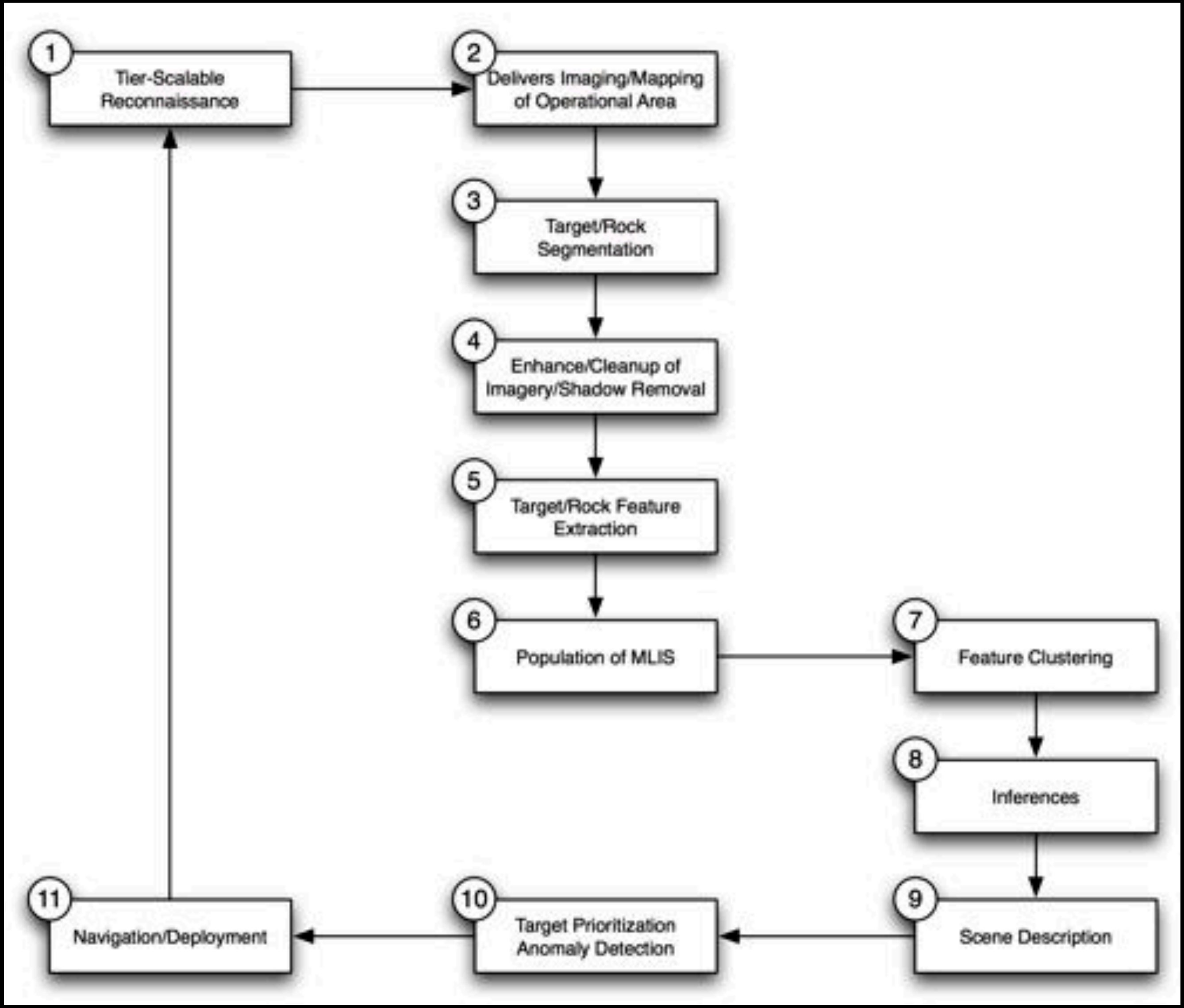
Heading: 14.4° Speed: 57%

Coordinate: (020,078)

Operational Autonomy
&
Anomaly Detection

A new field for PHM?!

Automated Global Feature Analyzer (AGFA, Fink et al., 2008)
Operational Level 1 Diagram



1 Tier-Scalable Reconnaissance

2 Delivers Imaging/Mapping of Operational Area

3 Target/Rock Segmentation

4 Enhance/Cleanup of Imagery/Shadow Removal

5 Target/Rock Feature Extraction

6 Population of MLIS

7 Feature Clustering

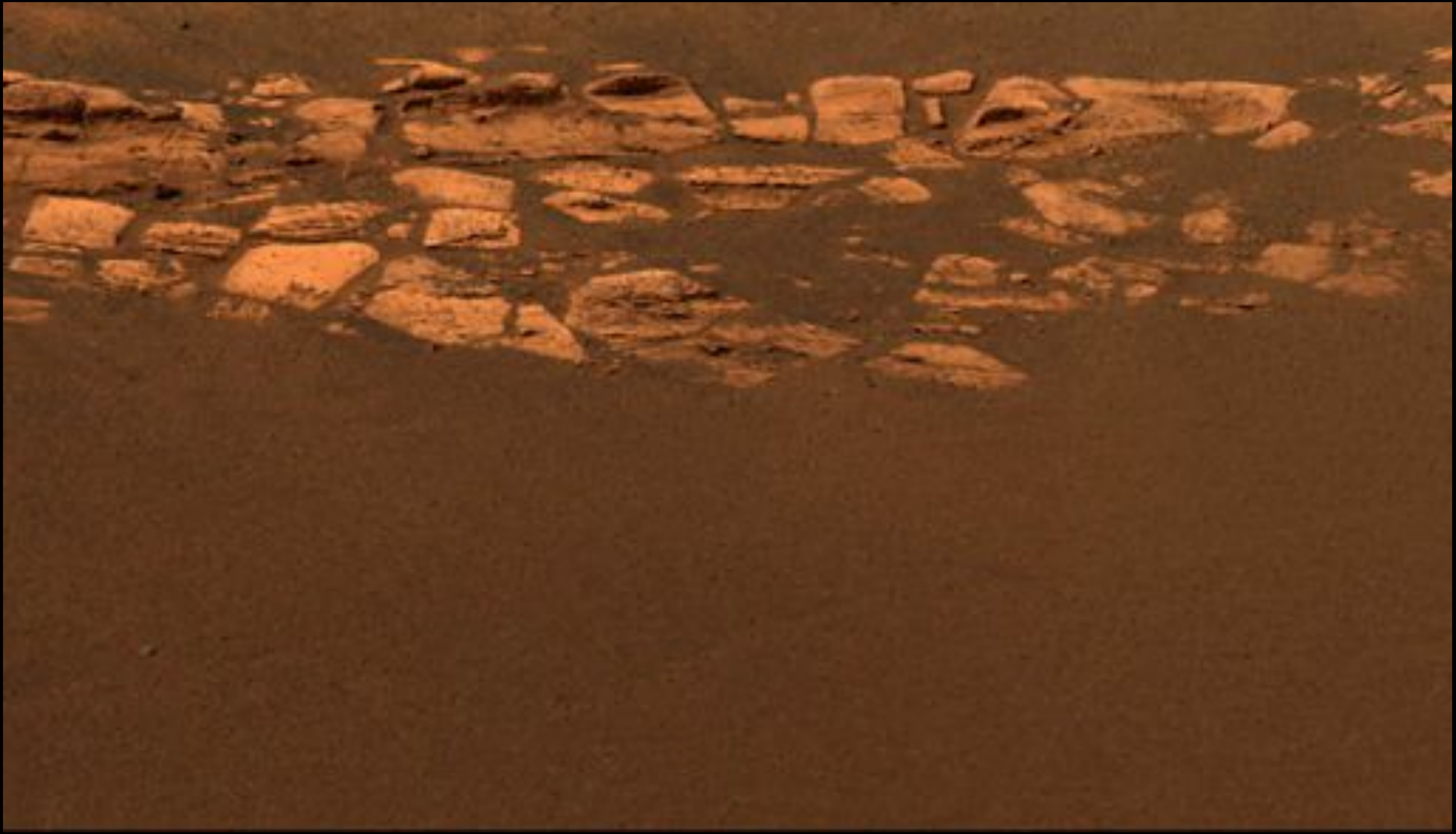
8 Inferences

9 Scene Description

10 Target Prioritization Anomaly Detection

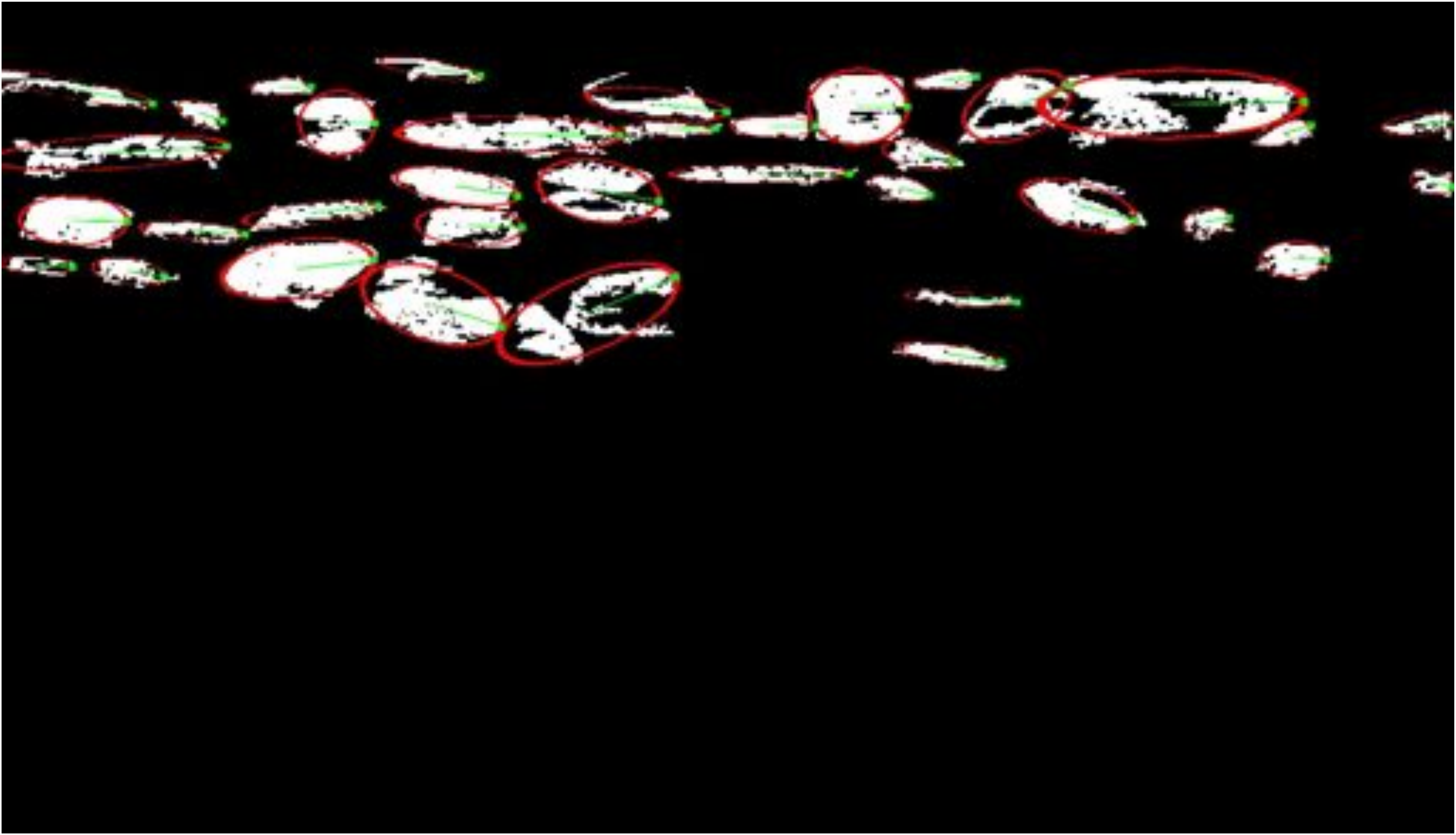
11 Navigation/Deployment

AGFA
Example Imaged Operational Area



[MER Image Courtesy NASA]

AGFA
Example Processed Operational Area



AGFA
Example Target (Rock) Features

Color

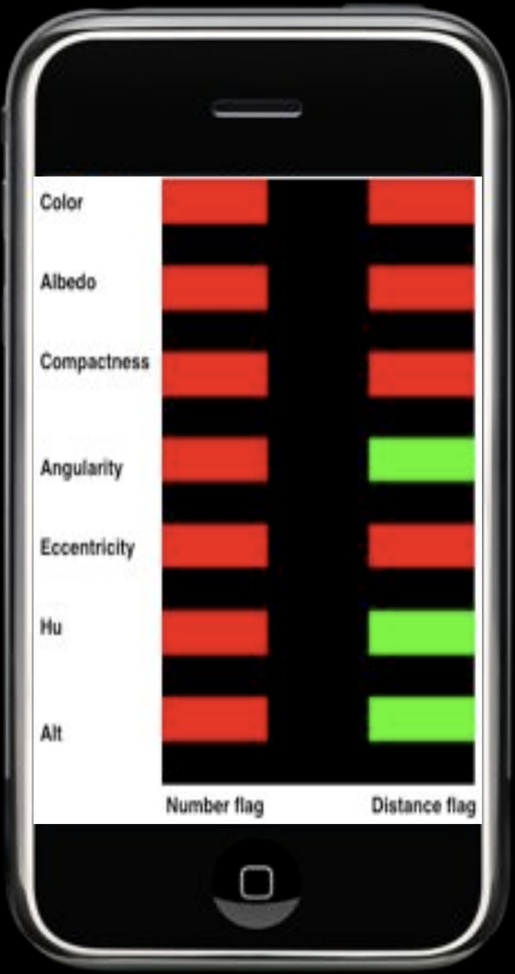
Angularity

Albedo

Texture/Vesicularity

AGFA (Fink et al., 2008)
AGFA Anomaly Detection: Conceptual Example

AGFA



	Number flag	Distance flag
Color	🟥	🟥
Albedo	🟥	🟥
Compactness	🟥	🟥
Angularity	🟥	🟩
Eccentricity	🟥	🟥
Hu	🟥	🟩
Alt	🟥	🟩

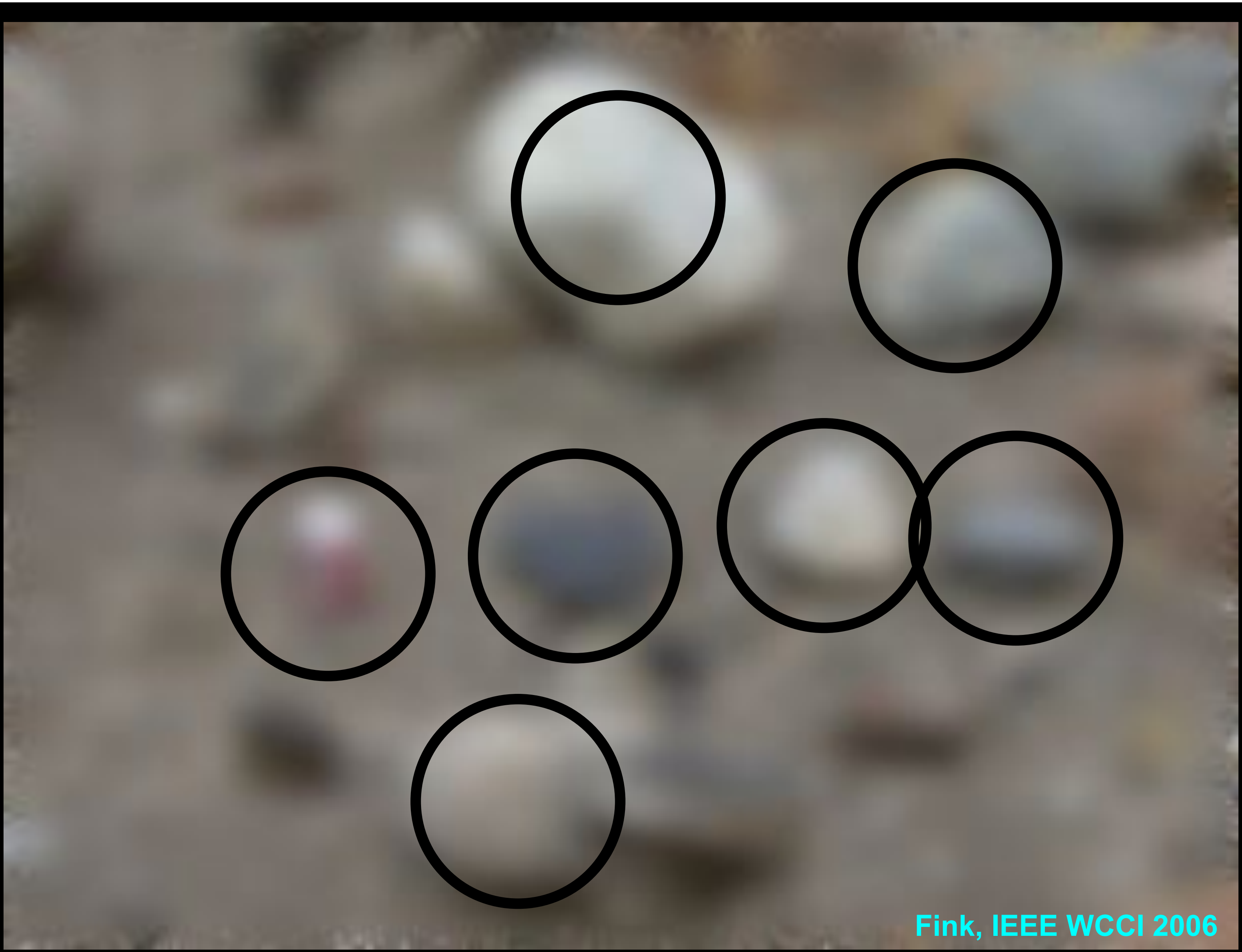
Preliminary Feature/Reconnaissance Data (coarse)

Raw Sensor Data

Fink, IEEE WCCI 2006

Preliminary Feature/Reconnaissance Data (coarse)

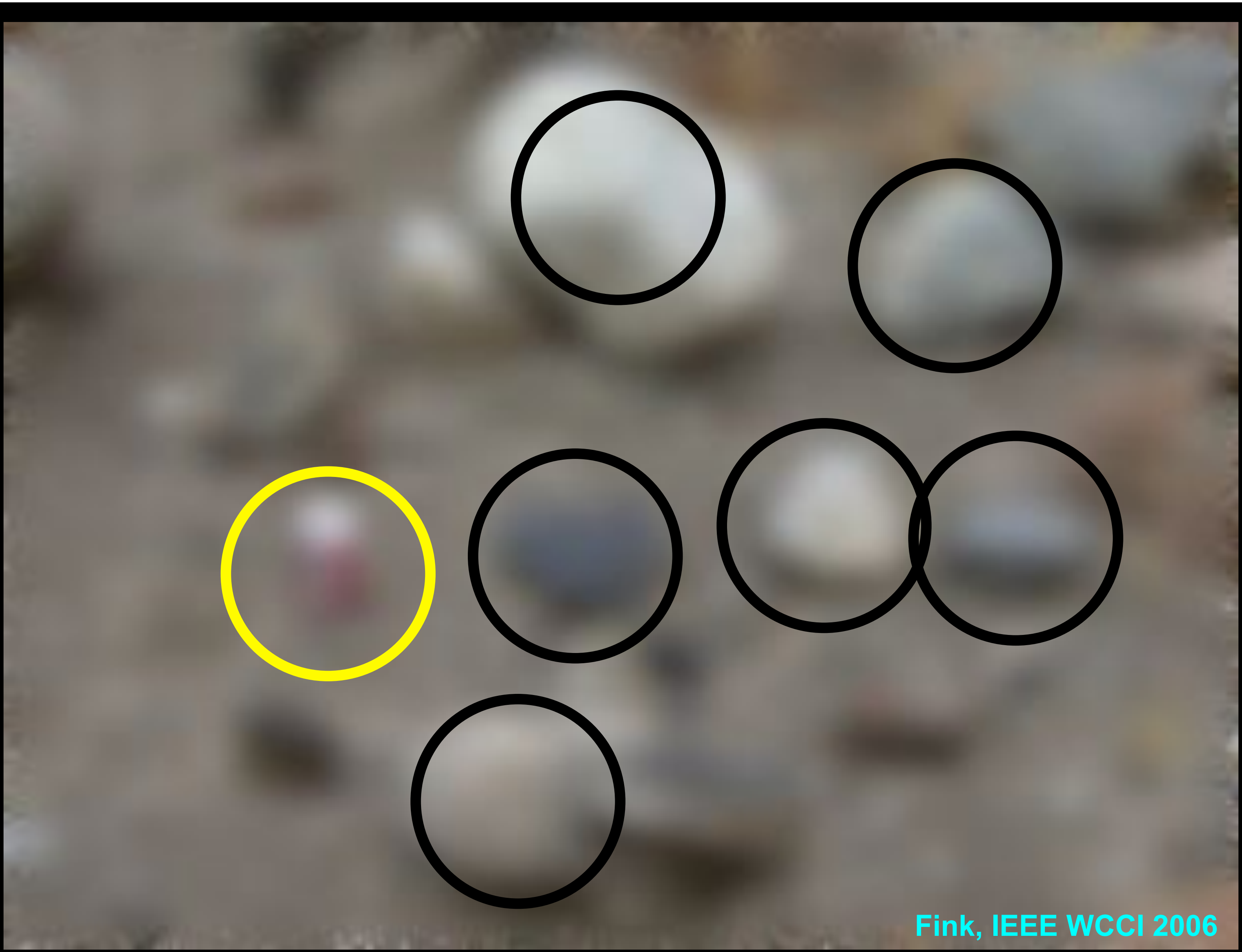
Target Identification



Fink, IEEE WCCI 2006

Preliminary Feature/Reconnaissance Data (coarse)

Target Prioritization



Fink, IEEE WCCI 2006

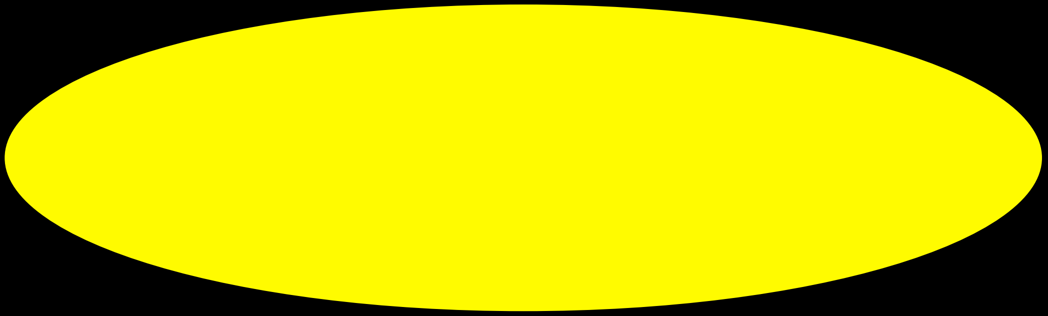
Ground-Truth
Follow-up (In-situ) High-resolution Sensor Data

Fink, IEEE WCCI 2006

Formulation of Working Hypotheses

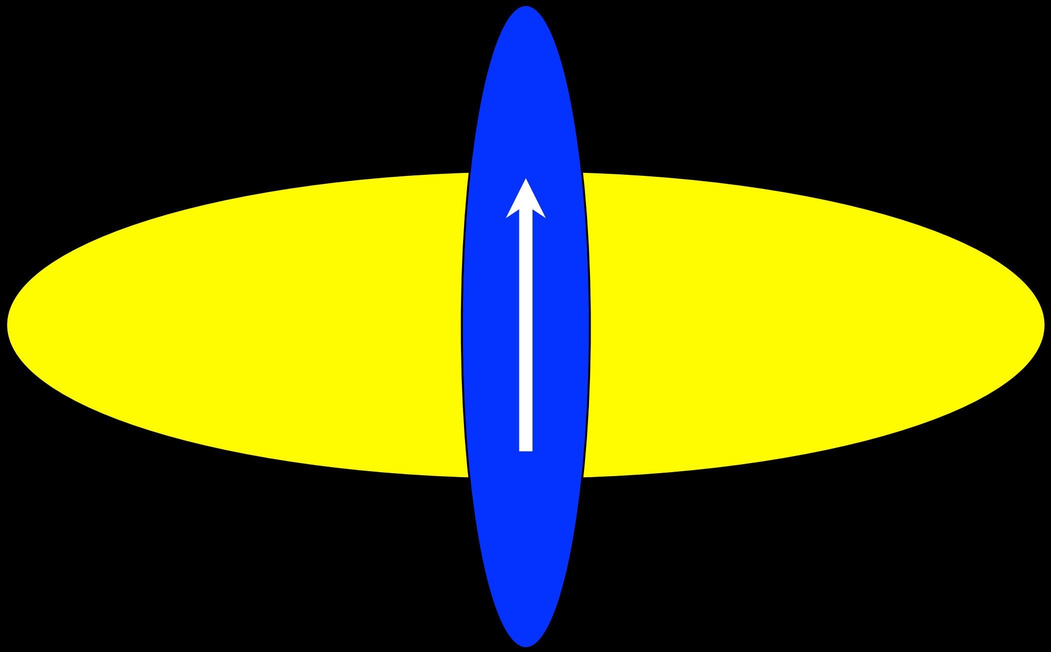
Test Scenario: Fluvial Event

Pre Geologic Process Situation



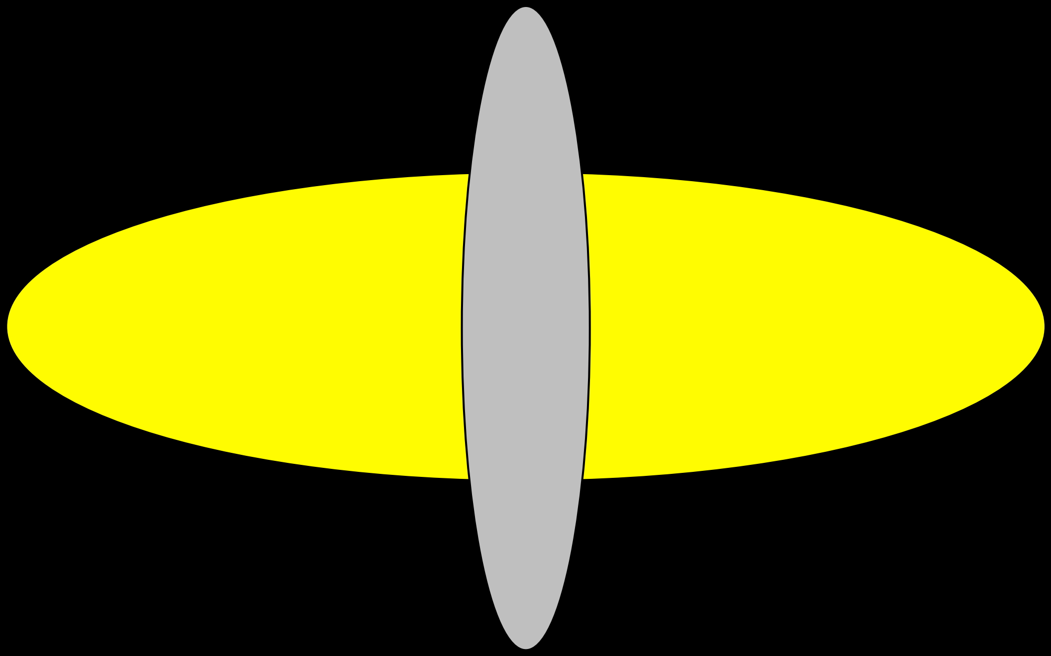
Formulation of Working Hypotheses
Test Scenario: Fluvial Event

Geologic Process, e.g., fluvial



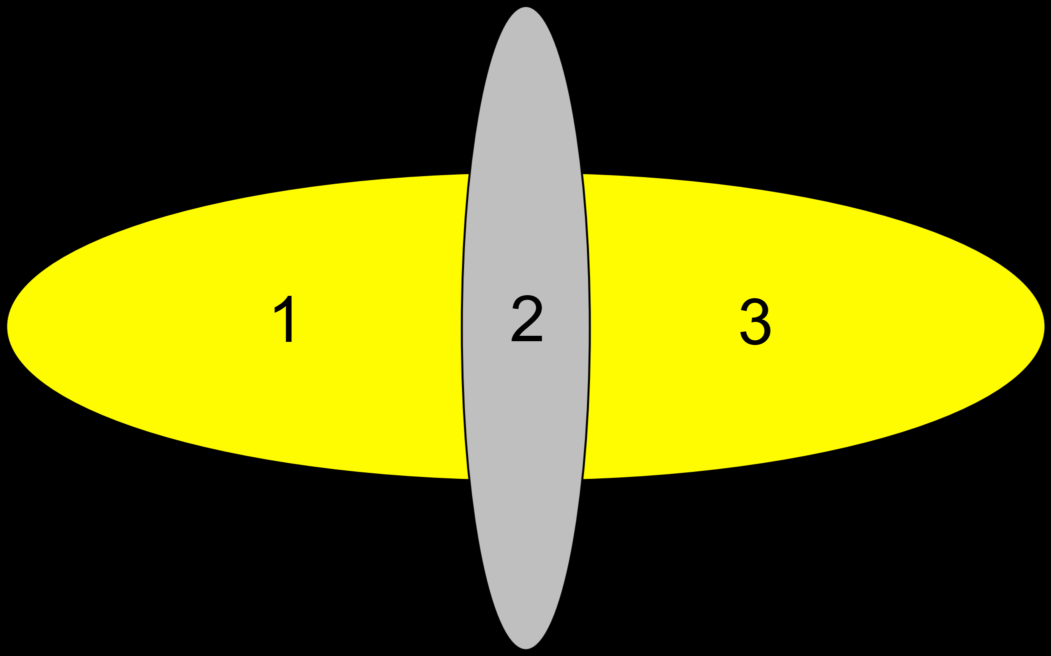
Formulation of Working Hypotheses
Test Scenario: Fluvial Event

Post Geologic Process Evidence as “seen” by the Rover



Formulation of Working Hypotheses
Test Scenario: Fluvial Event

"Seen" as 3 different deposits?

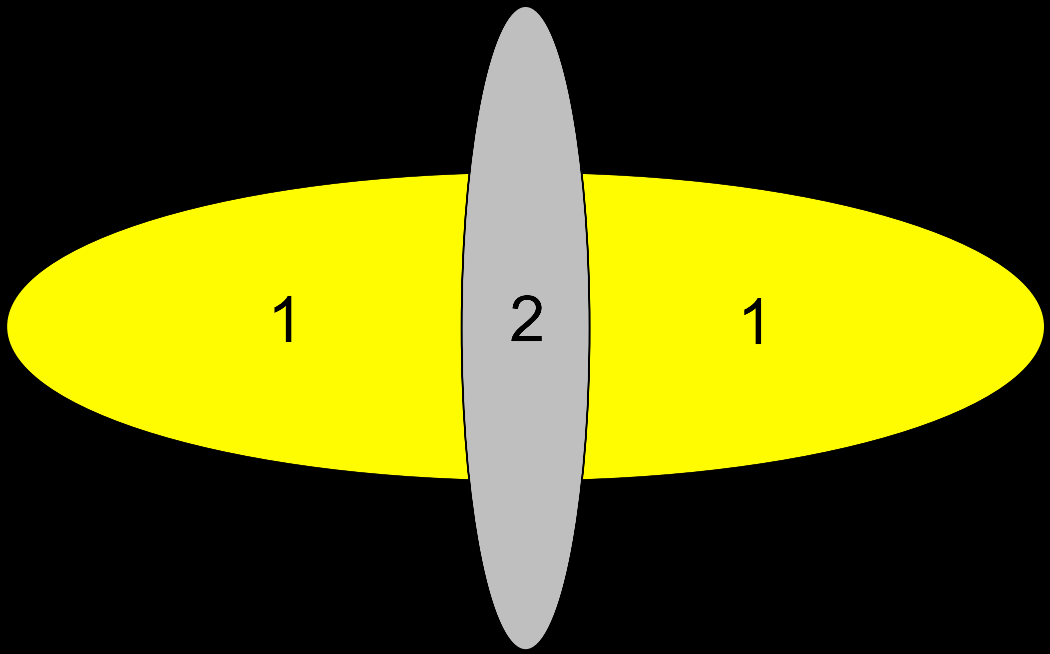


If so, geologic history of this region may be unclear/random!

Formulation of Working Hypotheses

Test Scenario: Fluvial Event

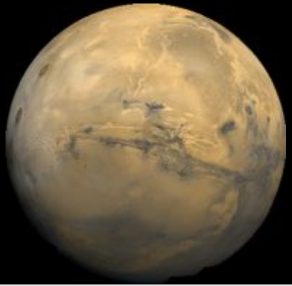
“Seen” as 2 different deposits?



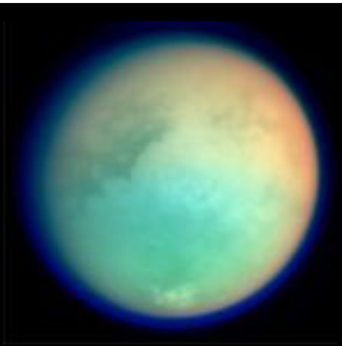
If so, geologic process may have taken place in the past, e.g., flood!

Extraterrestrial Outlook

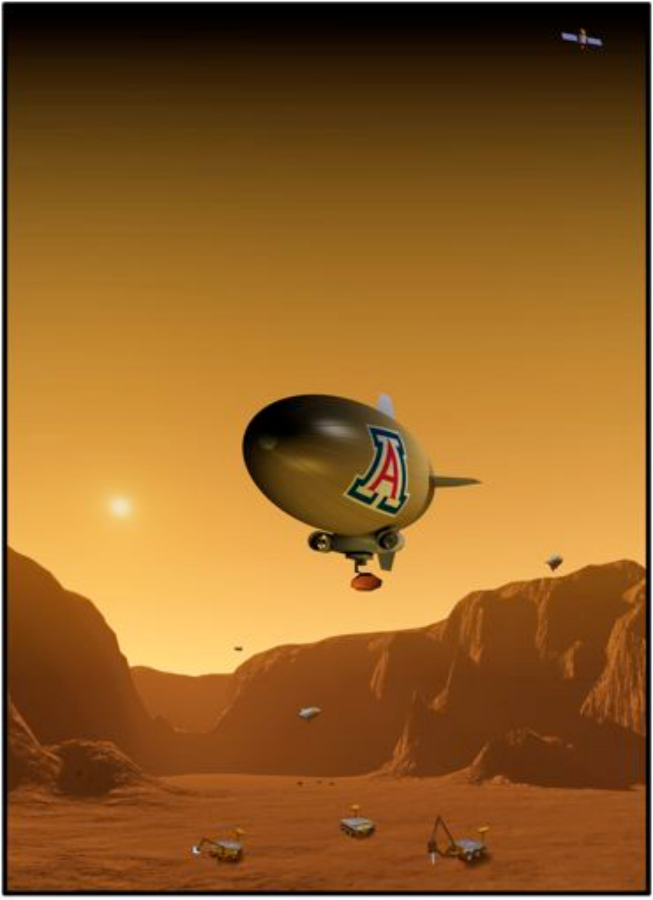
Future Space Exploration Missions



Mars



Titan



Contact Information

Wolfgang Fink, Ph.D.

Visual and Autonomous Exploration Systems Research Laboratory

Depts. of Electrical & Computer Engineering and Biomedical Engineering
University of Arizona

and

Division of Physics, Mathematics & Astronomy
California Institute of Technology

wfink@email.arizona.edu
http://autonomy.arizona.edu