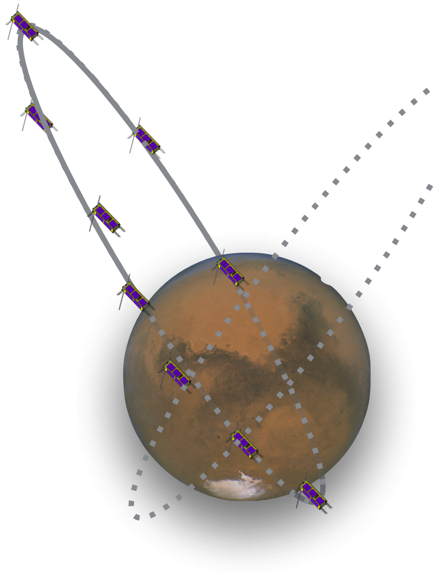
2014
Interplanetary Small Satellite Conference
beyond LEO

Massachusetts Institute of Technology

CubeSat
polito team

POLITECNICO DI TORINO

CubeSats networks beyond Earth: advanced mission concepts for the support of the human exploration of Mars



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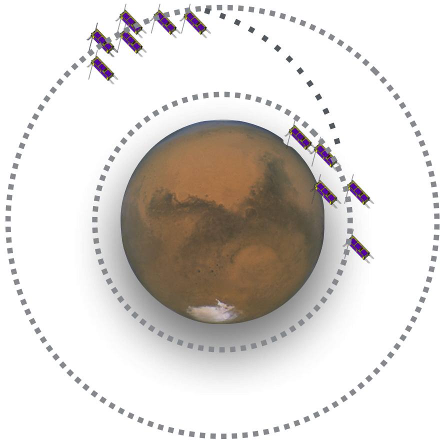
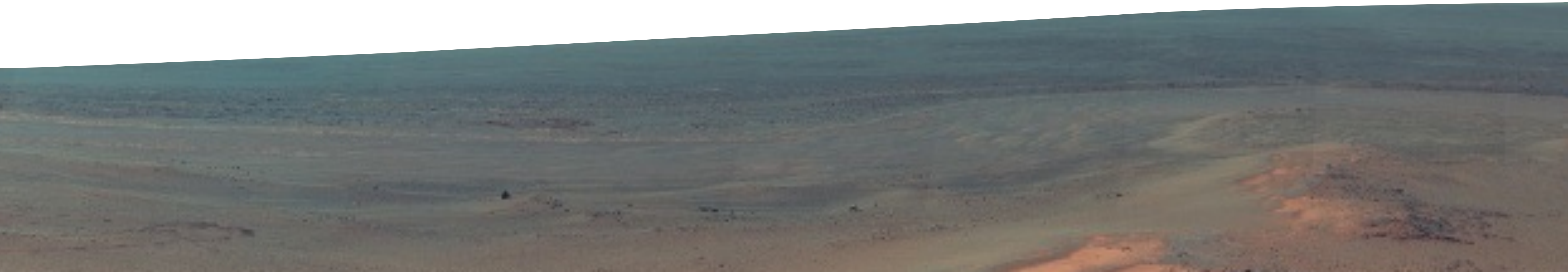
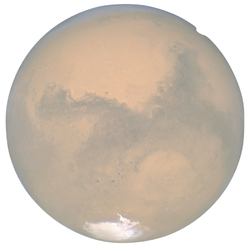


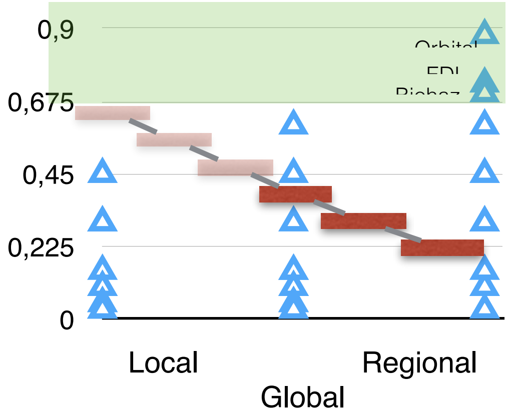


Introduction

- Concept development: Interplanetary CubeSat mission - focus on **Mars** exploration



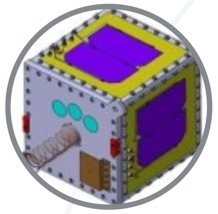
- Mission Architecture design method to evaluate **Science Value** throughout the design process



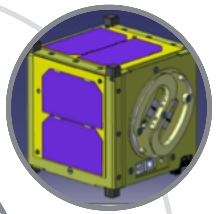
- **International** Collaboration: exchange program PoliTo - MIT 2014

CubeSat Team @ Polito: hands-on projects

SPACE IN A CUBE: MISSIONS OF THE FUTURE
Our CubeSat missions aim at conceiving new scenarios and technologies to serve the scientific community while educating students in the challenging field of space engineering

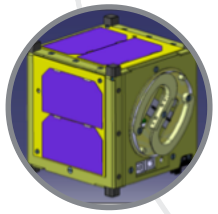


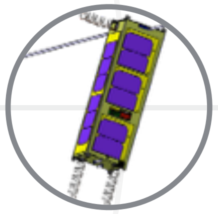
PicPoT
Earth Imaging - Tech Demonstrator
Launched **2006**



e-str@r-II
A-ADCS test
Environmental Test Campaign
ESA FYS - **2014**

e-str@r-I
A-ADCS test
Launched **2012**



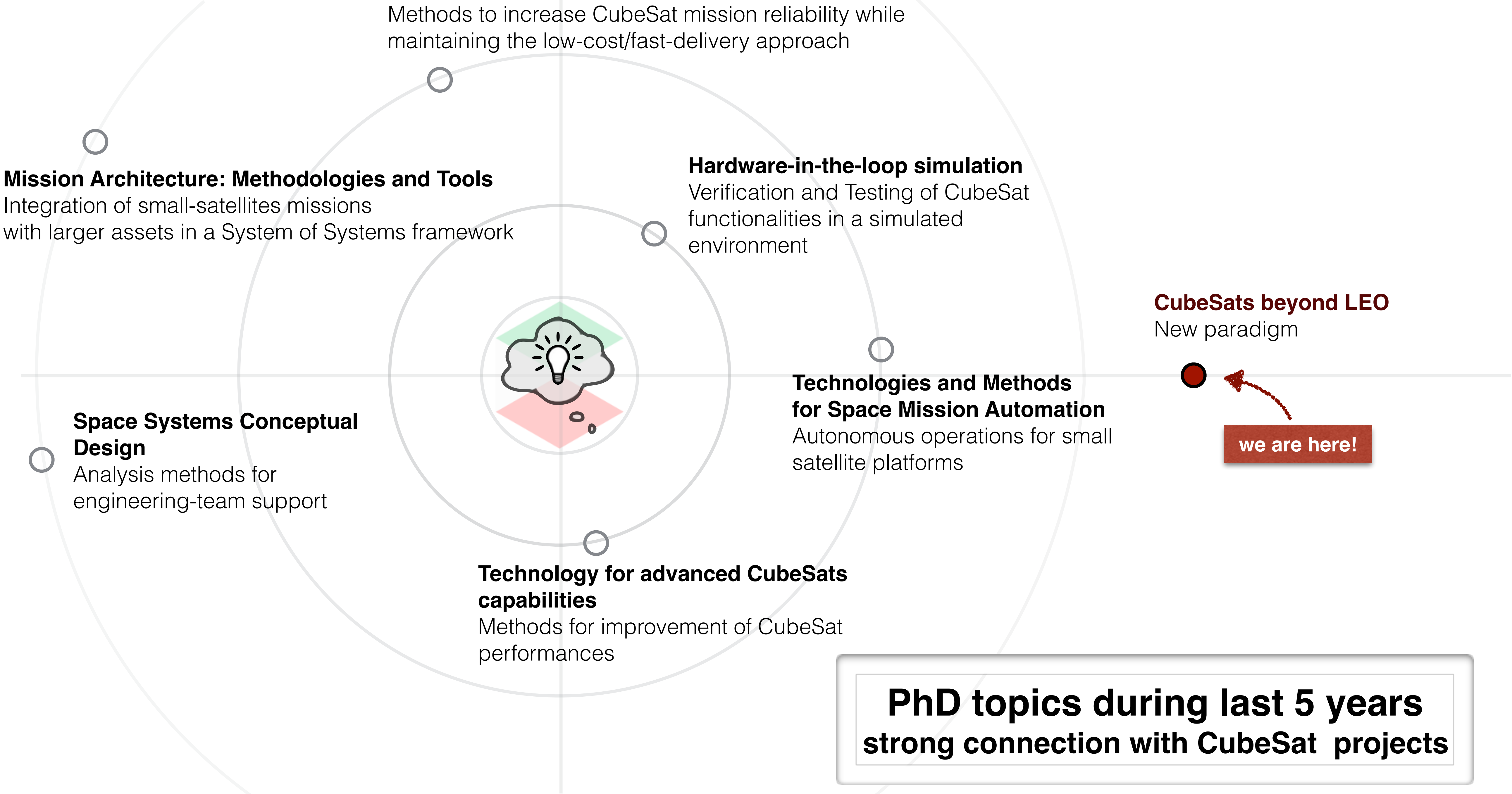


3-STAR
GNSS reflectometry experiment
2015-2016

2009-2014
30 undergraduate students
15 graduate students
6 PhD fellowships

2 ESA competitions won
1U bus for LEO - ADCS algorithms and devices - HIL testing platform
On-board software - antenna deployment - communication systems

CubeSat Team @ PoliTo: research



Dependability analysis of small-satellite missions
Methods to increase CubeSat mission reliability while maintaining the low-cost/fast-delivery approach

Mission Architecture: Methodologies and Tools
Integration of small-satellites missions with larger assets in a System of Systems framework

Hardware-in-the-loop simulation
Verification and Testing of CubeSat functionalities in a simulated environment

CubeSats beyond LEO
New paradigm

we are here!

Space Systems Conceptual Design
Analysis methods for engineering-team support

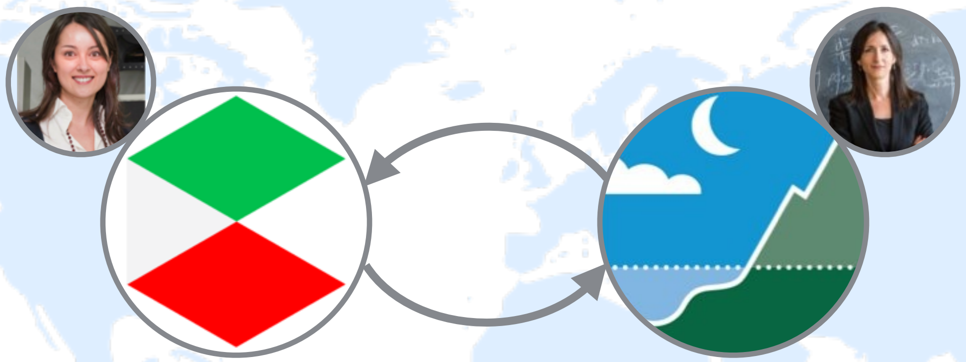
Technologies and Methods for Space Mission Automation
Autonomous operations for small satellite platforms

Technology for advanced CubeSats capabilities
Methods for improvement of CubeSat performances

PhD topics during last 5 years
strong connection with CubeSat projects

Collaboration with MIT - EAPS

- Research collaboration: exchange program 2014
  - Enhance the science capabilities of CubeSats, by exploiting the synergies of two complementary research groups



Mechanical and
Aerospace Engineering -PoliTo
Prof. Sabrina Corpino

- PicPot
- e-st@r-I
- e-st@r-II
- 3-star

Earth, Atmospheric and Planetary
Science - MIT
Prof. Sara Seager

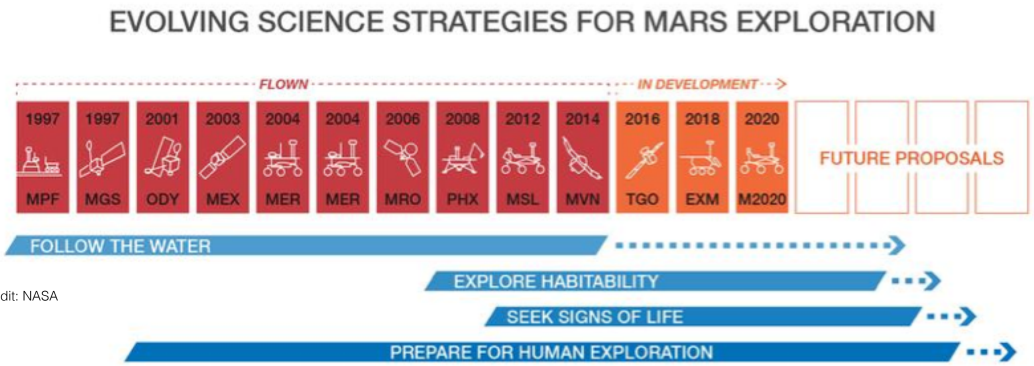
- CommCube 1 & 2
- ExoplanetSat
- TSat
- SOLARA/SARA

  - CubeSat beyond LEO: generate a planetary exploration mission concept
  - Evaluate the science value throughout the course of a Mission Architecture process

A network of CubeSats in support to the human exploration of Mars

Why human exploration of Mars?

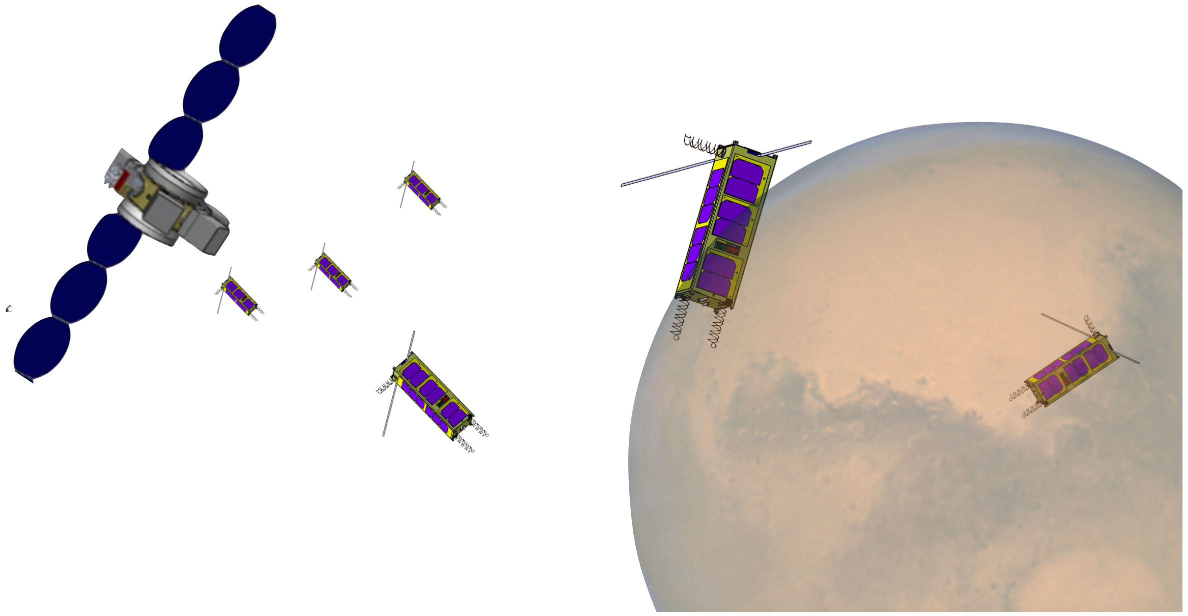
- Well established robotic exploration program
- Scientific knowledge gaps exist, precursor activities and measurements needed in order to plan a human mission



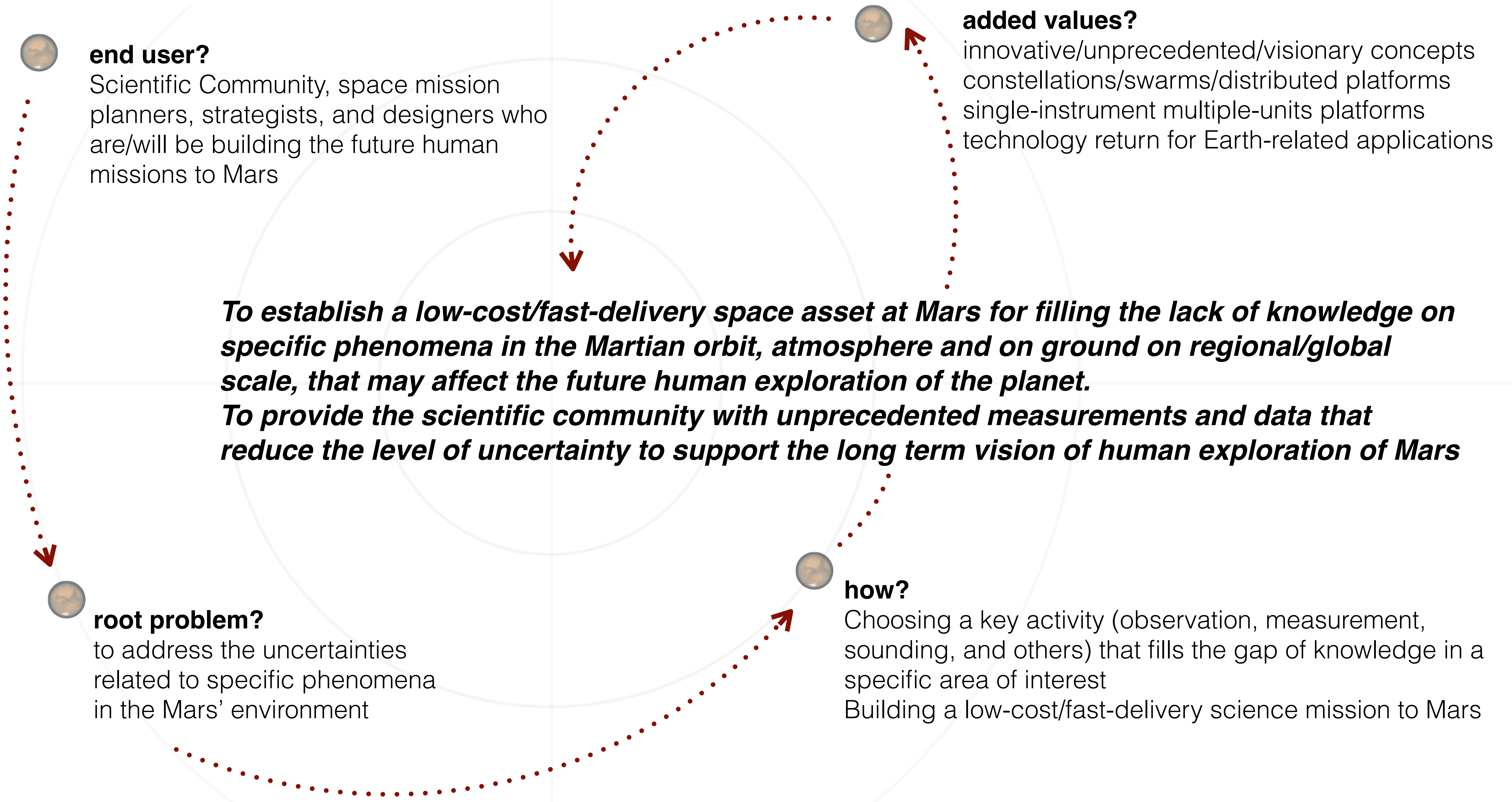
credit: NASA

Why CubeSats?

- unique features as distributed systems (constellations, swarms, networks)
    - simultaneous/shared sampling
    - massive science data return
    - staged deployment
- innovative concepts: enable us to imagine new ways to explore Mars we never thought before



Mission Statement



end user?
Scientific Community, space mission planners, strategists, and designers who are/will be building the future human missions to Mars

added values?
innovative/unprecedented/visionary concepts
constellations/swarms/distributed platforms
single-instrument multiple-units platforms
technology return for Earth-related applications

To establish a low-cost/fast-delivery space asset at Mars for filling the lack of knowledge on specific phenomena in the Martian orbit, atmosphere and on ground on regional/global scale, that may affect the future human exploration of the planet.
To provide the scientific community with unprecedented measurements and data that reduce the level of uncertainty to support the long term vision of human exploration of Mars

root problem?
to address the uncertainties related to specific phenomena in the Mars' environment

how?
Choosing a key activity (observation, measurement, sounding, and others) that fills the gap of knowledge in a specific area of interest
Building a low-cost/fast-delivery science mission to Mars

Mission Architecture: Science Value flow

- **Structured flow-down design process to generate baseline concept**
  - Reduce the risk of prioritizing one immature, high-cost-uncertainty concept
  - Allows rapid design iterations in later analyses
  - Concept Maturity Level increases at any step

Identify stakeholder

Program Goals

List & prioritize Science goals

Mission Goals

Identify specific investigations

Investigations

Map investigation to measurements

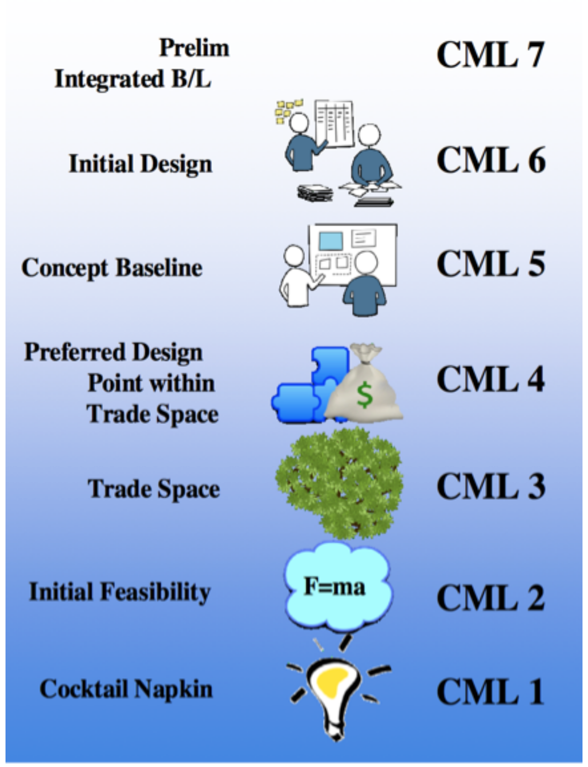
Measurements

Map instruments to measurements

Science Instruments

Select instruments

Concept



Concept Maturity level
a classification system for characterizing various levels of concept maturity (M.Adler, JPL)

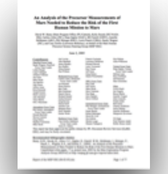
- CML 1 to 5 (baseline concept) in the first 6 months
  Fast process with multiple-concept design in parallel

- Science Value estimated through the overall process with utility metrics

Stakeholders and Program Goals

- Survey a broad range of documents

Human Exploration of Mars:
Design Reference
Architecture 5.0



Precursor measurements to
reduce the risk of the first
human mission to Mars

Safe on Mars: Precursor Measurement
necessary to support human exploration
on the Martian surface

Vision and Voyages
for Planetary Science in
the Decade 2013-2022

Mars Science Goals
Objectives and Priorities
MEPAG, JPL

MEPAG 2012 Goal IV update

Based on incorporation of new analysis from the P-SAG

Draft for community review.

Please send comments to hamilton@boulder.swri.edu and Charles.J.Budney@jpl.nasa.gov.

By October 4, 2012.

**Mars Exploration Program Analysis Group
Goal IV: PREPARE FOR HUMAN
EXPLORATION**

- Assembling a science+engineering team
  to derive science goals and priorities
  - First "brainstorming" session at MIT, Jan 2014
  - Design process at Politecnico di Torino, Mar-Jun 2014

Science Goals Analysis

Strategic Knowledge Gaps

The gaps in knowledge needed to achieve a specific goal

Landing sites and hazards

Lower Atmosphere

Forward contamination

Crew Health & Performance

Water Resources

Upper Atmosphere

Orbital Particulates

Back contamination

Dust Effects on Surface Systems

Atmospheric ISRU

Gap-Filling Activities

The works that contribute to closing a SKG

GFAs as defined by MEPAG - Goal IV

A1-1. Global temperature field.	B4-1. Electricity
A1-2. Global aerosol profiles and properties	B4-2. Dust physical, chemical and electrical properties
A1-3. Global winds and wind profiles	B4-3. Regolith physical properties and structure
A3-1. Orbital particulate environment	B5-1. Identify and map special regions
B1-1. Dust Climatology	B6-1. Dust physical, chemical and electrical properties
B1-2. Global surface pressure; local weather	B6-2. Dust column abundances
B1-3. Surface winds	B6-3. Trace gas abundances
B1-4. EDL profiles	B7-1. Regolith physical properties and structure
B1-5. Atmospheric Electricity conditions	B7-2. Landing site selection
B2-1. Biohazards	B7-3. Trafficability
B3-1. Neutrons with directionality	D1-3. Hydrated mineral compositions
B3-2. Simultaneous spectra of solar energetic particles in space and in the surface.	D1-4. Hydrated mineral occurrences
B3-4. Spectra of galactic cosmic rays on surface.	D1-5. Shallow water ice composition and properties
B3-5. Toxicity of dust to crew	D1-6. Shallow water ice occurrences

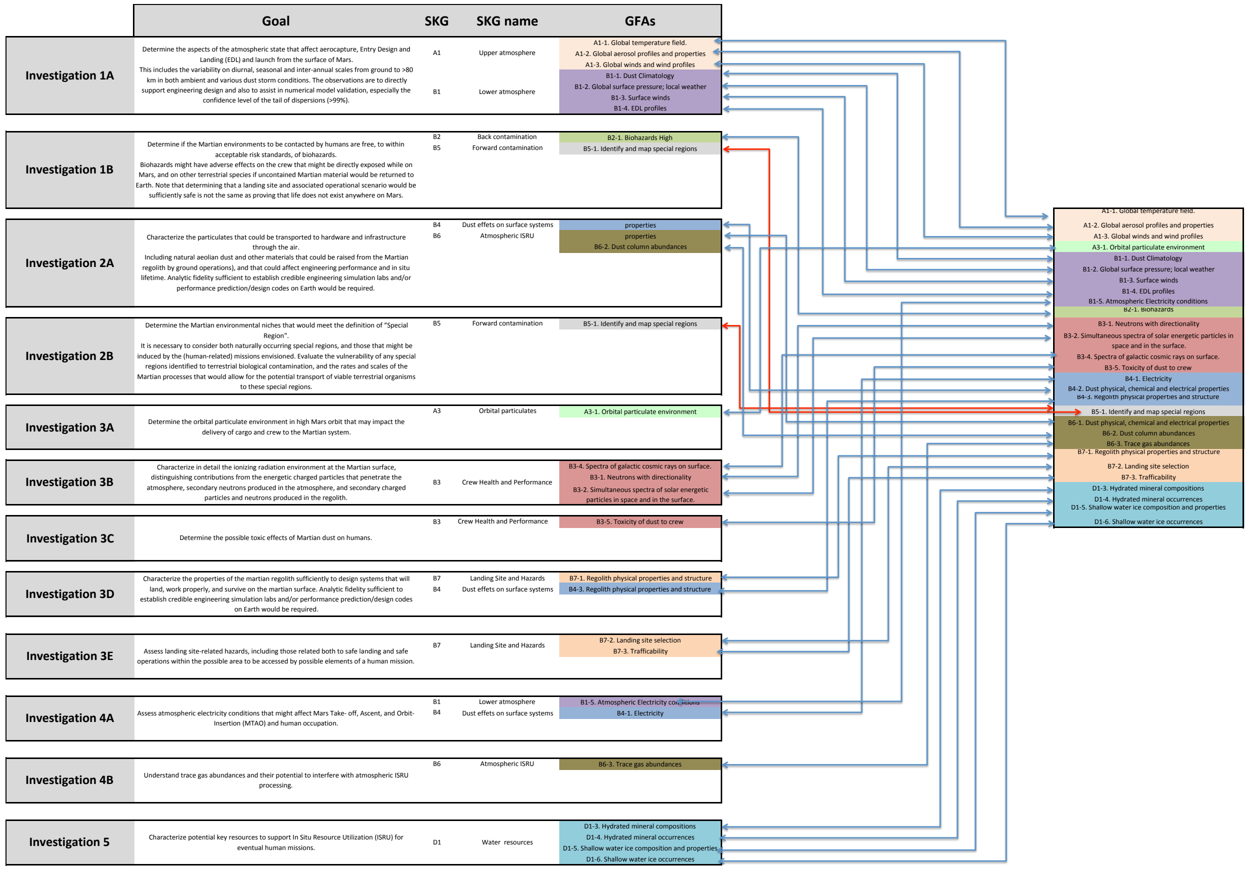
Example: upper atmosphere gap…

The current Martian atmospheric observations (density, pressure, temperature, aerosols and dynamics) have significant limitations for supporting aero-capture and aerobraking design, especially for human-scale missions

…and needed activities

- *Global Temperature Field*
- *Global aerosol profiles and properties*
- *Global winds and wind profiles*

Science Goals Analysis



	Goal	SKG	SKG name	GFAs
Investigation 1A	Determine the aspects of the atmospheric state that affect aerocapture, Entry Design and Landing (EDL) and launch from the surface of Mars. This includes the variability on diurnal, seasonal and inter-annual scales from ground to >80 km in both ambient and various dust storm conditions. The observations are to directly support engineering design and also to assist in numerical model validation, especially the confidence level of the tail of dispersions (>99%).	A1 B1	Upper atmosphere Lower atmosphere	A1-1. Global temperature field. A1-2. Global aerosol profiles and properties A1-3. Global winds and wind profiles B1-1. Dust Climatology B1-2. Global surface pressure; local weather B1-3. Surface winds B1-4. EDL profiles
Investigation 1B	Determine if the Martian environments to be contacted by humans are free, to within acceptable risk standards, of biohazards. Biohazards might have adverse effects on the crew that might be directly exposed while on Mars, and on other terrestrial species if uncontained Martian material would be returned to Earth. Note that determining that a landing site and associated operational scenario would be sufficiently safe is not the same as proving that life does not exist anywhere on Mars.	B2 B5	Back contamination Forward contamination	B2-1. Biohazards High B5-1. Identify and map special regions
Investigation 2A	Characterize the particulates that could be transported to hardware and infrastructure through the air. Including natural aeolian dust and other materials that could be raised from the Martian regolith by ground operations), and that could affect engineering performance and in situ lifetime. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth would be required.	B4 B6	Dust effets on surface systems Atmospheric ISRU	properties properties B6-2. Dust column abundances
Investigation 2B	Determine the Martian environmental niches that would meet the definition of "Special Region". It is necessary to consider both naturally occurring special regions, and those that might be induced by the (human-related) missions envisioned. Evaluate the vulnerability of any special regions identified to terrestrial biological contamination, and the rates and scales of the Martian processes that would allow for the potential transport of viable terrestrial organisms to these special regions.	B5	Forward contamination	B5-1. Identify and map special regions
Investigation 3A	Determine the orbital particulate environment in high Mars orbit that may impact the delivery of cargo and crew to the Martian system.	A3	Orbital particulates	A3-1. Orbital particulate environment
Investigation 3B	Characterize in detail the ionizing radiation environment at the Martian surface, distinguishing contributions from the energetic charged particles that penetrate the atmosphere, secondary neutrons produced in the atmosphere, and secondary charged particles and neutrons produced in the regolith.	B3	Crew Health and Performance	B3-4. Spectra of galactic cosmic rays on surface. B3-1. Neutrons with directionality B3-2. Simultaneous spectra of solar energetic particles in space and in the surface.
Investigation 3C	Determine the possible toxic effects of Martian dust on humans.	B3	Crew Health and Performance	B3-5. Toxicity of dust to crew
Investigation 3D	Characterize the properties of the martian regolith sufficiently to design systems that will land, work properly, and survive on the martian surface. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth would be required.	B7 B4	Landing Site and Hazards Dust effets on surface systems	B7-1. Regolith physical properties and structure B4-3. Regolith physical properties and structure
Investigation 3E	Assess landing site-related hazards, including those related both to safe landing and safe operations within the possible area to be accessed by possible elements of a human mission.	B7	Landing Site and Hazards	B7-2. Landing site selection B7-3. Trafficability
Investigation 4A	Assess atmospheric electricity conditions that might affect Mars Take- off, Ascent, and Orbit-Insertion (MTAO) and human occupation.	B1 B4	Lower atmosphere Dust effets on surface systems	B1-5. Atmospheric Electricity conditions B4-1. Electricity
Investigation 4B	Understand trace gas abundances and their potential to interfere with atmospheric ISRU processing.	B6	Atmospheric ISRU	B6-3. Trace gas abundances
Investigation 5	Characterize potential key resources to support In Situ Resource Utilization (ISRU) for eventual human missions.	D1	Water resources	D1-3. Hydrated mineral compositions D1-4. Hydrated mineral occurrences D1-5. Shallow water ice composition and properties D1-6. Shallow water ice occurrences

A1-1. Global temperature field.
A1-2. Global aerosol profiles and properties
A1-3. Global winds and wind profiles
A3-1. Orbital particulate environment
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B1-2. Global surface pressure; local weather
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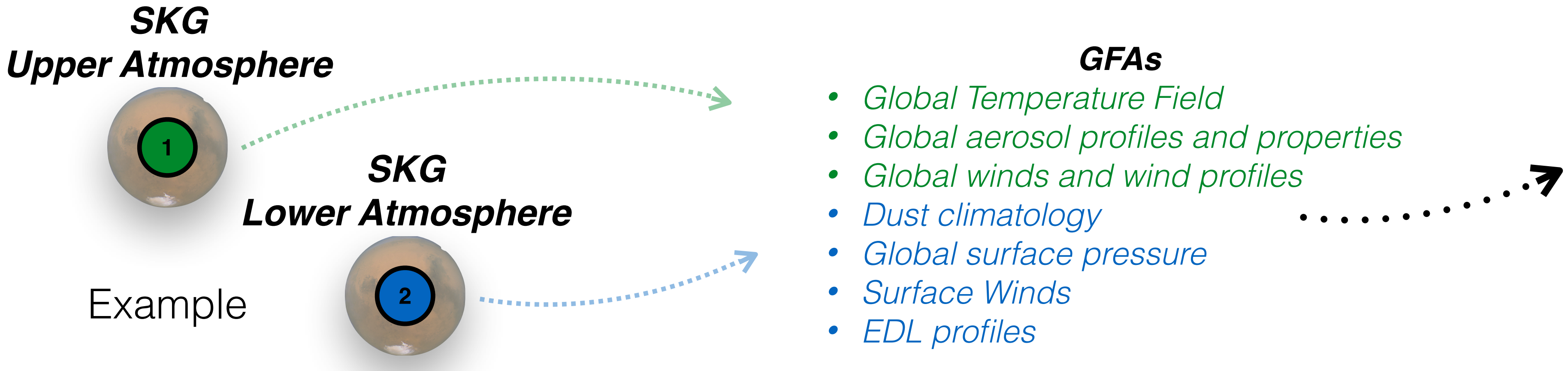
D1-6. Shallow water ice occurrences

Map activities to investigations:

- Investigation are high-level science goals that enclose a set of GFAs
- One investigation can be driven by a single or multiple activities.
- *Single-activity-driven* investigations are attractive: (with few measurements one could completely address a specific goal and "maximize" scientific return)
- A *mission utility* definition is necessary to avoid premature prioritizing of uncertain / unfeasible / high-cost concept



SKG
Upper Atmosphere

SKG
Lower Atmosphere

Example

GFAs

- *Global Temperature Field*
- *Global aerosol profiles and properties*
- *Global winds and wind profiles*
- *Dust climatology*
- *Global surface pressure*
- *Surface Winds*
- *EDL profiles*

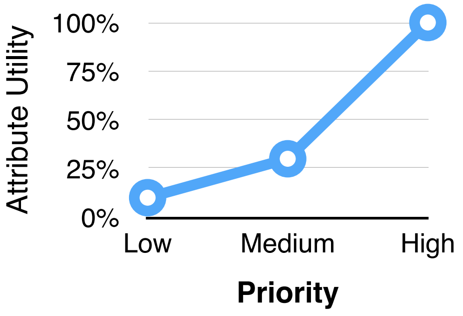
Investigation

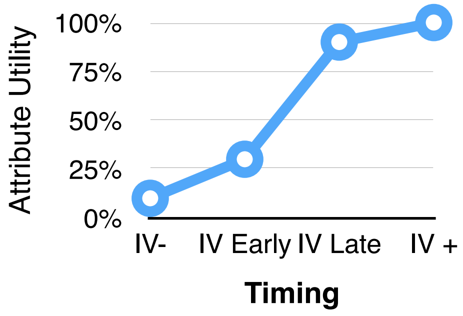
Determine the aspects of the atmospheric state that affect aerocapture, Entry Descent and Landing (EDL) and launch from the surface of Mars.

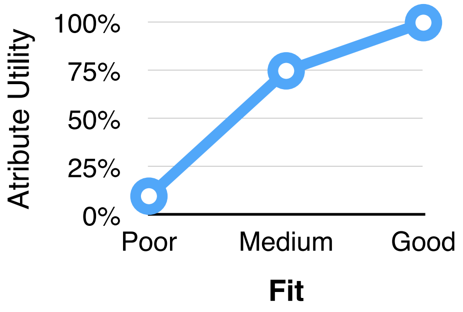
Mission Utility

- Need to narrow the focus on Investigations that maximize science value
    - Attributes selection: ***priority + timing + fit***
        - **High priority** activities are those mitigating high risk or enabling critical needs
        - **Early timing** activities are those needed to in advance for planning an architecture of human missions to Mars orbit and surface
        - **Good fit** activities are those enabled by emerging capabilities of distributed small-satelites (e.g. simultaneous measurements capability, shared sampling)
    - Building an aggregate utility function and rank GFAs $U=\sum_{i=1}^{n} k_i U_i$

	Priority	V
High	Recognized as an enabling critical need or mitigates high risk items	+
Medium	Less definitive need or mitigates moderate risk items	-
Low	Need uncertain or mitigates lower risk items	—
	Timing	
IV-	Needed to plan human missions to Mars orbit	++
IV Early	Needed to plan architecture of the first human missions to the martian surface	+
IV Late	Needed to design systems for first human missions to the martian surface	-
IV +	Needed for sustained human presence on the martian surface	—
	Fit	
Good	Enabled by emerging capabilities of distributed small-satellites	++
Medium	May be equivalently enabled by existing consolidated assets	+
Poor	Do not match with the emerging capabilities of distributed small-satellites	—

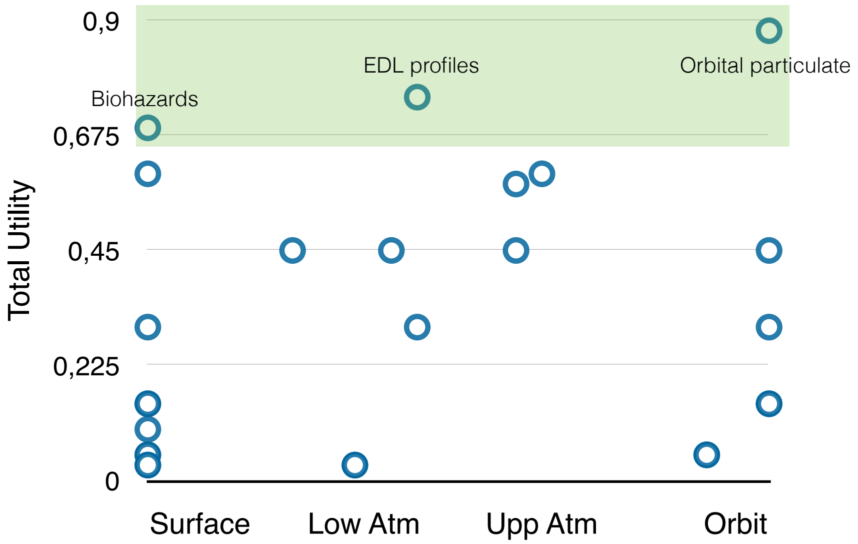






Mission Utility

- *zones-of-interaction* analysis shows high-utility GFAs for **surface, low atmosphere and orbit**
- Activities with highest utility need measurements on **global/regional scale**
- Three different mission concepts can be explored: each showing high science value in the form of aggregated utility
- How can be traded-off with respect to CubeSats capabilities?

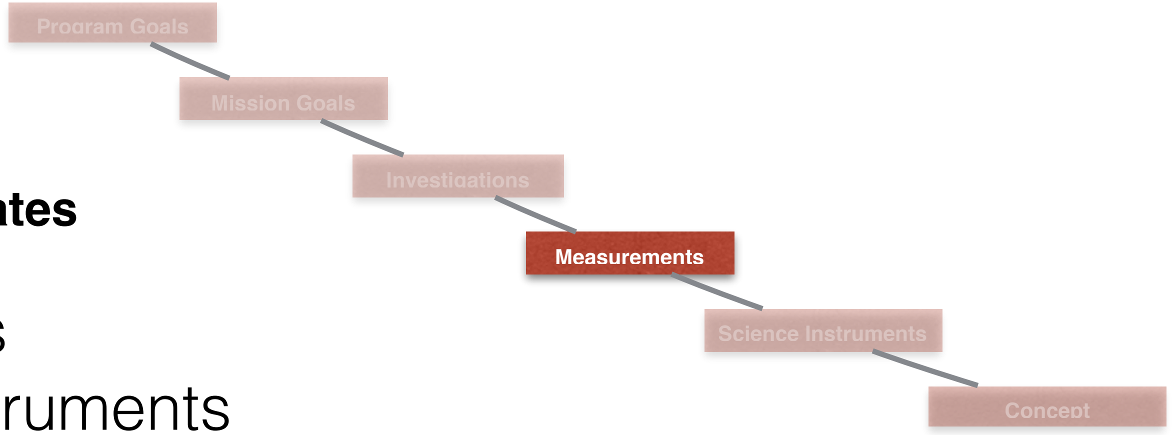


SMSD Project Work

- Space Missions and System Design master course, Mar-Jun 2014

- 3 teams - 3 Mission Concepts based on the 3 high-utility Investigations
    1. **Atmosphere sounding**
    2. **Search for subsurface life/biohazard**
    3. **Micrometeoroids and dust belts hazards estimates**
- complete the Mission Architecture process
  mapping measurements to candidate instruments

Engineering feasibility and cost to be evaluated for final concept selection



Program Goals

Mission Goals

Investigations

Measurements

Science Instruments

Concept

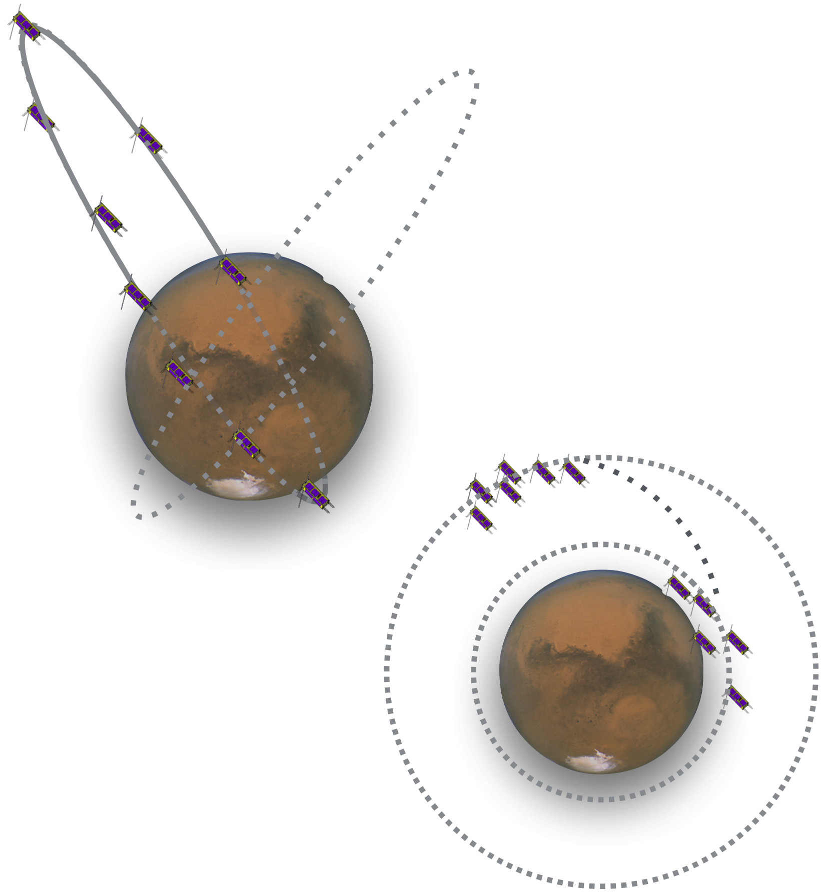
Concept A: micrometeoroids and dust belts

Investigation	Determine the orbital particulate environment in high Mars orbit that may impact the delivery of cargo and crew to the Matian system
Activitiy	Orbital particulate
Measurements	Spectroscopy - Impact detection Imaging (optical-NIR)
Strategy	Remote Sensing - In-Situ analysis

- **Human Exploration Support**: reducing risk associated with delivery of crew to the Martian orbit
- **Engineering and Scientific relevance**: understanding size/frequency distribution of micrometeoroids would help mission architecture planning and engineering design.

Goals

- To investigate the statistics distribution through the Martian year of Martian micrometeoroids mass, velocity, and composition
- Search for Martian dust rings and determine the spatial and particle size distribution, composition, origin, density, and their time evolution



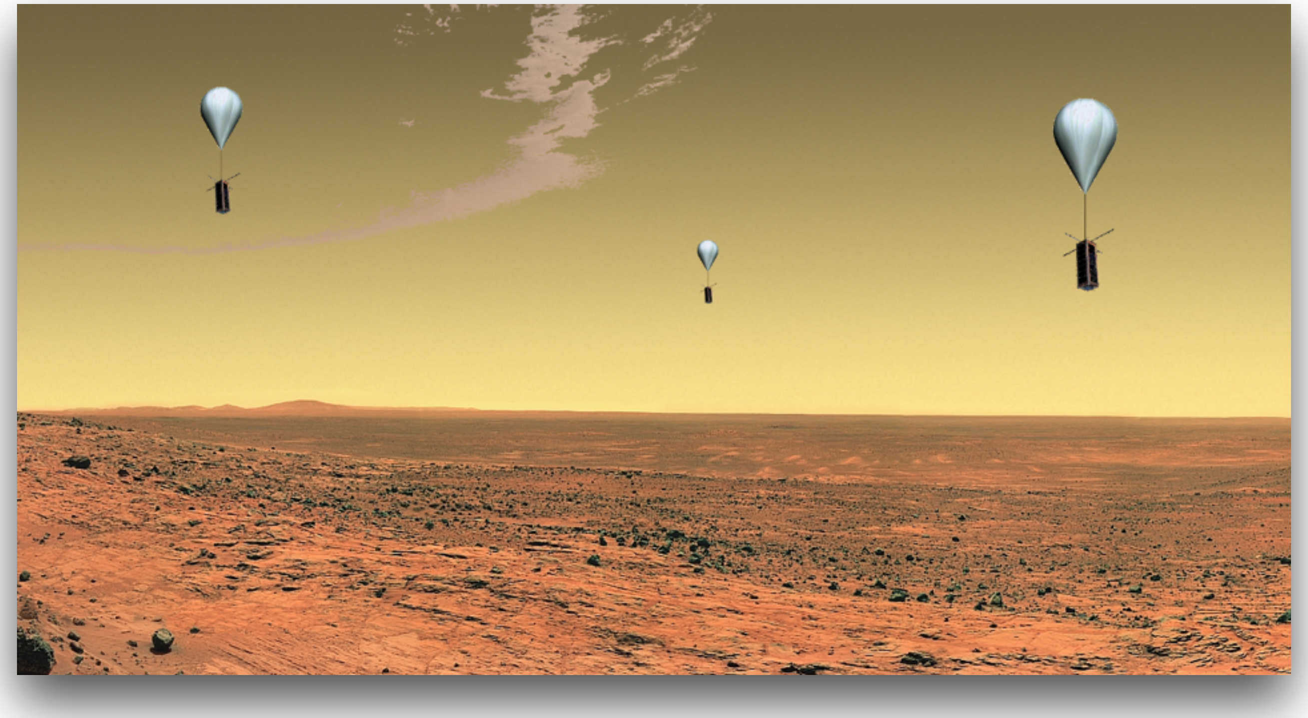
Concept B: atmosphere sounding

Investigation	Determine the aspects of the atmospheric state that affect aerocapture, Entry, Descent and Landing
Activitiy	EDL profiles
Measurements	Temperature, Pressure and Density variations, Wind speed, Humidity
Strategy	In-Situ analysis - Balloons

- **Human Exploration Support**: provide the density information necessary to determine entry trajectories, atmospheric heating and deceleration rates. Precursor measurements necessary to reduce risk of loss of crew during EDL.
- **Engineering and Scientific relevance**: global scale validation of atmospheric numerical models

Goals

- To validate a global standard Martian atmosphere model.
- To study how lower atmosphere chemically interacts with martian surface and future mission equipment.
- To understand how the atmosphere protects Mars from the space environment.

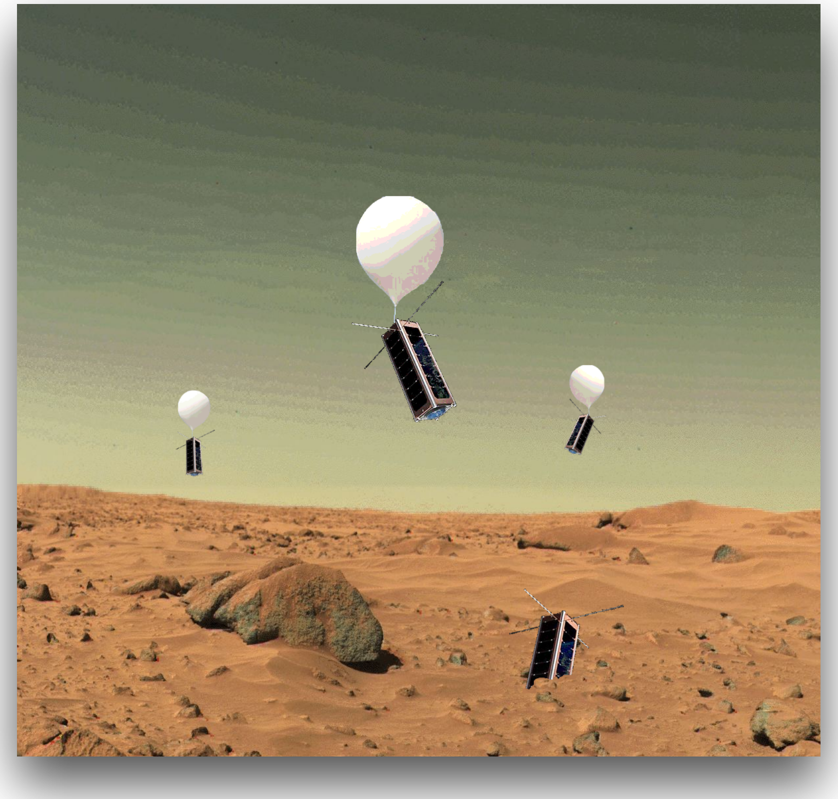


Concept C: subsurface life - biohazards

Investigation	Determine if Martian environments to be contacted by humans are free of biohazards that might have adverse effects on the crew
Activitiy	Biohazards
Measurements	regolith composition - spectroscopy biomarkers detection
Strategy	In-Situ analysis - penetrators

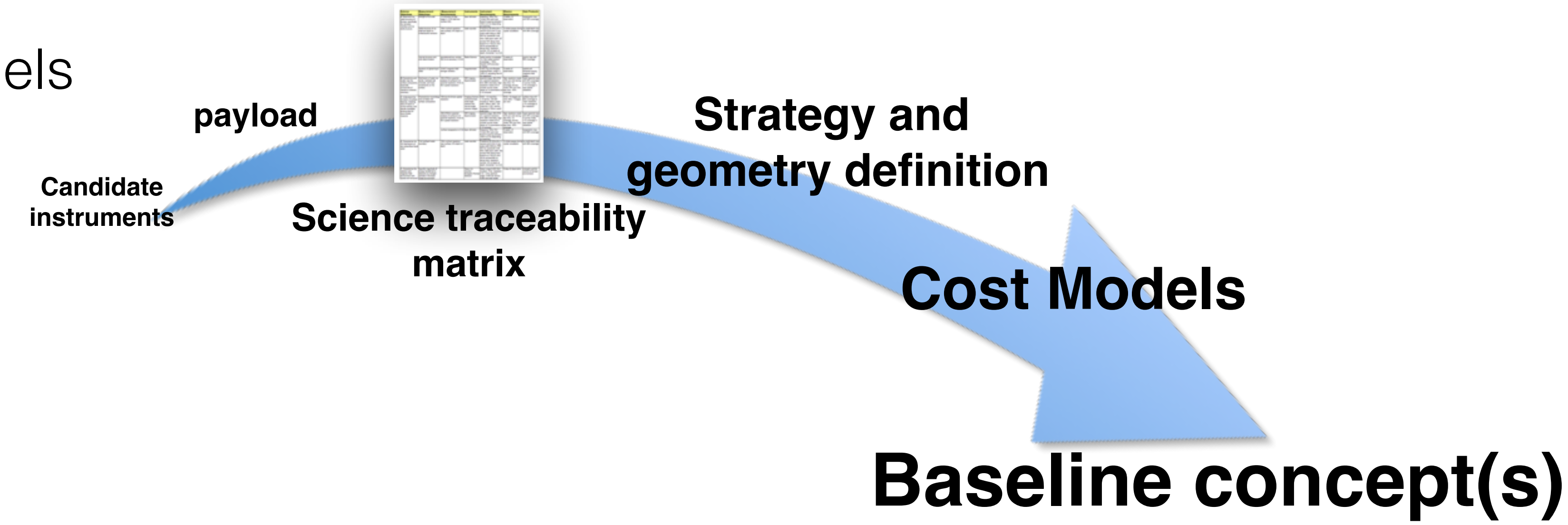
- **Human Exploration Support**: reducing risks associated with direct exposure of human flight crew to surface environment
- **Engineering and Scientific relevance**: understanding if past/present life existed/exists on Mars. Determine if airborne dust is a mechanism for transport of biohazards

- **Goals**
  - To study soil characteristics and chemical element composition
  - To investigate liquid and/or water ice in the subsurface
  - To look for biomarkers or biohazards



Future work

- Mission payload sets can be generated from a list of candidate instruments
- STM for assessing both missions and system engineering requirements
- Mission strategies (e.g. launch/ride-share, deployment, atmosphere entry/orbit insertion). Data delivery (communication strategy)
- Geometry definition (# spacecraft, swarm/constellation)
- Preliminary parametric cost models



Candidate instruments

payload

Science traceability matrix

Strategy and geometry definition

Cost Models

Baseline concept(s)

Conclusions

- A concept development can be a difficult task without a **structured approach** to the Mission Architecture process

- The top-down process from broad program goals to specific science objectives, investigation and measurements can reach a **complex level of decomposition**

- Stakeholder prioritization and custom utility metrics can help in narrowing the problem, focusing on the activities that **maximize the Science Value** of a proposed mission concept

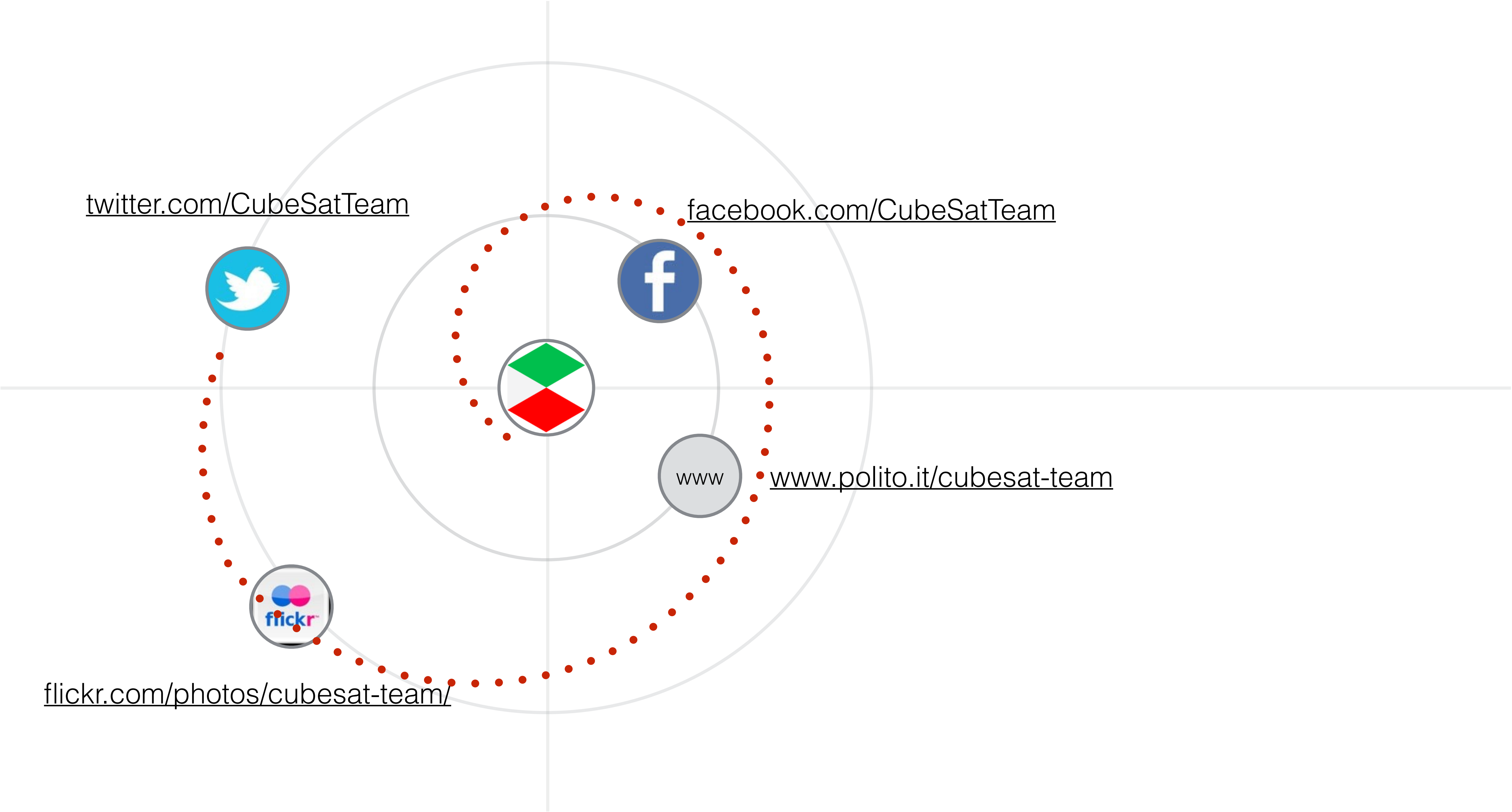
- In this study the **unique features** of **CubeSats as distributed systems** have been evaluated against the **need of precursor global measurements** in advance to planning a human mission to Mars.

- At least three **investigations** for three different **subjects** (orbit, atmosphere, surface) seem to fit promisingly

- The engineering and technical **feasibility** of the three concepts will be addressed in a later step of the collaboration between PoliTo - MIT, along with the detailed definition of the 3 concepts

- The PoliTo CubeSat team is open to a debate on the topic and any proposed collaboration is welcome!

Thank you!



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