Mars18

Your Next Frontier

Mars Society International Student Design Competition

University of Stuttgart, Germany

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MAR8

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Mission Objectives

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Pave the way to Mars for human exploration and utilization in the year 2018

- As safe, reliable and cheap as possible -

- Stepping stone to manned interplanetary landing missions
- Reignite a worldwide interest in space exploration
- Facilitate the development of more advanced technologies

⇒ 5.2 B$, 63 t, 2 launches, 3.3 kW, 34 m^3, minimized risk of short- and long-term harm to crew

Launch Vehicle

1st Launch

Falcon Heavy (SpaceX)

- Carries Propulsion Module into orbit
- Maiden flight in 2015

2nd Launch

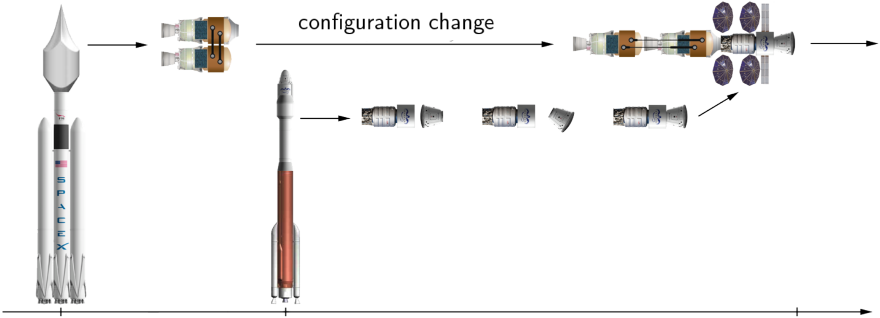
Atlas V 441 (ULA)

- Carries Mars Transfer Vehicle into orbit
- Man-rating expected by 2017 as part of CCDev

⇒ **Two launches** reduce mission complexity and launch cost

⇒ Utilization of reliable **man-rated launcher** to ensure crew safety

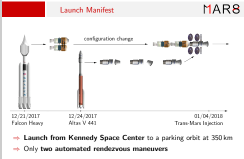
Launch Manifest



12/21/2017 Falcon Heavy | 12/24/2017 Altas V 441 | 01/04/2018 Trans-Mars Injection

⇒ **Launch from Kennedy Space Center** to a parking orbit at 350 km

⇒ Only **two automated rendezvous maneuvers**



- 15 t to Mars, $\Delta v = 4{,}841\,\mathrm{m/s}$ for the trans-Mars injection (+5% margin)
- Evaluation of past and future medium to heavy launch vehicles as well as upper stages and upper stage engines of all these launch vehicles
  - Falcon Heavy: Asymmetric Payload Fairing to increase payload volume
  - Atlas V 441: Reliable and flight-proven launch vehicle
- Utilization of available resources at Kennedy Space Center like cryogenic propellant storage (Launch Complex 39)
- No major developments of engines or upper stages required
- Automatic rendezvous maneuvers using the European ATV's RVS-3000

Launcher	Payload	Mass
Falcon Heavy	Propulsion Module	48 t
Atlas V 441	Mars Transfer Vehicle	15 t

Propulsion Module

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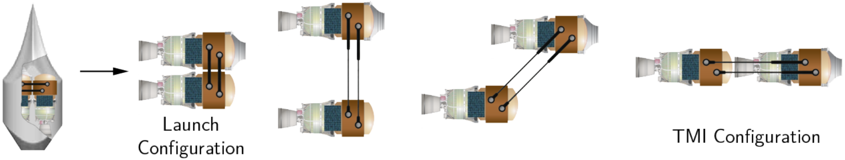
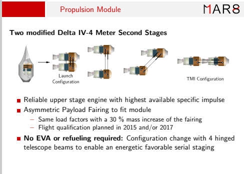
Two modified Delta IV-4 Meter Second Stages



- Reliable upper stage engine with highest available specific impulse
- Asymmetric Payload Fairing to fit module
  - Same load factors with a 30 % mass increase of the fairing
  - Flight qualification planned in 2015 and/or 2017
- **No EVA or refueling required:** Configuration change with 4 hinged telescope beams to enable an energetic favorable serial staging

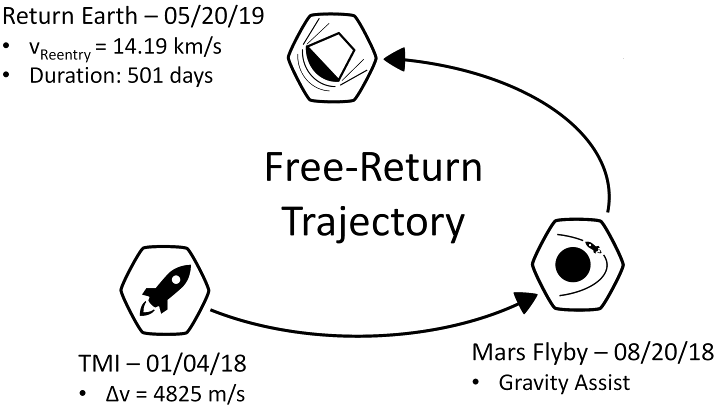


- Delta IV-4 Meter Second Stages use a RL-10 B2 engine with the highest available I_{sp} of 465 s and a thrust of 110 kN
- Detailed design of additional components of Propulsion Module
  - Gravity-stabilized, equipped with additional AOCS, Docking Port and EPS to perform a docking maneuver with the MTV
  - Boil-off is considered through additional MLI and a propellant margin

Table: Mass breakdown of Propulsion Module

	1st Stage	**2nd Stage**
Delta IV Second Stage	2,850 kg	2,850 kg
Propellant	20,410 kg	20,410 kg
Docking Structure & EPS	142 kg	580 kg
AOCS	35 kg	152 kg
MLI insulation	334 kg	334 kg
Total at TMI	23,771 kg	24,326 kg

Trajectory



⇒ No interference with Venus' sphere of influence

⇒ **Low Δv** for trans-Mars injection and only **one gravity assist**

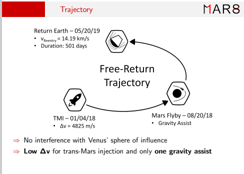


Table: Considered trajectories found with Lambert solver POINT

	Start Date - Arrival Date	Δv Departure	Δv Flyby	v_∞ Arrival	Duration
1	02/05/2018 - 07/12/2019	3,586.2 m/s	1,558.6 m/s	11,070.1 m/s	435 d
2	07/15/2018 - 07/14/2019	9,342.8 m/s	0	12,835.0 m/s	361 d
3	01/04/2018 - 05/19/2019	4,825.5 m/s	0	8,786.3 m/s	501 d

- No. 1: Increased complexity and mass due to propulsive maneuver at Mars
- No. 2: Short mission duration but high Δv at departure not feasible
- No. 3: Selected as compromise between Δv, duration and entry velocity

Table: Results of the calculation of GMAT for No. 3

	Date	v_∞ [m/s]	DLA	RLA	v_{peri} [m/s]	C3 [km^2/s^2]
Departure Earth	04.01.2018 18:59	6220.7	−89.3°	16.6°	12543.4	38.7
Mars flyby	20.08.2018 18:31	5375.0	−1.53°	−121.9°	7258.1	28.9
Arrival Earth	20.05.2019 16:28	8855.7	3.6°	−72.9°	14186.9	78.4

Human Factors

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Suitable candidates → Synchronizing circadian system

Human Interaction

Reducing microgravity effects

Physical Health

Monitoring
- LTMS-Vest

Musculoskeletal
- Resistance exercise
  - o Similar effect to iRED/ARED
- Vibrating plate
- Cyclic Ergometer
- Bisphosphonate (70 mg weekly)

→ 150 kg – all training devices
→ 1.5 h twice a day

Physical workout & nutrition

Bungee cords Vibrating plate

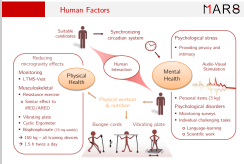
Mental Health

Psychological stress
- Providing privacy and intimacy

Audio-Visual Stimulation

- Personal items (3 kg)

Psychological disorders
- Monitoring surveys
- Individual challenging tasks
  - o Language-learning
  - o Scientific work



- A combination of a vibrating plate, bungee cords together with an antiresoptive drug (bisphosphonate) will minimize the bone loss
  - Improved economy of size and weight compared to iRED/ARED
  - Diet plan supports physical workouts
- Most predictable physical risks can be treated without drugs and in a non-invasive way (e.g. venous thrombosis or muscle atrophy)
- Psychological stress is minimized by a controlled sleep/wake cycle and privacy
  - Circadian system will be synchronized through lighting control
- Prevention of psychological disorders (e.g. depression or lack of motivation)
  - Audio-visual stimulation will treat the crew passively in terms of sleep, mood and concentration
  - Individually chosen tasks like learning a new language or mastering a new skill will maintain cognitive function and give short term success
  - Psychological status is monitored by periodical digital surveys
- Other basic human needs such as communication and sexual interaction need to be reviewed further for deep space missions

Structures

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- Fulfills requirements on mass, volume and availability best
- Dragon will be tested and man rated
- Metallic 3D-Printer for spare parts
- No umbilical cables
- No external piping or EVAs
- Modified and habitable trunk

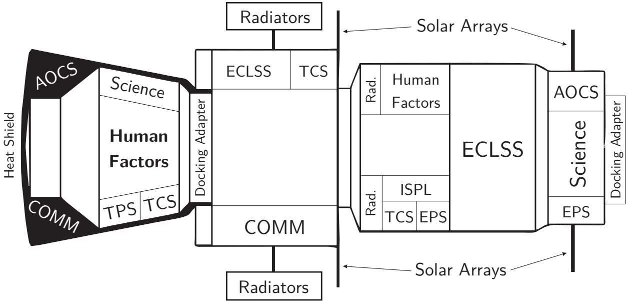
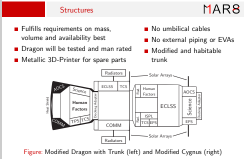


Figure: Modified Dragon with Trunk (left) and Modified Cygnus (right)



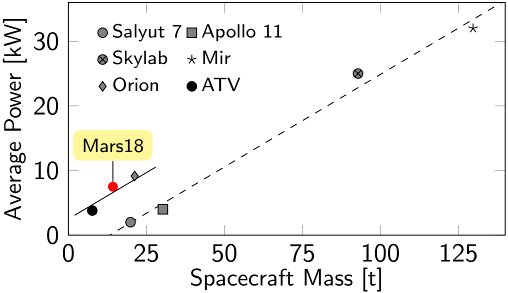
- No external piping: everything can be maintained by the astronauts from the inside, no EVAs required
- Layout allows for dangerous substances (hydrazin, hydrogen) to be stored in proper environments (vacuum) in the trunks. They could still be made accessible through selectively pressurized compartments
- Artificial gravity devices require larger habitat volumes than currently feasible
- Orion capsule will not be available until after 2023

Substantial modifications of the Dragon Trunk make it a viable extension of the spacecraft and useful for future missions. Experience with proposed setup and docking maneuvers from lunar missions. Moreover, there is very little refitting needed after docking maneuver in LEO. This simplicity increases safety and reliability. Furthermore, the proposed distribution of systems results in some cases in redundancy through separation.

Electrical Power System

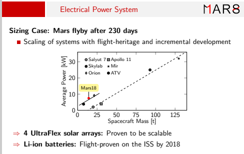
Sizing Case: Mars flyby after 230 days

- Scaling of systems with flight-heritage and incremental development



⇒ **4 UltraFlex solar arrays:** Proven to be scalable

⇒ **Li-ion batteries:** Flight-proven on the ISS by 2018



- Flyby at Mars: lowest solar flux and moderate degradation
- Environmental, array, distribution losses and 10 % contingency
- Arrays cover average power and charge batteries, used for daily peaks, Mars flyby and reentry

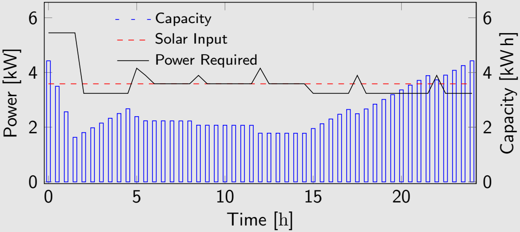


Figure: Average and peak power distribution

- 4 UltraFlex solar arrays (⌀5 m) with gallium arsenide solar cells are utilized
  - Arrays are already in development as part of Orbital's Cygnus module
  - Deployment of two arrays is sufficient to cover power in Earth orbit
- 2 stacks of redundant Li-ion batteries each with roughly 4.5 kW h capacity
  - Trade-off between conventional, regenerative fuel cells & batteries

Env. Control & Life Support System

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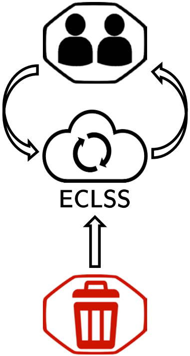
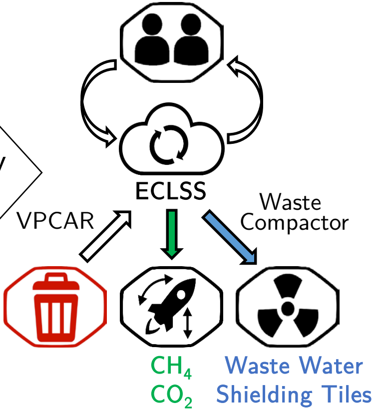
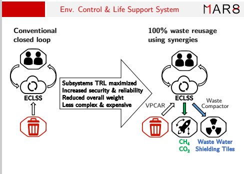
Conventional closed loop



Subsystems TRL maximized
Increased security & reliability
Reduced overall weight
Less complex & expensive

100% waste reusage using synergies

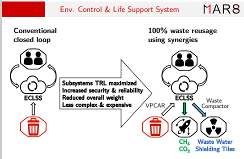




Mars18 ECLSS is designed in detail and a simulation of the full mission duration was carried out to ensure sufficient storage.

Due to an overall mass reduction, as much waste as possible has to be recycled. With conventional life support system design, advanced technologies have to be employed to reuse 100% of produced waste. Mars18 ECLSS uses **synergies** with other subsystems to reuse waste products.

- → Low complexity despite 100% waste reusage
- → Comparably cheap
- → Little usage of low TRL technology (only VPCAR & Waste Compactor)
- → Increased security and reliability, reduced overall weight
- → No storage of large amounts of hazardous gaseous hydrogen
- → No cryogenic storage of gas necessary



Further synergies are employed with the radiation protection system

- Water tank and feces tank are made of Polyethylene (PE)
- Food lockers made of PE and food is used for shielding
- Water surplus used to increase radiation shielding and ECLSS reliability
- Wet wipe packages are used for shielding

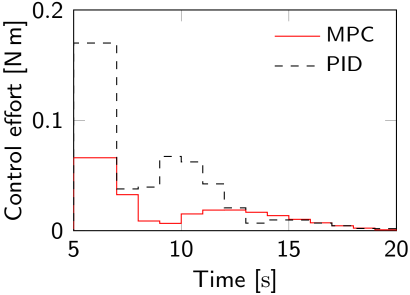
Security and reliability

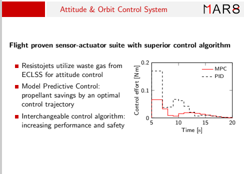
- System is designed fail safe
- VPCAR is not scaled down to our needs to ensure availabilty by 2018
- Water regained from Waste Compactor is not used by crew for security
- Fire detection and suppression

Attitude & Orbit Control System

Flight proven sensor-actuator suite with superior control algorithm

- Resistojets utilize waste gas from ECLSS for attitude control
- Model Predictive Control: propellant savings by an optimal control trajectory
- Interchangeable control algorithm: increasing performance and safety





- The spacecraft is controlled by flight proven sensor-actuator-suite with additional resistojets exploiting ECLSS waste gas for attitude control
- Measures taken to save propellant: Gravity gradient stabilization in Earth orbit, automatic docking with ATV's RVS-3000, momentum wheels desaturated by resistojets with ECLSS waste gas
- Model Predictive Control (MPC) offers better controller performance with concurrent propellant savings through an optimal control trajectory
  - A similar procedure was successfully tested within the PRISMA project
  - Drawback: MPC can not be used during reentry due to stringent time constraints, but control algorithms are interchangeable
  - Parameters and code can be optimized mid-flight
- MPC superiority manifests itself by explicitly considerating input, state and output constraints. MPC minimizes an objective function weighting the trajectory as well as input parameters like propellant usage

2014-08-06

Mars18
└─Spacecraft
  └─Attitude & Orbit Control System
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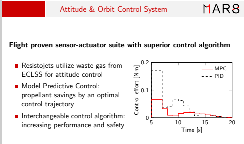
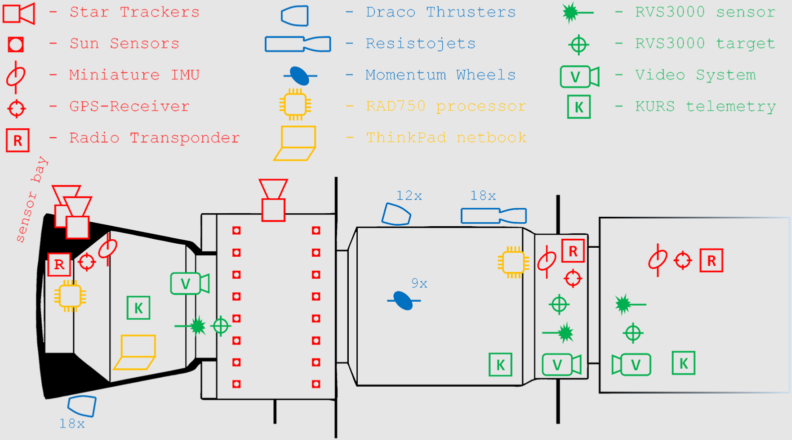
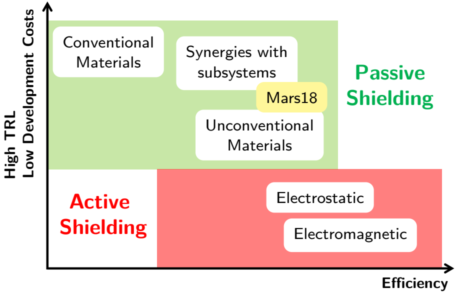


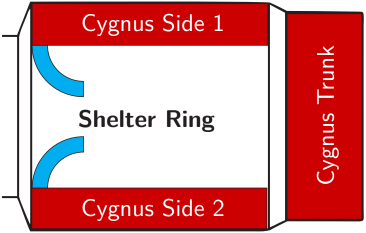


Radiation Protection

Main protection: Increasing amount of H_2O/Polyethylene (PE)

- Payload distribution
- PE-tiles from waste compactor
- Reinforced PE-tanks
- PE sleeping bags and vests



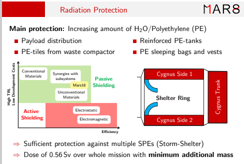


⇒ Sufficient protection against multiple SPEs (Storm-Shelter)

⇒ Dose of 0.56 Sv over whole mission with **minimum additional mass**

2014-08-06

Mars18
└Spacecraft
 └Radiation Protection
  └Radiation Protection



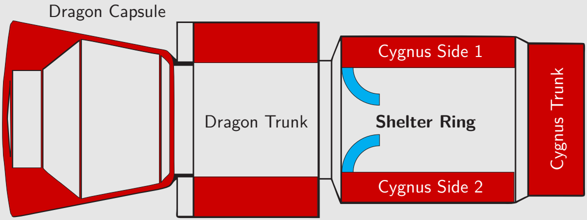
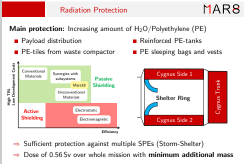
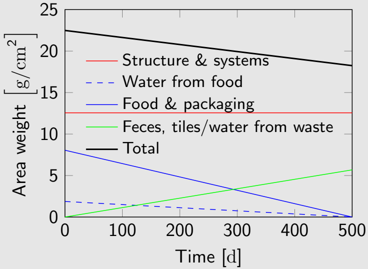


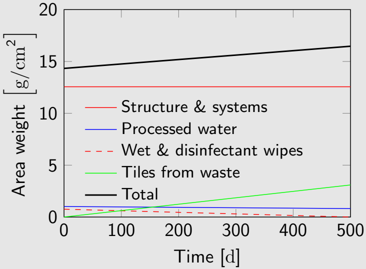
Figure: Definition of different shielding zones

- Dose < 0.6 Sv $\rightarrow$ Risk for radiation induced cancer rises $< 1\%$
- Iterative simulation of radiation exposure with SPENVIS to optimize the shielding efficiency
- Duration of stay in Dragon is minimized $\rightarrow$ Less shielding required & less reentry mass
- Sleeping bags and vests give an optimal relation of mass and volume to shielding-efficiency
- Amifostine (used after an SPE) is known to help very well at an one time application, not suitable for long-term treatment





(a) Cygnus Side 1



(b) Cygnus Side 2

- PE-tanks around Cygnus have different wall thickness to achieve the same value as the TransHab Radiation Shield Water Tank (5.74 g/cm^2 of water) as storm shelter during SPEs
- Additional PE shelter-ring compensates slow sun alignment and reinforces less shielded radiation paths

Thermal Control System

Different extreme conditions require **flexible & robust thermal control** to maintain an appropriate temperature environment

			
Sizing Case	Earth orbit	Mars flyby	Aerobraking
Type	Active Fluid in closed-loop & radiators		Passive Heat sink (Water)
Activity	4 panels deployed	2 panels deployed	

⇒ Carbon-carbon **reduces mass** of radiators by 50%

⇒ Non-toxic fluids **allow maintenance**

⇒ **Synergy**: ECLSS provides over 60% of water for the heat sink

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- Earth (hot, 11 kW waste heat) and Mars (cold, 5 kW waste heat) are the critcal cases:
  - Solar radiation Q_s, albedo radiation Q_a and infrared radiation Q_{ir}
  - Generated heat from subsystems and humans Q_{diss}

  $\rightarrow$ $Q_s + Q_a + Q_{ir} + Q_{diss} - Q_{out} = 0$
- Active closed-loop thermal control system
  - 4 deployable carbon-carbon radiators with $7.5 m^2$ each
  - Separated cycles and redundant elements
  - Water (internal) and water-glycol (external) as working fluids
- Prolonged duration without the spacecraft's active thermal control system during reentry:
  - 221 kg water (137 kg from ECLSS) is used as a heat sink
  - Heated water is released as vapor into the atmosphere/space

Thermal Protection System

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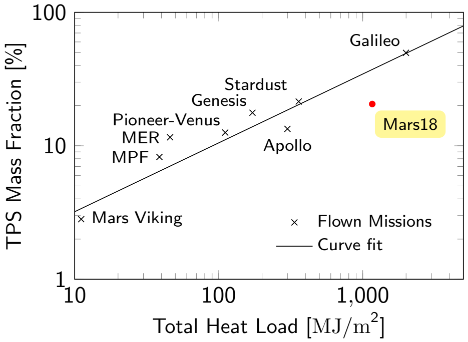
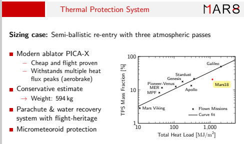
Sizing case: Semi-ballistic re-entry with three atmospheric passes

- Modern ablator PICA-X
  - Cheap and flight proven
  - Withstands multiple heat flux peaks (aerobrake)
- Conservative estimate
  - → Weight: 594 kg
- Parachute & water recovery system with flight-heritage
- Micrometeoroid protection





- Dimensioning of the TPS for the most critical case within the constraints (perigee altitude 60 km)
- Reusability of PICA-X necessary to withstand multiple atmospheric passes
- Conservative estimation for vaporization heat of PICA-X with the data of Apollo heat shield Avcoat material: 26.516 MJ/kg
- Assumption: 86% - 88% of the total heat load occur at a temperature above the ablation temperature of the heat shield material

  → Thickness of ablated layer can be calculated: 162 mm

- Aluminum-cover with a jettison-mechanism on top of heat shield to protect against impacts of micrometeoroids

Communications & Science

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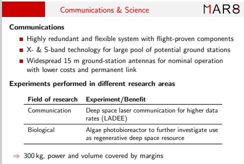
Communications

- Highly redundant and flexible system with flight-proven components
- X- & S-band technology for large pool of potential ground stations
- Widespread 15 m ground-station antennas for nominal operation with lower costs and permanent link

Experiments performed in different research areas

Field of research	Experiment/Benefit
Communication	Deep space laser communication for higher data rates (LADEE)
Biological	Algae photobioreactor to further investigate use as regenerative deep space resource

⇒ 300 kg, power and volume covered by margins



- Flight-proven elements (in contrast to laser comm with low TRL) provide sufficient data rates for TT&C, medical monitoring, science and video
  - Two redundant high-gain parabolic reflectors and two low-gain backup antennas are fed by four redundant transponder systems
  - Use of large antennas is expensive and limited: facilities with an antenna size of 15 m are chosen for nominal operation
- Over a time of roughly 150 days the data can only be transmitted with less than 200 kbps to 15 m ground stations
- Data rate decrease due to larger distance will be mitigated by increasing transmission time and using larger ground station antennas in the NASA DSN and ESTRACK network
- Separate UHF system: Possible relay communication with higher data rates and as emergency link (via e.g. Mars Reconnaissance Orbiter)

Mars18 Budgets

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		Mass [kg]	Power [W]	Volume [m^3]
	Structure	3,602	11	3
	Attitude and Orbit Control System	1,120	277	4
	Electrical Power System	338	0	< 1
	Thermal Protection System	815	0	1
	Communication System	149	154	< 1
	Radiation Protection	730	2	1
	Env. Control & Life Support System	3,825	1,474	16
	Thermal Control System	628	422	1
	Human Factors	423	357	3
	Scientific Payload	300	-	-
	System Dry Total + 20% Margin	**14,317**	**3,236**	**34**
	Propellant Rendezvous [kg]	710		
	Propulsion Module [kg]	48,097		
	System Wet Total [kg]	**63,124**		

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- System-wide margin of 20% and element margins depending on level of modifaction/development: 5%, 10% and 20%
- Total mass of the Mars Transfer Vehilce shortly after TMI: 14.5 t
- Total wet mass of the system in LEO: 63 t
- Mass of the capsule at reentry: 3.9 t
- Power budget consists of average (shown), peak power and waste heat
- Total available living space at TMI: 15.7 m^3
  - Above the tolerable, long-duration limit for manned missions (10 m^3)
  - Increases in correlation to the mission duration
- Remaining unpressurized volume: 6 m^3

  → Serves as margin and is available for science equipment

Return to Earth

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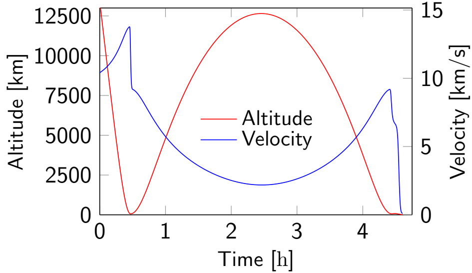
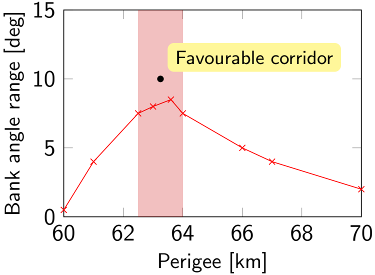
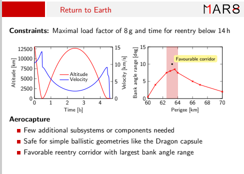
Constraints: Maximal load factor of 8 g and time for reentry below 14 h

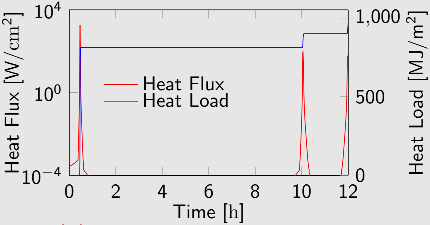




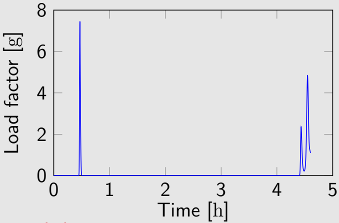
Aerocapture

- Few additional subsystems or components needed
- Safe for simple ballistic geometries like the Dragon capsule
- Favorable reentry corridor with largest bank angle range





(a) Heat flux/load for critical case



(b) Load factors at nominal case

- Nominal reentry at perigee altitude and bank angle of: 63.5 km and 98.5° (first pass), 65 km and 65° (second pass)

Table: Reentry window (bank angle for first pass, 0° for following passes)

	Perigee Altitude	Bank Angle	Load Factors	Duration
Upper window	71.45 km	174.5° – 185.5°	4.3 – 4.3 g	9.7 – 14 h
Selected trajectory	63.5 km	94° – 102.5°	6.9 – 7.9 g	1.3 – 14 h
Lower window	60 km	79.5° – 80°	8.0 g	12.1 – 13 h

Cost Estimation

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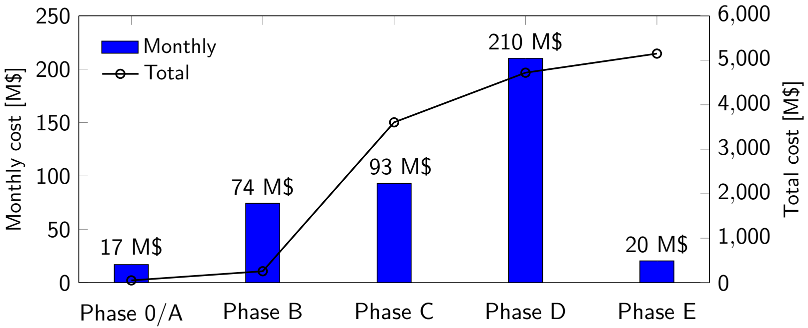
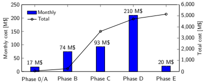
Approach: Combination of commercial/governmental cost models and analogies/build-up



- Costs are inflation-adjusted with an estimate for 2018
- Monthly basis for each phase: 21.66 work days

Approach: Combination of commercial/governmental cost models and analogies/build-up

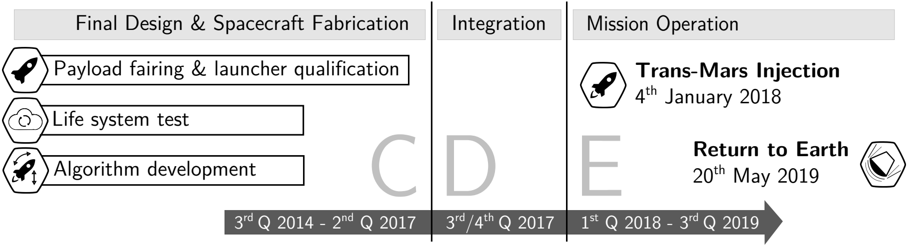


- Costs are inflation-adjusted with an estimate for 2018
- Monthly basis for each phase: 21.66 work days

Table: Total cost breakdown (including additional 20% margin)

Subitem	**Costs [M$]**	**Applied cost estimation**	**[%]**
Structure	557	*Analogy/build-up*	10.8
AOCS	382	*AMCM*	7.4
EPS	19	*Analogy/build-up & USCM*	0.4
Launch & Propulsion	821	*Analogy/build-up*	15.9
TPS	7	*Analogy/build-up*	0.1
Communication	48	*USCM*	0.9
Radiation	4	*Analogy/build-up*	0.1
ECLSS	1982	*AMCM*	38.5
TCS	858	*AMCM*	16.6
Human Factors	43	*Analogy/build-up*	0.8
Sum	**4,721**		**91.6**
Ground & Flight Operations	429	*TransCost*	8.4
Total	**5,150**		**100**

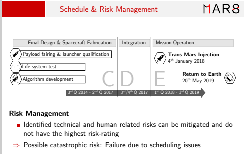
Schedule & Risk Management



Risk Management

- Identified technical and human related risks can be mitigated and do not have the highest risk-rating

⇒ Possible catastrophic risk: Failure due to scheduling issues



- Development of individual items depending on level of alterations and TRL
  - Procurement and scaling of items: 3 and 6 months respectively
  - All items are $\geq$ TRL 6 (except Asymmetric Payload Fairing, TRL 4)
- Detailed launch system development, integration and manifest integrated with other planned launches (COTS, CST-100, DreamChaser)
- Failure due to scheduling: mitigation through strong public support and solid/transparent finances

Table: Risk matrix (Breakdown on www.mars18.de)

	insign.	minor	moderate	major	catastrophic
very likely					
likely			16,24		
possible		17,26,28	18		23
unlikely		5	14	6,15,27	7,22,25
rare			1,10	4,9,20	2,3,8,11,12,13,19,21

Thank You For Your Attention

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- Mission is possible in 2018 with strong public support
- Launch window 2021 would allow development of advanced habitats (TransHab, Nautilus)
  - ⇒ Greater habitat volume important for safety and comfort (Asymmetric payload fairing, ARED)

Support

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Astos Solutions

Constellation aerospaceresearch.net

DGLR

IRS

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