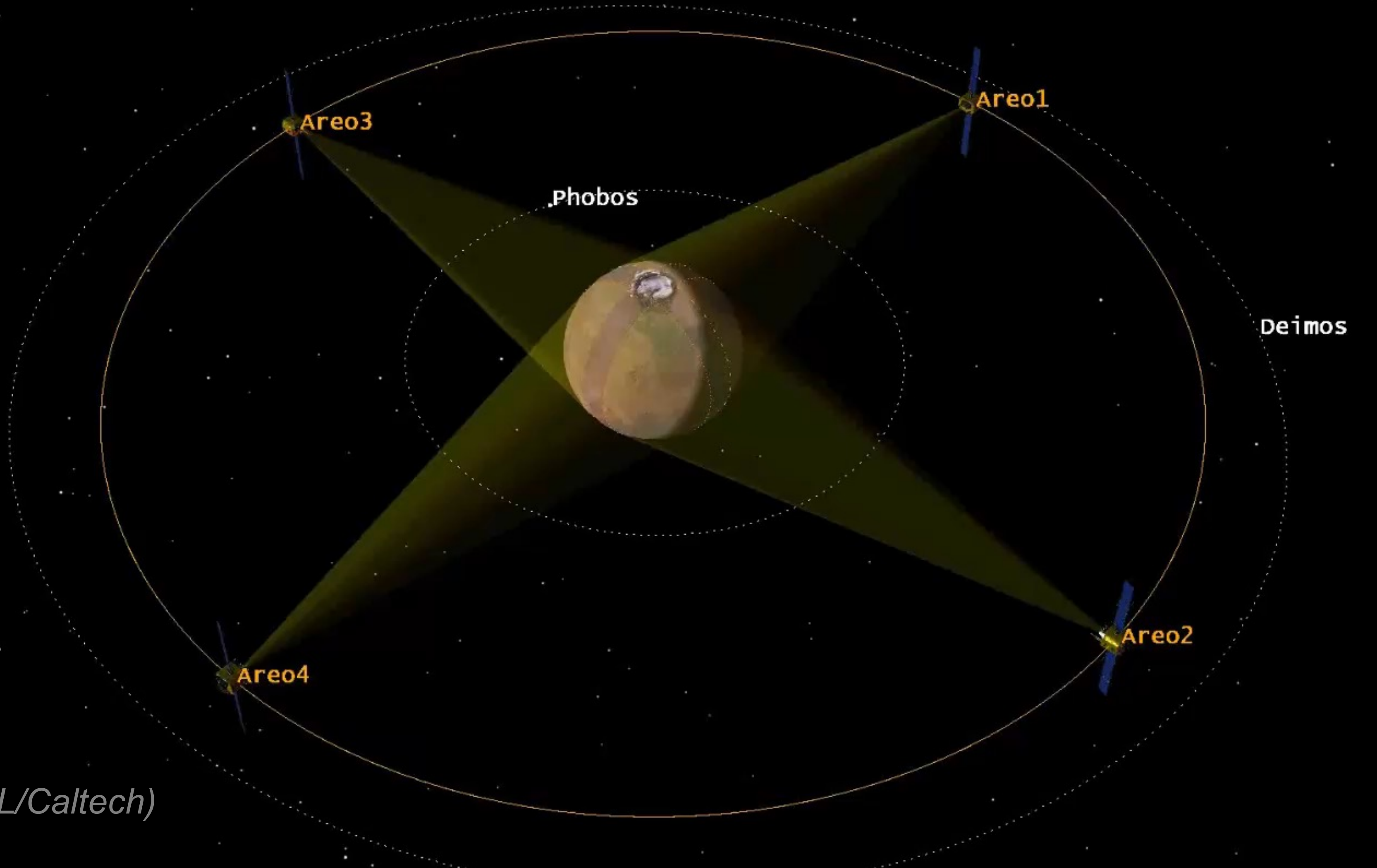
Mars Smallsat Mission & Instrumentation Studies for Global Meteorology & Space Weather Monitoring

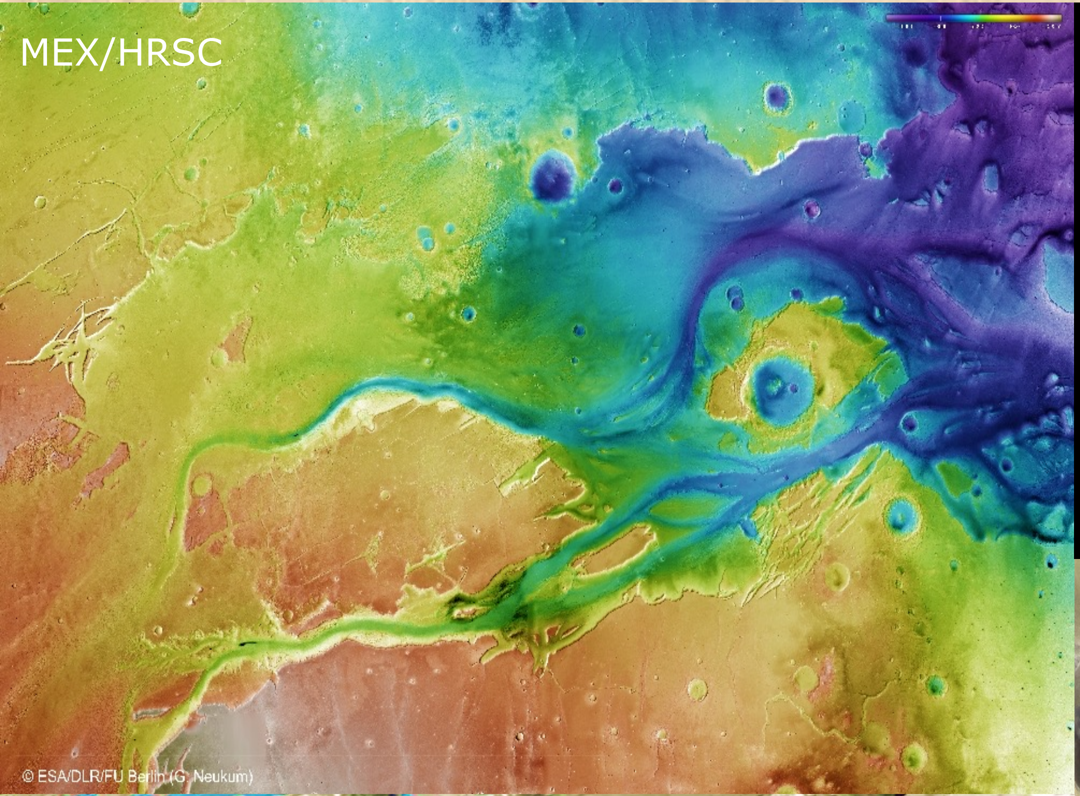
A. Cardesin-Moinelo, L. Montabone + international science consortium

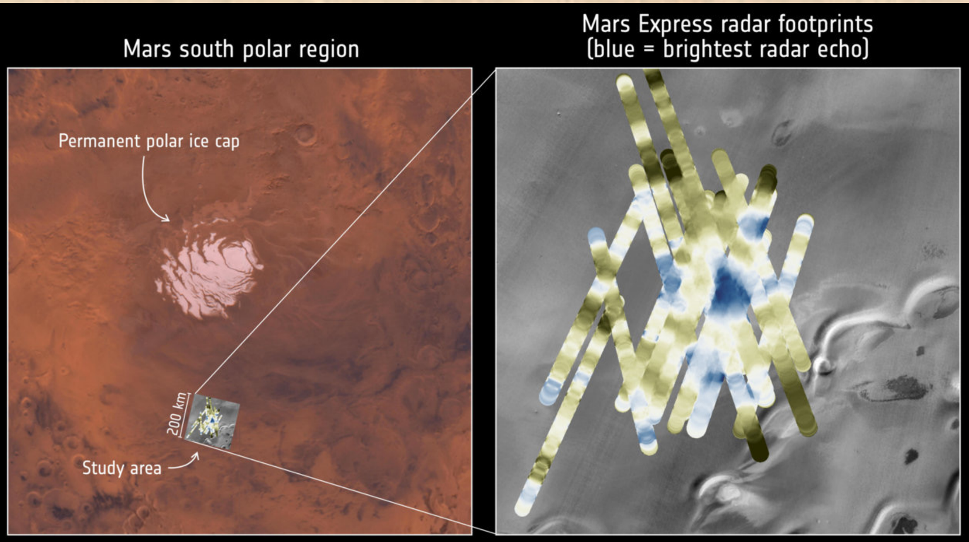


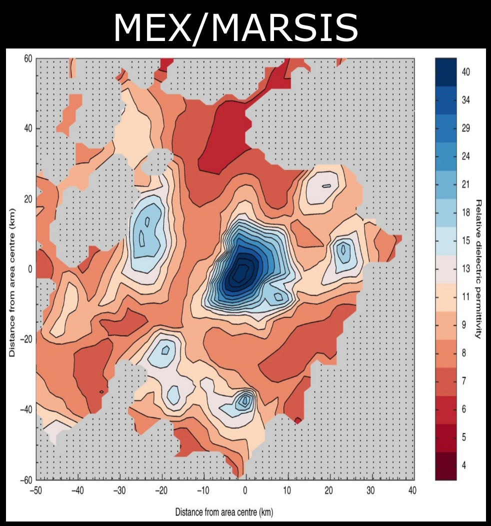
R. C. Woolley (JPL/Caltech)

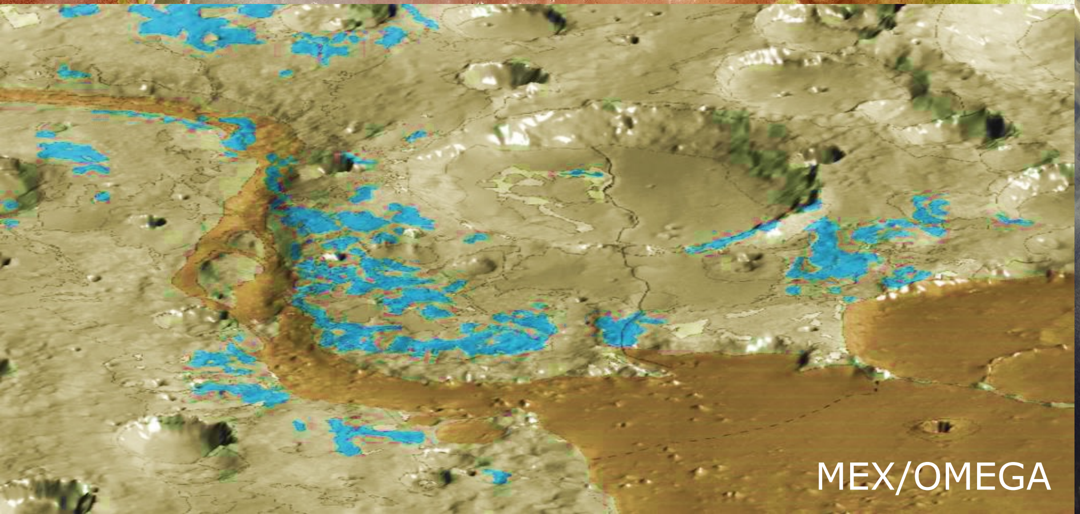
ESA SSW, Aranjuez 25 January 2024

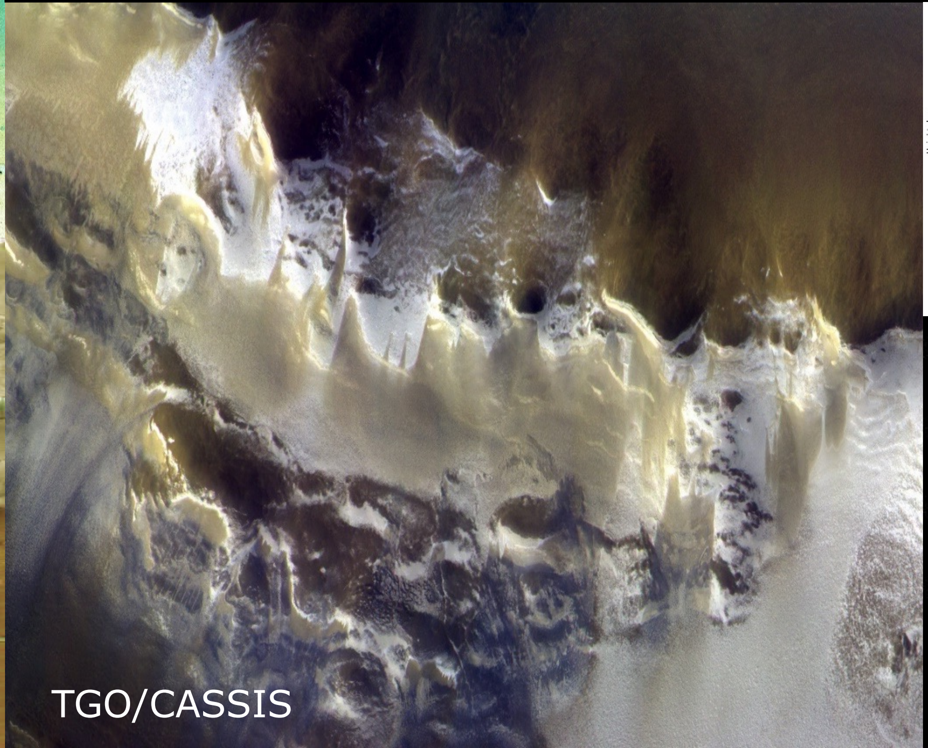
Mars missions historically focused on high resolution. **More detail = better !?!**

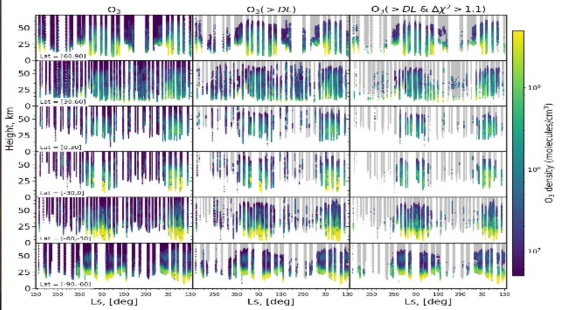


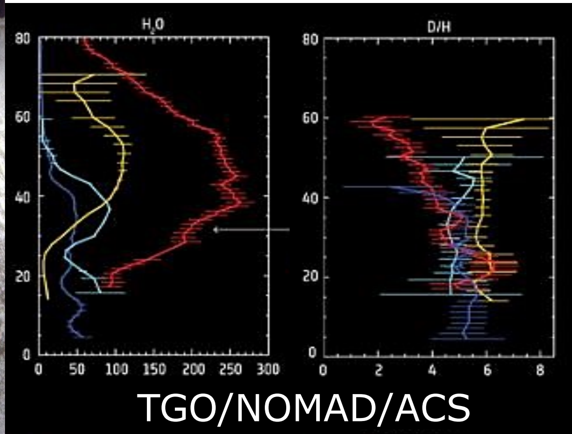






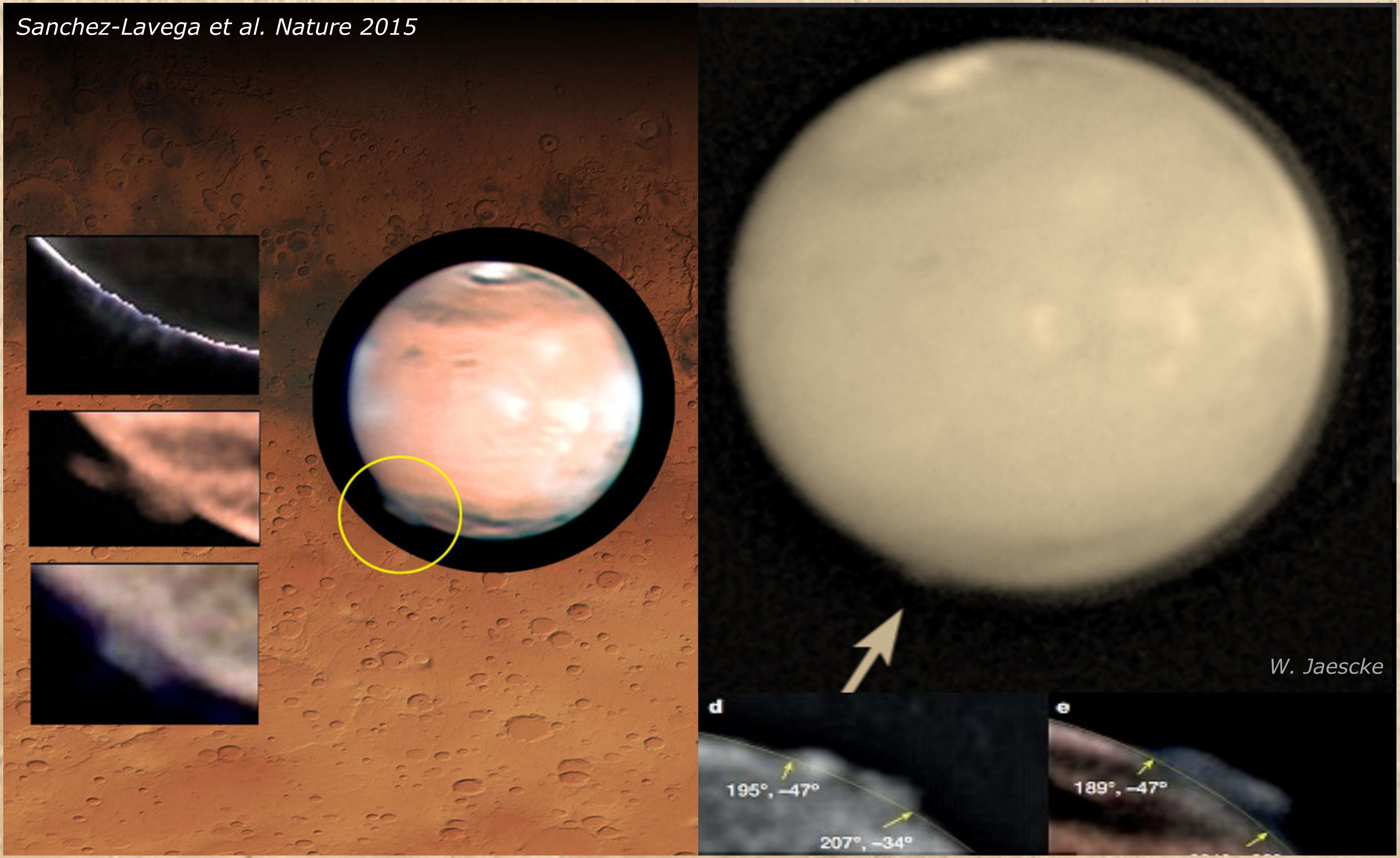






2015: Mysterious ~250km “plume” discovered from Earth!!!

NOT SEEN BY ANY MARS MISSION! ➔ We are missing the global picture!



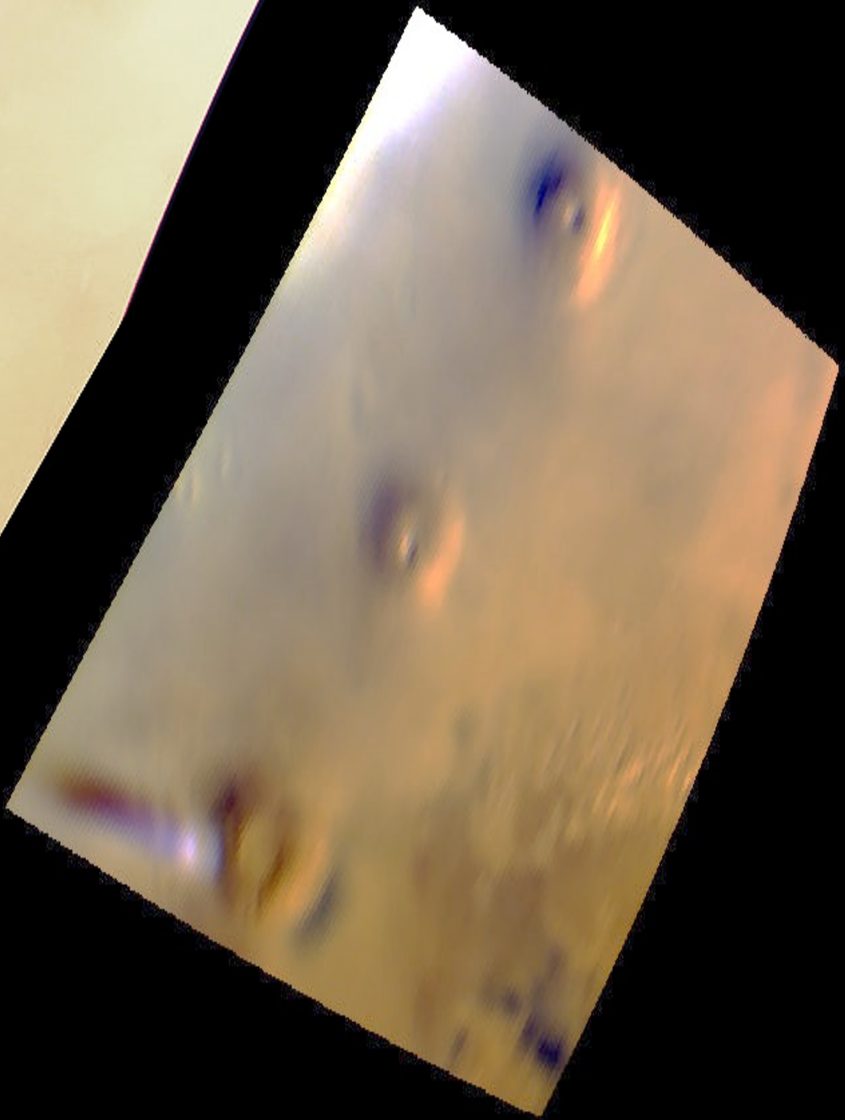
2018: Mars Express added VMC camera + High altitude obs. for global monitoring

***ESA research project** ➔ **"Discovery" of the Arsia Mons Elongated Cloud!!!**

Hernandez-Bernal et al.
JGR 2020 & 2022

VMC Global Monitoring

HRSC High-Res VIS Image



OMEGA VIS-NIR Spectrum

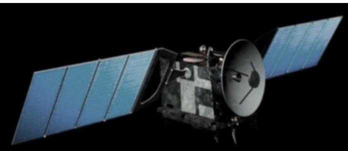
MWWM 2022: Mars Wind and Wave Mapping *ESA Research Project

Atmospheric winds and gravity waves using Earth Telescopes, Mars Express and Trace Gas Orbiter

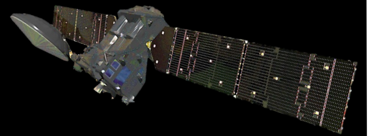
Alejandro Cardesin-Moinelo, Patrick Martin, Lucie Riu, Dima Titov, Colin Wilson, Emmanuel Grotheer, Michel Breitfellner (ESAC/ESTEC)
Pedro Machado, Francisco Brasil, Hermano Valido, Gabriella Gilli, Jose Silva, Daniela Espadinha (IA Lisbon, Portugal) + Brigitte Gondet (IAS, France) + …

Mars Wind

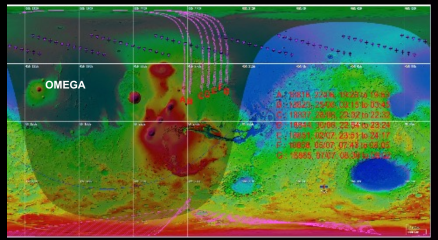
during Mars Global Dust Storm



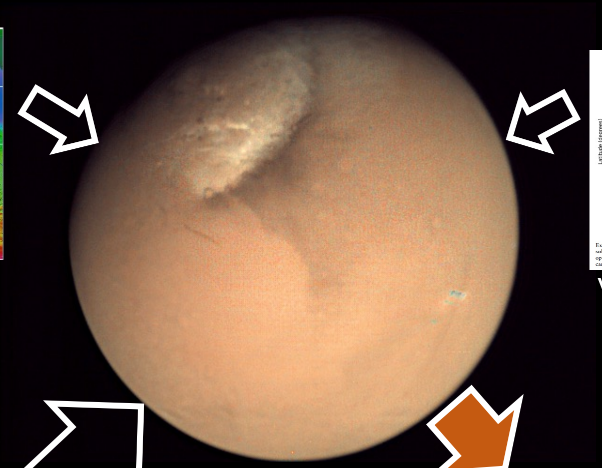
Mars Express

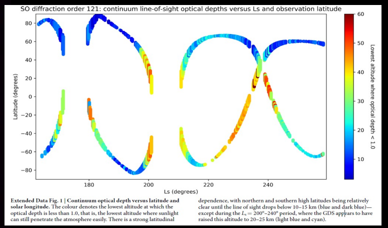


Trace Gas Orbiter



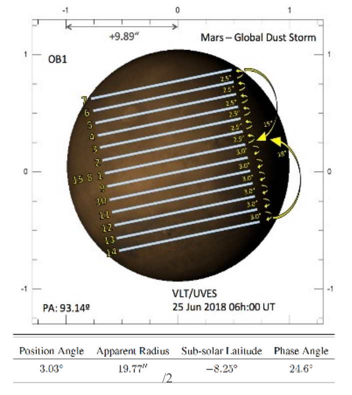
Context imaging + VIS/IR spectra



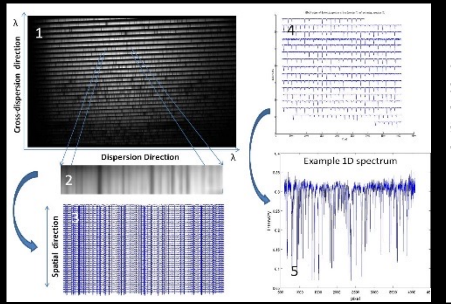


Vertical profiles optical depth

Very Large Telescope

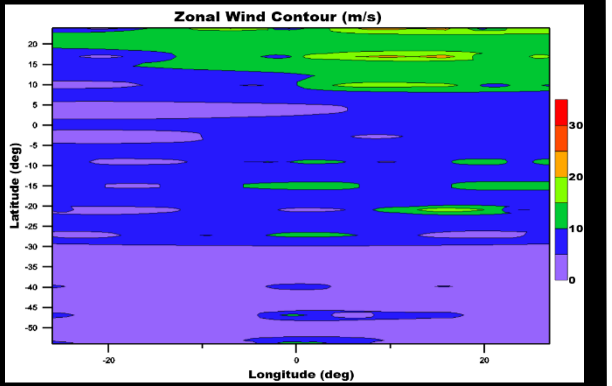


UV Solar radiation spectra reflected on dust storm layer



First Map of Winds on Mars

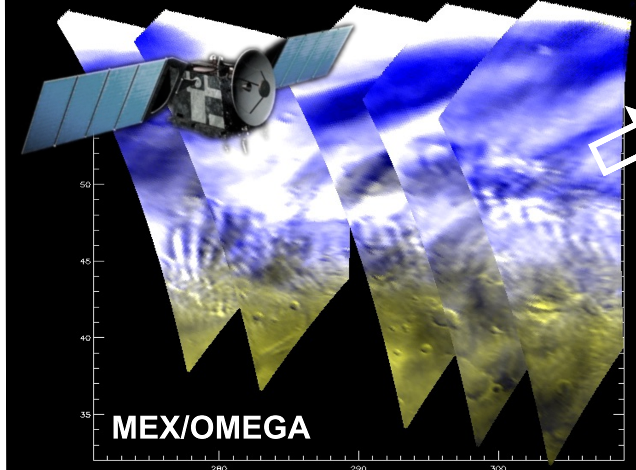
with Doppler velocity seen from Earth

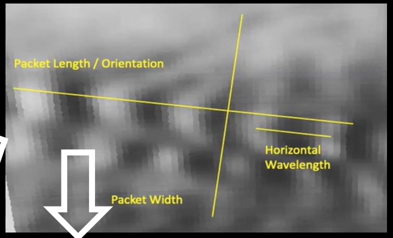


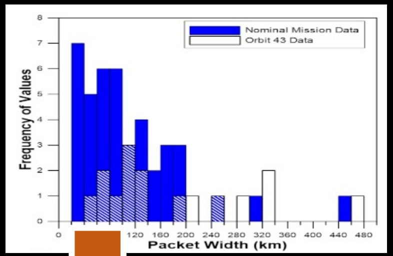
Machado et al. 2024 (in prep…)

Wave Mapping

Detection and analysis of atmospheric gravity waves

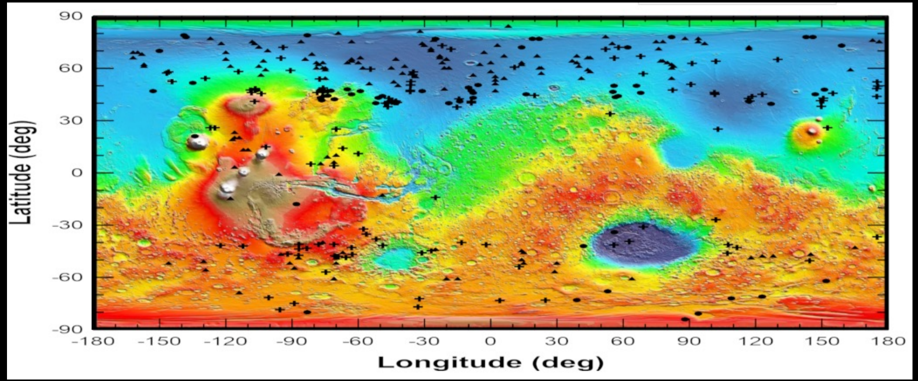






First Map of Gravity Waves on Mars

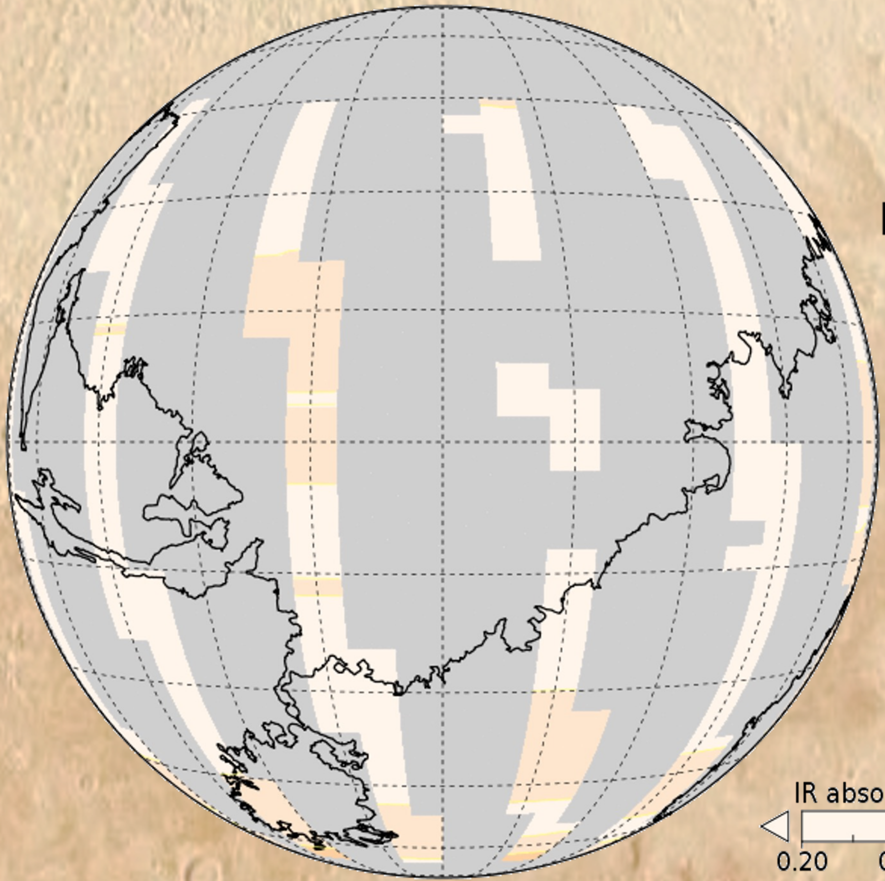
catalogue database of morphological properties



Brasil et al, A&A 2024 (under review)

We are “missing” the Global picture:
Community needs Global Weather Monitoring from High Altitude

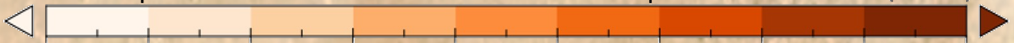
Low altitude Polar Orbiter



Centered on 15° W, 0° lat

MY 24 ; Ls~220° ; Sol-of-Year 438

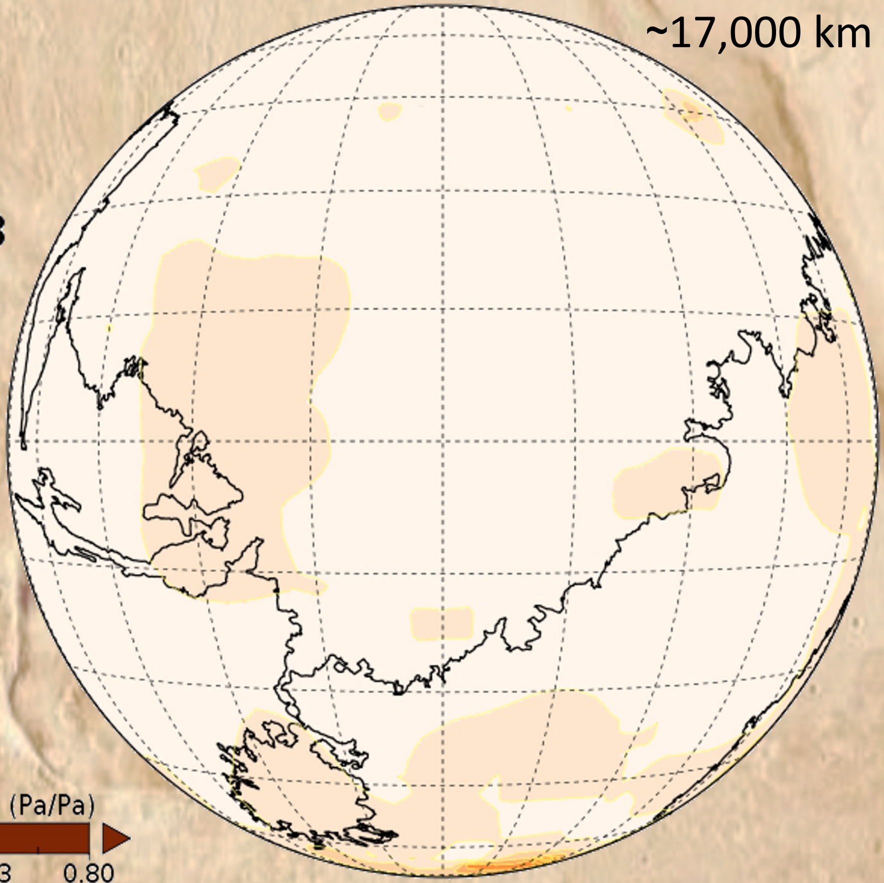
Regional Dust Storm
Column Depth Opacity
Simulation
(MGS / TES)



Montabone, Icarus (2015), JGR-Planets (2020).
Synthetic images from observations (@~17,000 km)

High-Altitude Areostationary Orbiter

~17,000 km

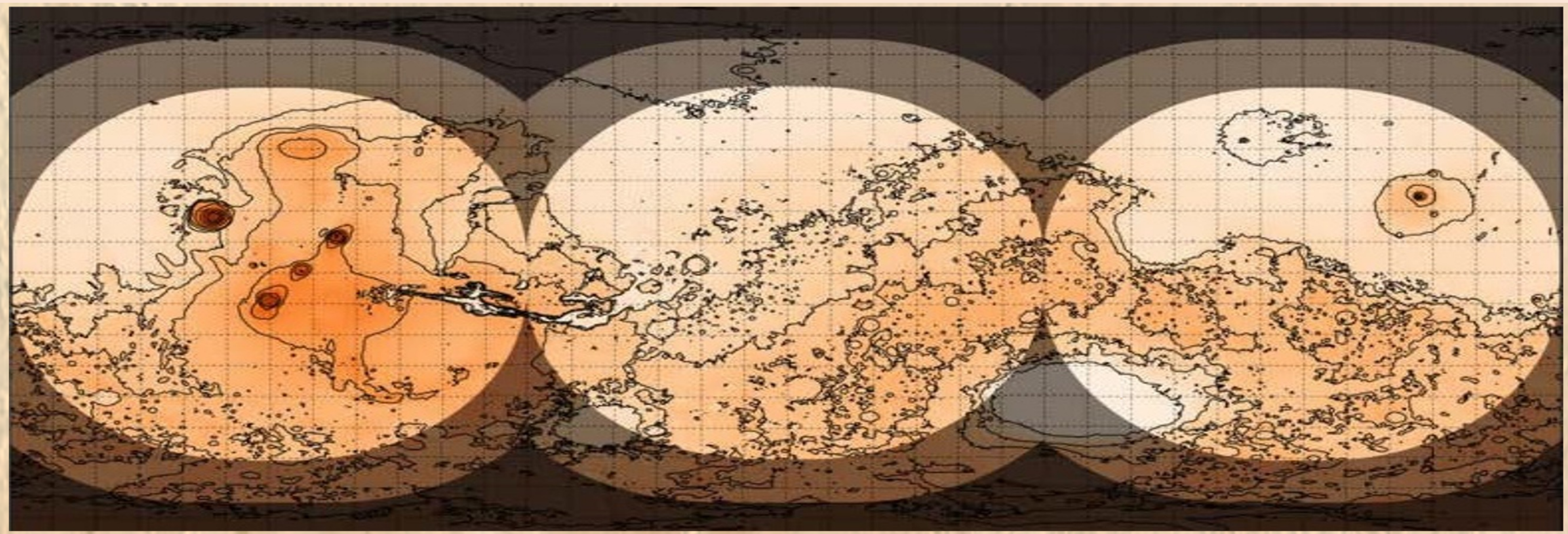


Centered on 15° W, 0° lat

Example: "minimal" Areostationary 3-SC Constellation Coverage

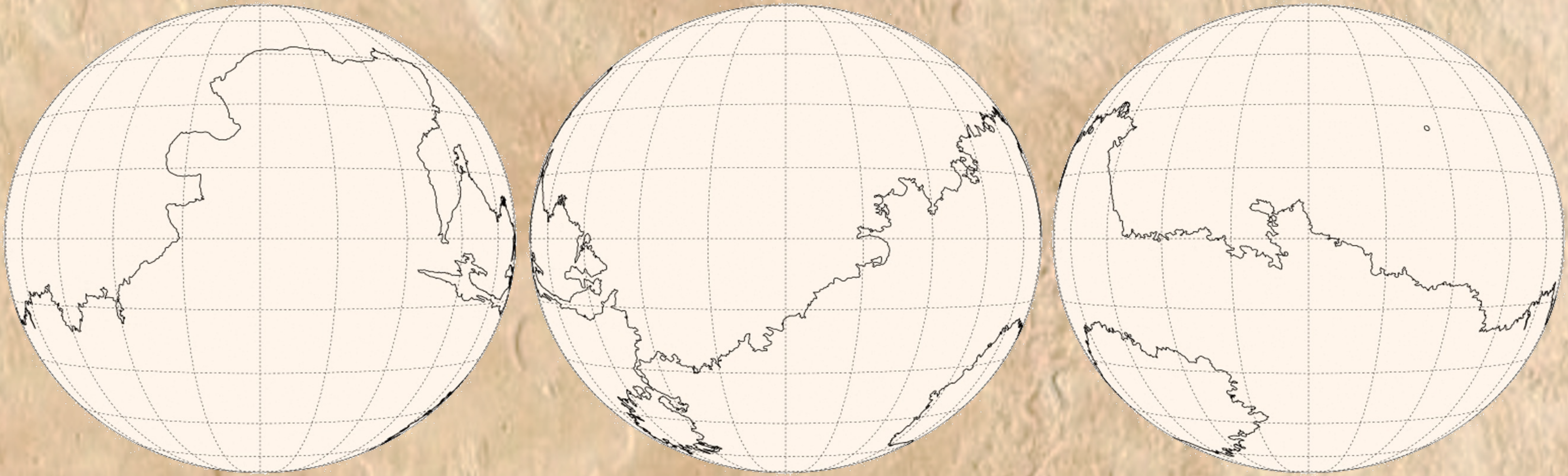
Continuous
Simultaneous
Quasi-global

Coverage

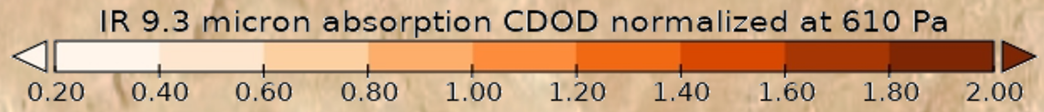


areostationary views from about 17,000 km

"Global" Dust Storm Simulation
MY 34 ; Ls ~ 186°
(MRO / MCS)



Centered on **120° W,** 0° lat | Centered on **0° lon,** 0° lat | Centered on **120° E,** 0° lat



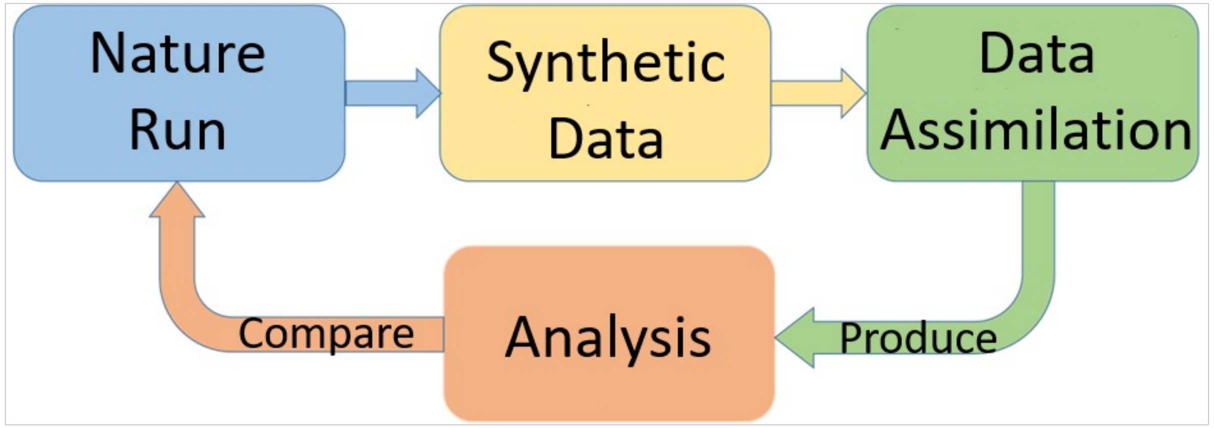
White Paper on benefits and applications of areostationary orbit
Montabone 2020

Montabone et al., JGR-Planets (2020)
Synthetic images from real observations (@~17,000 km)

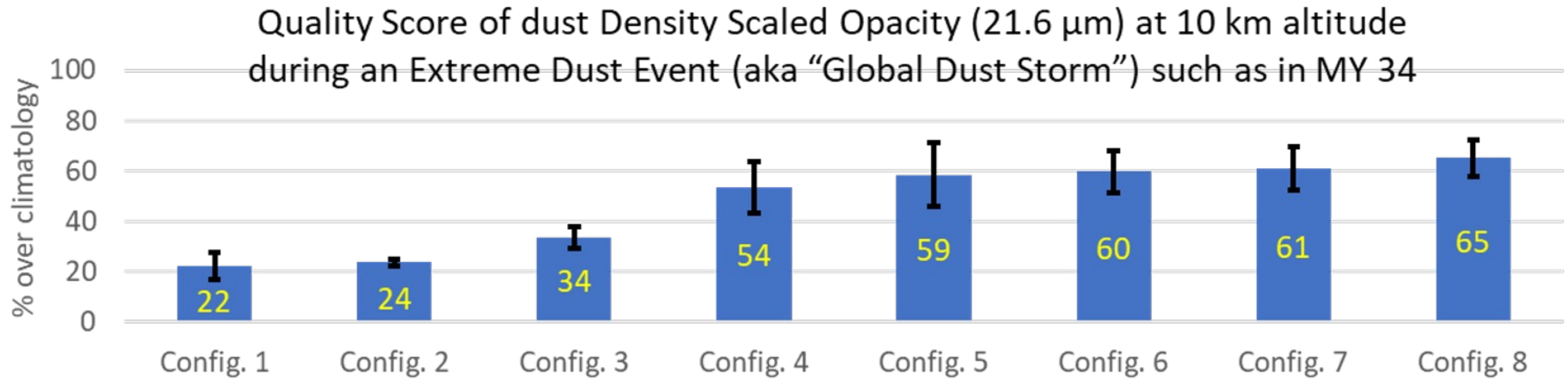
***ESA research project**

Observing System Simulation Experiments (OSSEs)

Quantitatively determine the "optimal" configuration and payload for weather-monitoring satellites



- **8 satellite configurations**: single and multiple
- **3 types of payload**: point and image (small/large FOV) radiometers
- **3 types of observations**: temperature/dust opacity profiles, column dust optical depths



Configuration legend

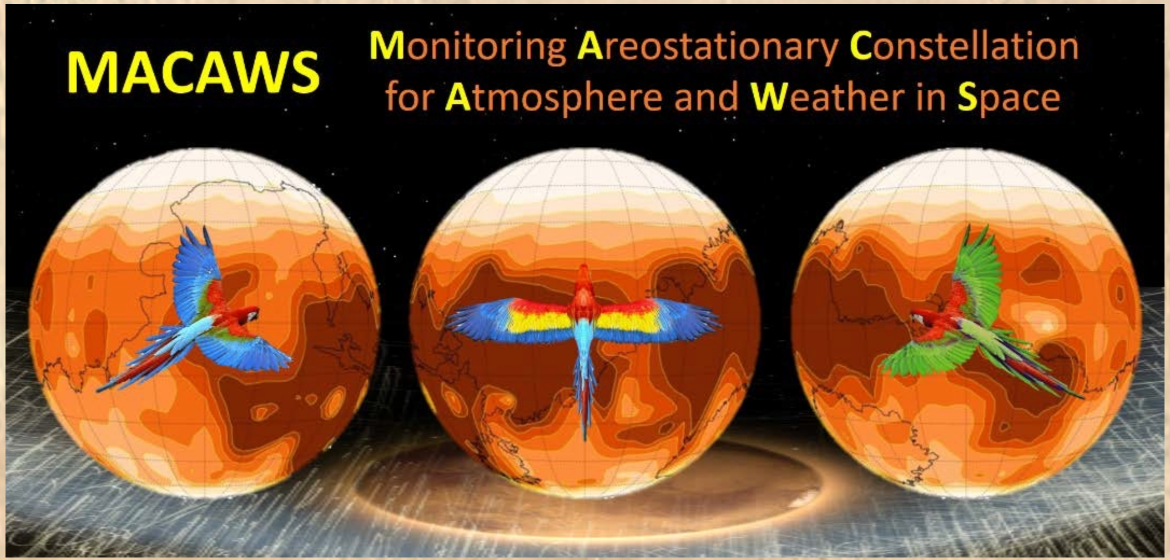
1: Polar, Sun-sync.
2: Polar, non Sun-sync. (NSS)
3: Polar NSS + Areo (small FOV)
4: Polar NSS + Areo (large FOV)
5: 4 x Mid-altitude
6: 3 x Areo (large FOV)
7: Polar NSS + 4 x Mid-altitude
8: Polar NSS + 3 x Areo (large FOV)

UAEU جامعة الإمارات العربية المتحدة United Arab Emirates University

IPSL LMD The Open University esa

ESA report available for SWIMALONG – TN1b project

Example: "minimal" Mission concept Areostationary 3-SC Constellation



- **High-Altitude constellation, 3 small satellites** (minimum) **areostationary** (or quasi)
- Payload for **atmospheric weather** and **space weather** investigations:
  - Atmospheric weather: **VIS-TIR-UV cameras** (+NIR spectrometer, …?)
  - Space weather: **magnetometer**, **ion/electron analyzer**, **radiation monitor**…
- Estimated mission cost: **<200 M€** (Phase A-F, launch excluded)
- **Technology basically ready** (high TRL, COTS available)
- Estimated launch: ~2030? (piggyback MSR and/or International Mars Ice Mapper?)

TABLE 1: LIST OF MACAWS MEASUREMENTS

Investigation	Physical parameters					Observable quantities		Instrument requirements	
	Description	Spatial resolution	Cadence	Range	Precision	Description	Energy / wavelength / frequency	Description	FOR or IFOV
Atmospheric weather	Extent of (dust/water ice) aerosol clouds	H ≤ 5 km	≤ 30 min	5 km to global	5 km	Radiance	400-750 nm (VIS RGB)	Visible camera	IFOV ≤ 0.3 mrad
	Duration of (dust/water ice) aerosol clouds	H ≤ 5 km	≤ 30 min	Fraction of the hour to tens of sols	30 min	Radiance	400-750 nm (VIS RGB)	Visible camera	IFOV ≤ 0.3 mrad
	Horizontal wind components	H ≤ 5 km	≤ 30 min	0-200 m/s	10 m/s	Displacement of (dust/water ice) cloud feature	400-750 nm (VIS RGB) or starting from 200 nm (UV)	Visible or UV camera	IFOV ≤ 0.3 mrad
	Atmospheric temperature (5~45 km)	H ≤ 5 km ; V = 10 km	≤ 30 min	110-260 K	1 K	Radiance	Around 15 µm (TIR)	Thermal IR spectrometer / radiometer	IFOV ≤ 3.5 mrad
	Surface temperature	H ≤ 5 km	≤ 30 min	130-320 K	1 K	Radiance	Around 7.9 µm, or around 32 µm, or beyond 50 µm (TIR)	Thermal IR spectrometer / radiometer	IFOV ≤ 3.5 mrad
	Dust column optical depth	H ≤ 5 km	≤ 30 min	0 - 5 referenced to 1064 nm	10-20%	Radiance	Around 9.3 µm (TIR), or a broadband signal in NIR, or at 220 nm (UV)	Thermal IR spectrometer / radiometer – Near-IR spectrometer – UV imager	IFOV ≤ 3.5 mrad
	Water ice column optical depth	H ≤ 5 km	≤ 30 min	0 - 5 referenced to 1064 nm	10-20%	Radiance	Around 11.8 µm (TIR), or at 1254 nm or 1500 nm (NIR), or at 320 nm (UV)	Thermal IR spectrometer / radiometer – Near-IR spectrometer – UV imager	IFOV ≤ 3.5 mrad
	Carbon dioxide ice column optical depth	H ≤ 5 km	≤ 30 min	0 - 5 referenced to 1064 nm	10-20%	Radiance	Around 22 µm (TIR), or at 1428 nm (NIR)	Thermal IR spectrometer / radiometer – Near-IR spectrometer	IFOV ≤ 3.5 mrad
	Water vapour column abundance	H ≤ 5 km	≤ 30 min	5-400 pr-µm	10-20%	Radiance	Around 41 µm (TIR) or near 2602 nm (NIR)	Thermal IR spectrometer / radiometer – Near-IR spectrometer	IFOV ≤ 3.5 mrad
	Surface pressure	H ≤ 5 km	≤ 30 min	150-1500 Pa	5-10 Pa	Radiance factor (I/F)	Around 2007 nm (NIR)	Near-IR spectrometer	IFOV ≤ 3.5 mrad
Space weather	Solar EUV spectral irradiance	N/A	16 s	1E-6 to 3E-2 W/m2/nm	15% (dI/I)	Same as physical parameter	10-20 nm, 17-22 nm, 121.6 nm	Solar EUV monitor	-2° to +2°, centered on Sun
	Interplanetary magnetic field vector	N/A	16 s	~1 to 3000 nT	0.3 nT or 10%	Same as physical parameter	N/A	Fluxgate mag	N/A
	Ion flux	N/A	16 s	1E7 to 1E10 eV/(cm2-s-st-eV)	10%	Same as physical parameter	~50 eV to 10 keV	Ion energy/angle analyzer	FOV: Cone of half angle 30° centered on Sun
	Superthermal electron flux	N/A	16 s	1E4 to 1E10 eV/(cm2-s-st-eV)	10%	Same as physical parameter	~1 eV to 10 keV	Electron energy/angle analyzer	FOV: 360° x 120°
	Energetic ions/electrons flux	N/A	20 min	1E1 to 1E6 eV/(cm2-s-st-eV)	10%	Same as physical parameter	50 keV to 5 MeV	Energetic ion/electron detector	FOV:40 x 40 deg centered on +/-Parker spiral dirs

The Case and Approach for Continuous, Simultaneous, Global Mars Weather Monitoring from Orbit

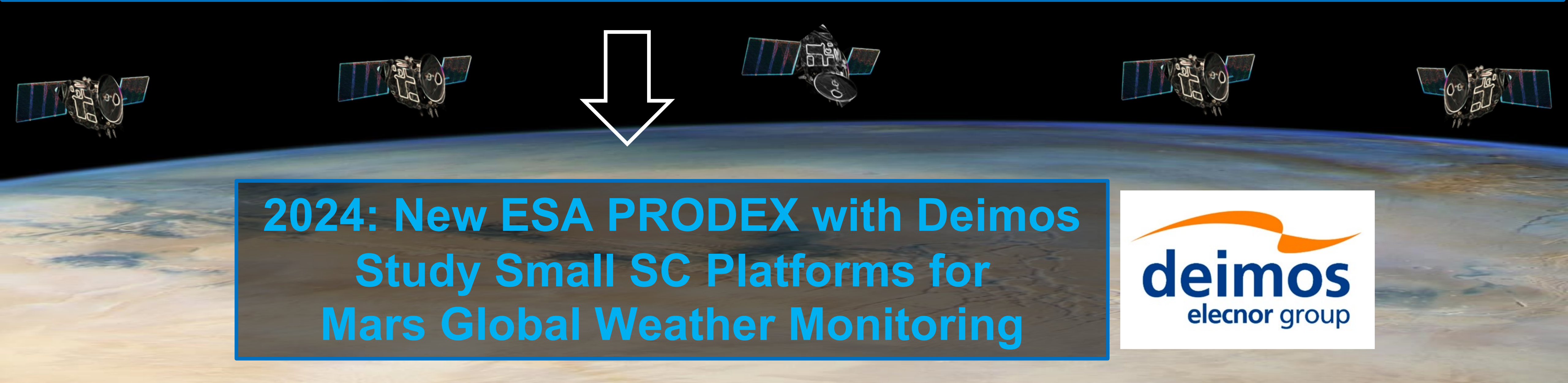
L. Montabone, S. Aoki, J.M. Battalio, T. Bertrand, M. Capderou,
A. Cardesin-Moinelo, F. Daerden, F. Forget, C. Gebhardt, B. Geiger, M. Giuranna,
S.J. Greybush, S. Guerlet, B. Guha, S.D. Guzewich, N.G. Heavens,
J. Hernández-Bernal, J.A. Holmes, O. Karatekin, A. Kleinboehl, R.J. Lillis, S.R. Lewis,
P. Machado, E. Millour, M.A. Mischna, F. Montmessin, H. Nakagawa, L. Neary,
K. Ogohara, F. Oliva, K.S. Olsen, M.R. Patel, A. Pankine, P.L. Read, S. Robert,
L. Ruiz Lozano, B. Ritter, A. Sánchez-Lavega, C.B. Senel, M.D. Smith, A. Spiga,
P.M. Streeter, L.K. Tamppari, O. Temel, D. Titov, A.C. Vandaele, M. Vincendon,
H. Wang, R.J. Wilson, M. Wolff, P. Wolkenberg, R.M.B. Young

"Community paper"
presented at

MAMO, Paris (June 2022)
COSPAR, Athens (July 2022)
EPSC, Granada (Sept. 2022)

SPANISH SCIENCE CONSORTIUM
Mars Small Satellite Constellations
for Mars Meteorology, Space Weather & Engineering Services

Cardesin-Moinelo, A.; Lopez-Puertas, M.; Lopez-Valverde, M.; Gonzalez-Galindo, F.
Sánchez-Lavega, A.; Hueso, R.; Hernandez-Bernal, J., T. del Río-Gaztelurrutia
Toledo, D.; Arruego, I.; Apestigue, V.; Diaz-Michelena, M. Rodriguez-Manfredi, J.A.; Pla-García, J. S. Sanchez-Cano, B.;
Geiger, B.; Migliari,.; Heavens, N. Montabone, L

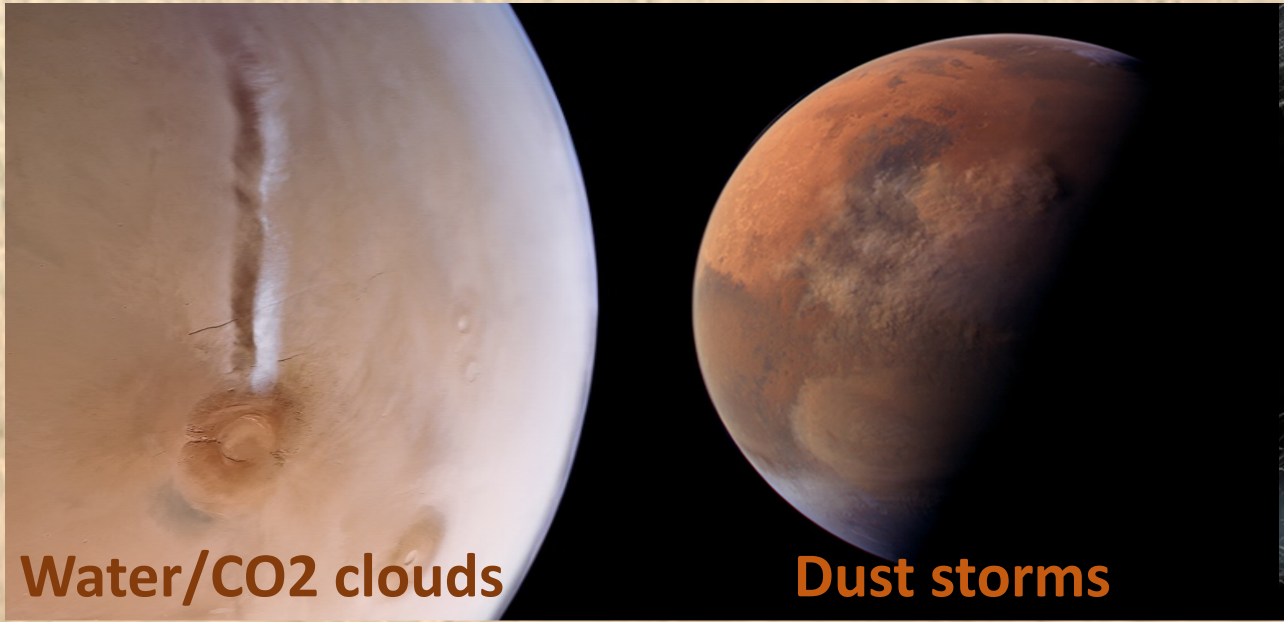


2024: New ESA PRODEX with Deimos
Study Small SC Platforms for
Mars Global Weather Monitoring

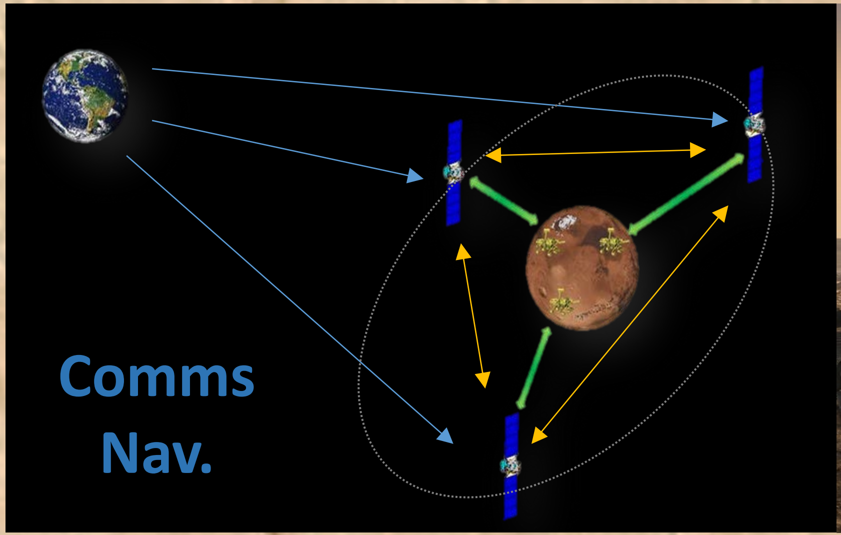
SUMMARY: Global Mars Monitoring is key

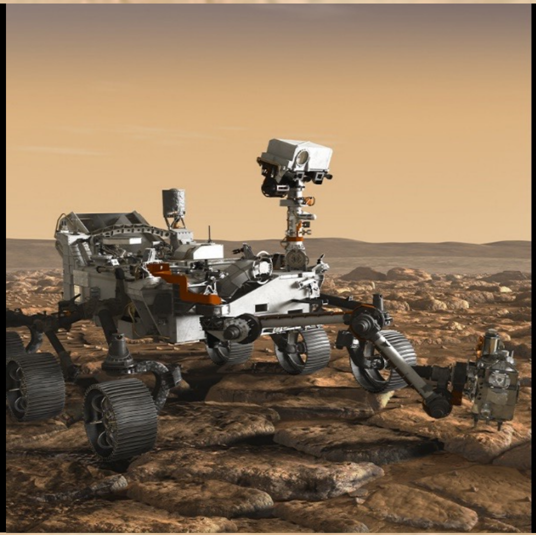
Mars Climate Science + Mars Exploration Tecnology

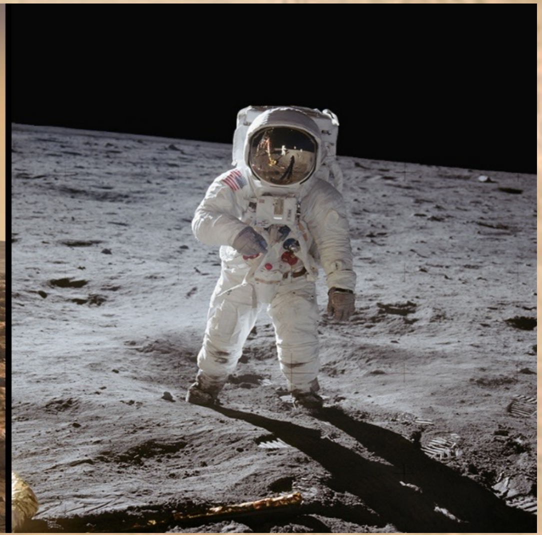
Global Mars Monitoring: Atmosphere (Water/Dust/T/P…) & Space Weather



+ Engineering Applications supporting Robotic & Human Exploration







OPEN QUESTIONS

<u>**Science Community needs Small Mars Global Monitoring Mission**</u>

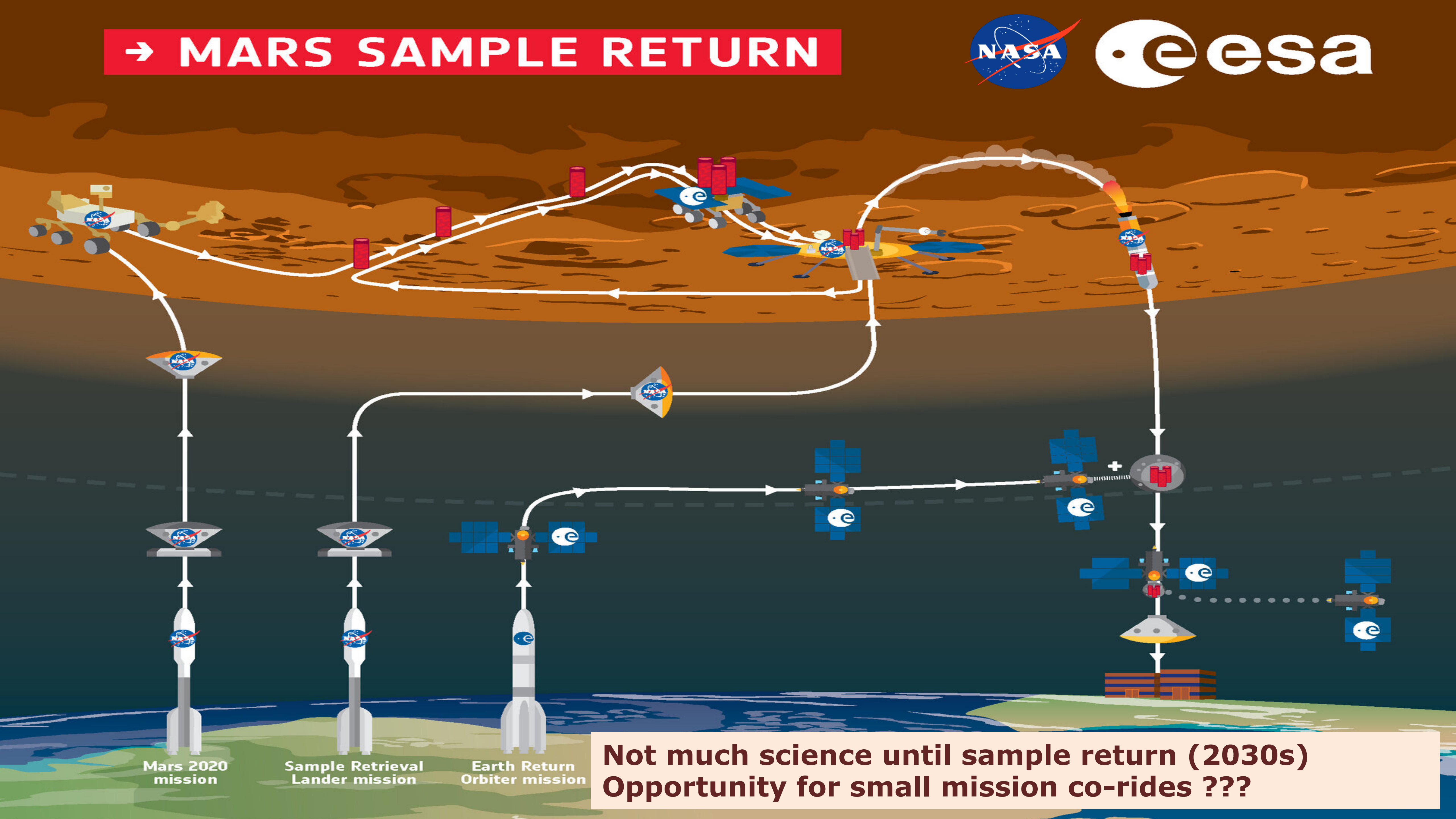
- **NASA Science program** (MEPAG/MCE-SAG) foresee Small Planetary Missions
- **ESA Exploration program** (TerraNovae/SciSpacE) has smallsats, but driven by technology dev.

→ Small Mars Global Monitoring Missions are flying in next decades,

driven by NASA or Industry, not ESA science (!)

- **ESA Science programme** currently does **NOT** have a well defined small mission program
  - ESA Voyage 2050 M-missions are too big, F-missions are too rare & specific/narrow
  - Opportunities for international collaboration, co-riding other Mars launches? MSR/I-MIM/…

<u>**ESA Science Small Mars Missions of Opportunity???**</u>

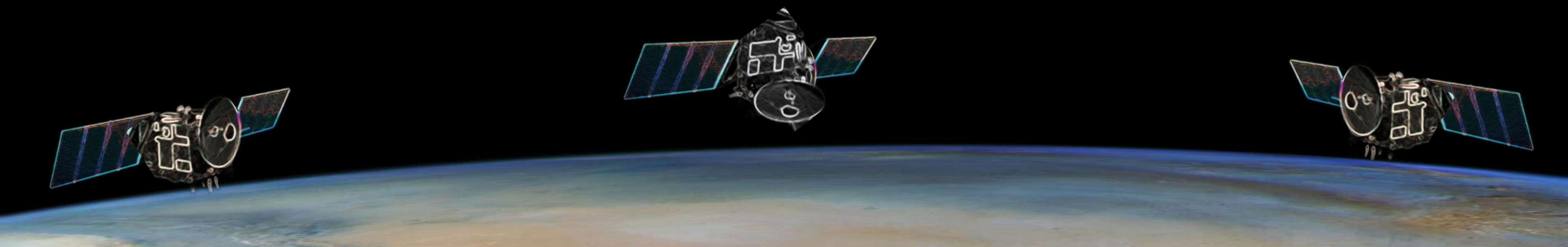


Not much science until sample return (2030s)
Opportunity for small mission co-rides ???

INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

THANKS



Estaciones Meteorológicas
M2020/MSL/Insight

CAB
AURORA TECHNOLOGY
UNIVERSITY OF LEICESTER
LMD
SPACE SCIENCE INSTITUTE
INSTITUTO NACIONAL DE TÉCNICA AEROESPACIAL

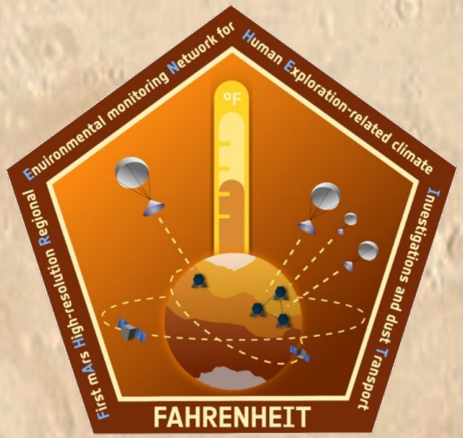
Some slides courtesy of ESA, NASA, L.Montabone, …

Image Credit HRSC Mars Express

Many Mission Concepts for Orbital Weather Studies

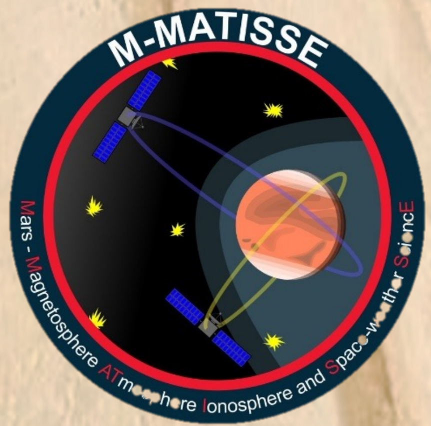
NASA MOSAIC 2020
Lillis et al.
(2021)

ESA SMARTieS 2021
Parfitt et al.,
Adv. Astron. (2021)



ESA FAHRENHEIT 2021
Vijendran et al.,
CDF (2021)

ESA MARCONI 2022
Parfitt et al.,
CDF (2021)



ESA M-MATISSE 2023
Sanchez-Cano et al.,
M- candidate

Community Small Mars Mission concepts: (NASA Low-Cost Science Mission Concepts Workshop 2022)

- **MACAWS** (Monitoring Areostationary Constellation: Atmosphere & Weather in Space), Montabone #5056, 2021
- **ANEMOI** (AreostatioNary Exploration of Meteorology by Orbital Imaging), Heavens et al., #5013, 2021
- **PAWSS** (Polar-orbiting Atmospheric Wind Small Satellite), Guzewich et al., #5035, 2021
- **MC³** (Mars Climate Cubesat Constellation), Kleinböhl et al., #5037, 2021
- **MSO** (Mars Stationary Orbiter), Malin et al., #5048, 2021
- **Aeolus**, Colaprete et al., #5061
- **Near-polar orbiter**, Tamppari et al., #5020, 2021

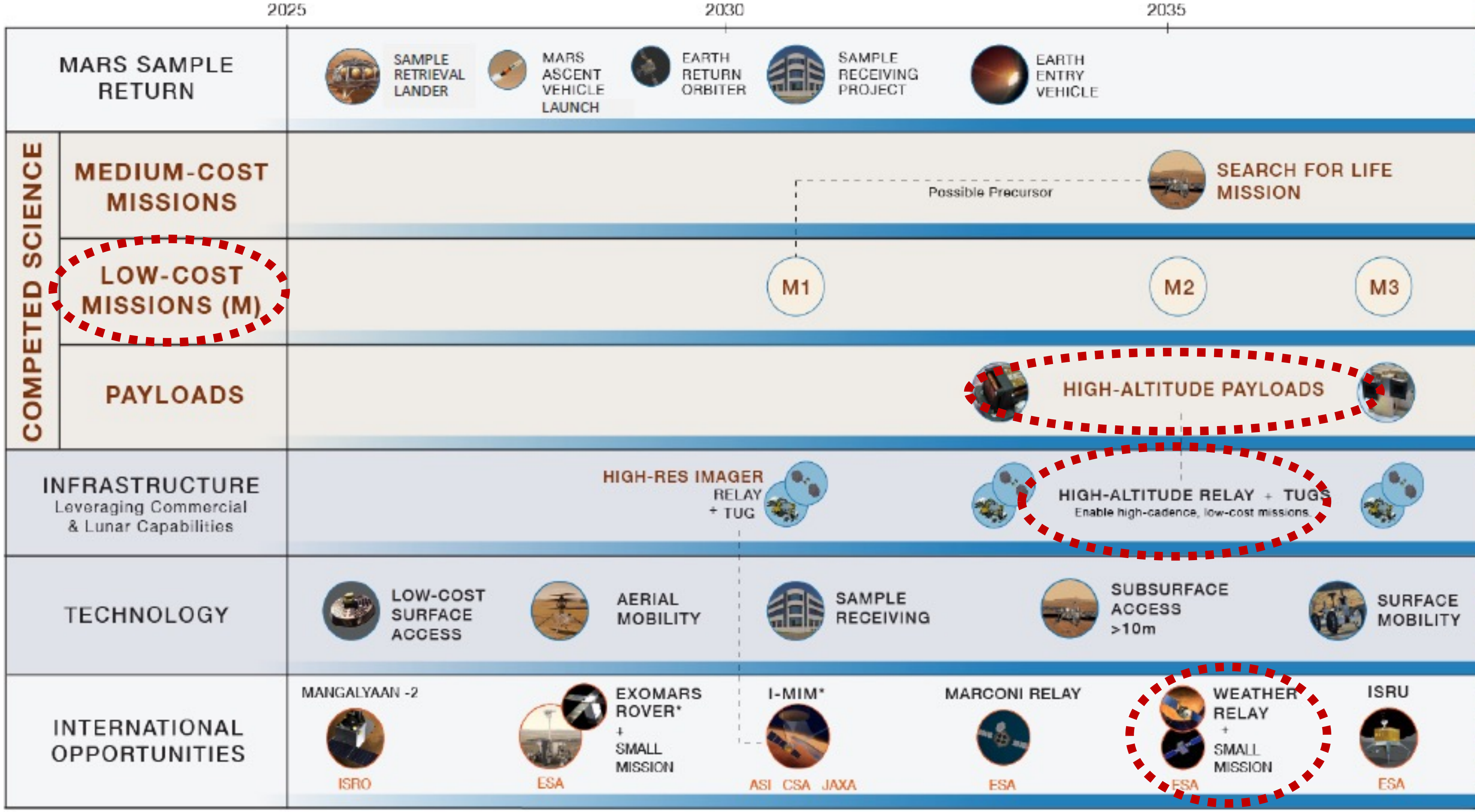
Exploration Roadmap TerraNovae 2030+ MARS

SECTION 4

Aspirational Program Timeline

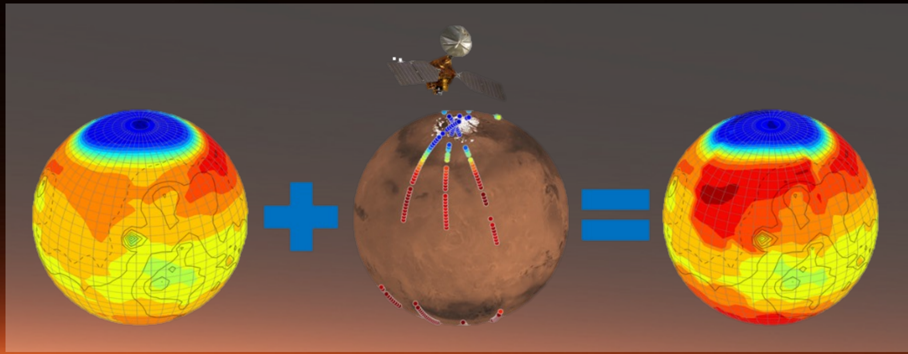
DRAFT

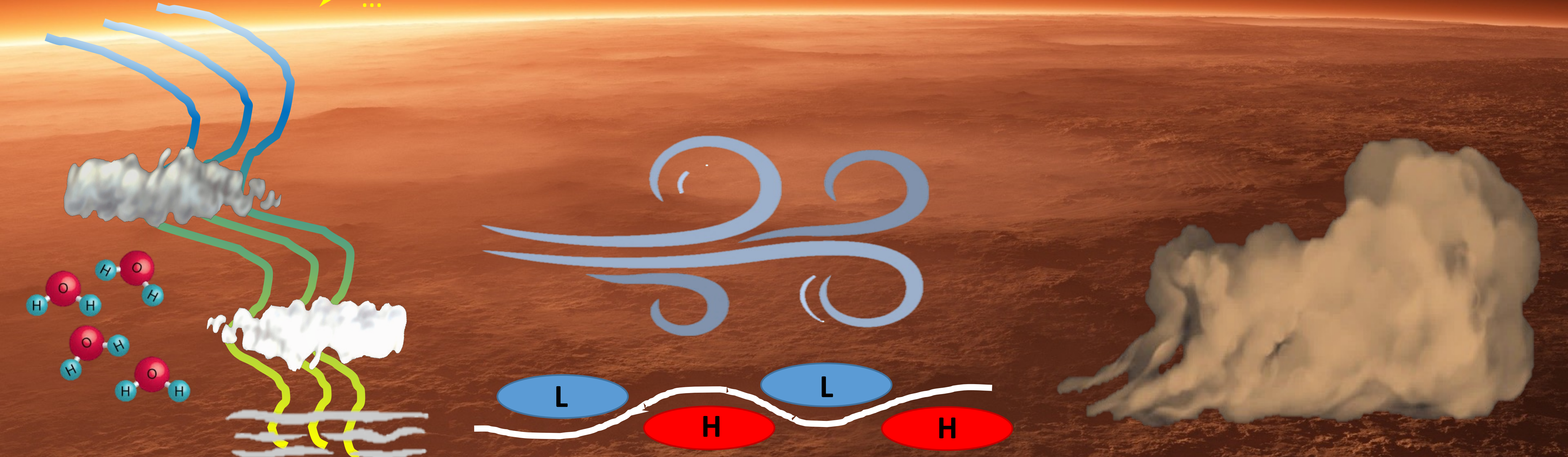
Mars Exploration Program (MEPAG) Timeline



Science Measurements

- Ionosphere / Magnetosphere / Solar wind interaction
- Aerosol (dust, H_2O ice, CO_2 ice) distributions
- Atmospheric and surface temperatures
- Atmospheric wind components
- Water vapor distribution
- Surface pressure
- …





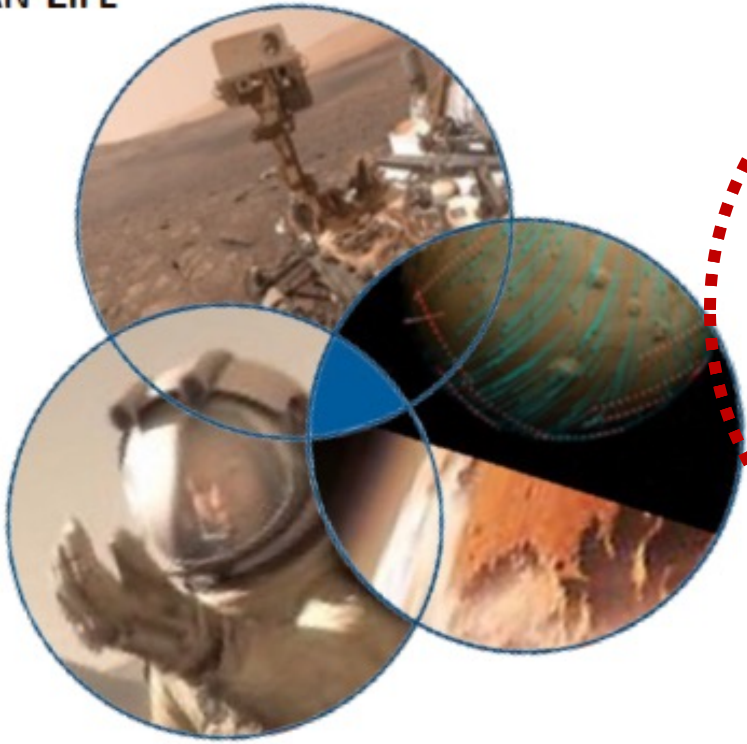
Montabone et al. 2022

High-Level Co-Equal Program Science Themes, 2023 - 2043

Driven by science, MEP will focus its systemic approach on the following science themes, **which draw upon the MEPAG** goals of life, climate, geology and preparation for human exploration.

Explore the Potential for Martian Life

Advance the search for past and present microbial life and habitable environments through time, while developing approaches that protect both Mars and Earth.



Discover Dynamic Mars

Understand the dynamic geological and climatological processes on Mars to illuminate the evolution of the Martian system, our home planet Earth, our solar system, and distant planets around other stars.

Support Human Exploration of Mars

Make observations that are synergistic with the objectives for human exploration of Mars and prepare for the science that humans will do once there.

SECTION 2
SCIENCE THEMES

DRAFT

EXPLORING MARS TOGETHER 2023 - 2043

SECTION 3

INITIATIVES FOR THE NEXT TWO DECADES

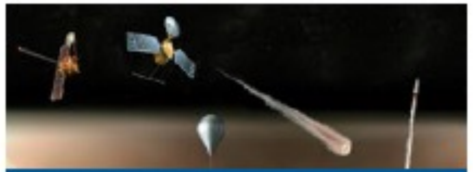
DRAFT

EXPLORING MARS TOGETHER 2023 - 2043

Program Initiatives for the Future of MEP

INITIATIVE 1

EXPAND OPPORTUNITIES TO EXPLORE MARS THROUGH COMPETED, LOWER-COST, MORE FREQUENT FLIGHT OPPORTUNITIES



INITIATIVE 2

STRENGTHEN AND BROADEN INFRASTRUCTURE AT MARS TO ENABLE A DIVERSE SET OF MISSIONS & NEW OPPORTUNITIES FOR PARTNERSHIPS

INITIATIVE 3

INVEST IN KEY TECHNOLOGIES TO ENABLE EXPANDED ACCESS TO, AND SCIENTIFIC UNDERSTANDING OF, MARS

INITIATIVE 4

ENABLE PARTICIPATION IN MARS EXPLORATION FOR ALL COMMUNITIES

Mars Architecture Strategy Working Group (MASWG)
&
Mars Concurrent Exploration Science Analysis Group (MCE-SAG)

Objective: define highest priority science questions, in parallel to MSR

Output recommendation:
Networks of low-cost missions working together
to address **major out standing Mars questions**, Dynamic Mars, imaging needs, mission classes, competed and low-cost missions

Announcements of Opportunity coming soon!
No specific missions / instruments pre-defined, call shall address one or more tracks

Expertos en Alta Atmósfera,
Espectrometría en MEX/TGO,
Modelado de atmósferas

GRACIAS

Expertos en Dinámica,
Cámaras MEX/MRO
Sensores Meteorológicos
M2020/MSL/Insight

Estaciones Meteorológicas
M2020/MSL/Insight

Operaciones
Científicas
MEX/TGO

Ionosfera y
Magnetosfera

Modelado
atmósferico

Modelado y detección
de Polvo

Sensores de Polvo y
Radiación y Magnetismo,
M2020/ExoMars

Some slides courtesy of ESA, NASA, L.Montabone, …

Image Credit HRSC Mars Express

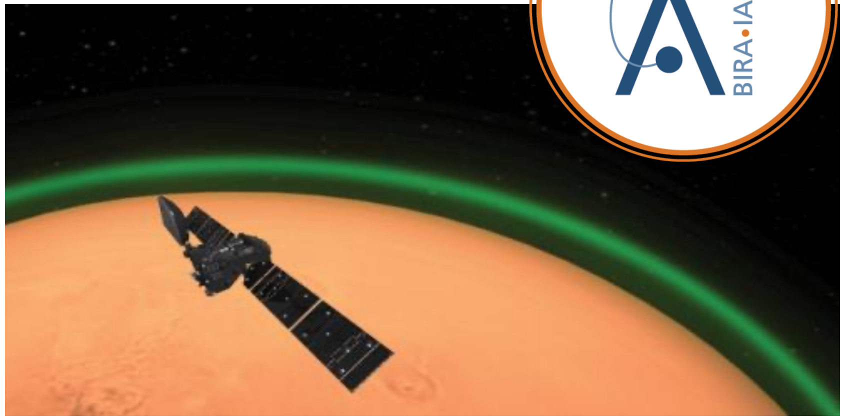
UV-VIS imager

Continuous & quasi-global monitoring

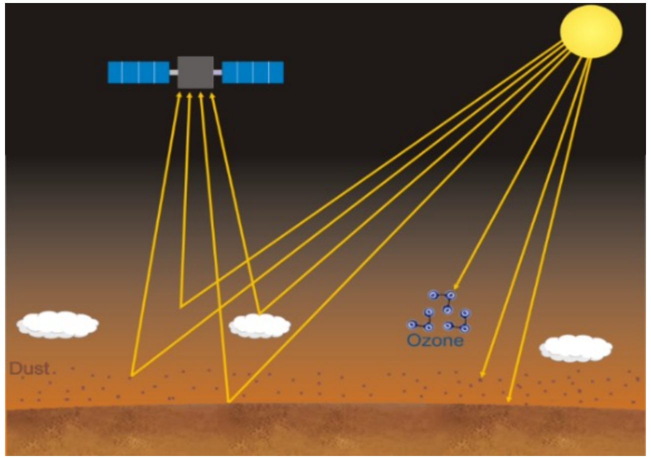
- Dust
- ice cloud aerosols
- O_3

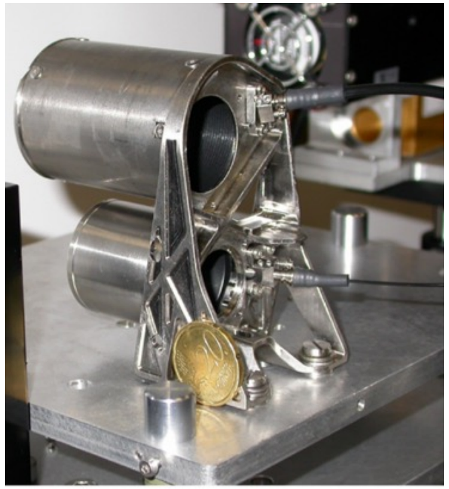
Viewing geometry: Nadir (off-axis)

Heritage from NOMAD on EMTGO



Gérard et al., Nat. Astron. 4 (2020) 1049-1052



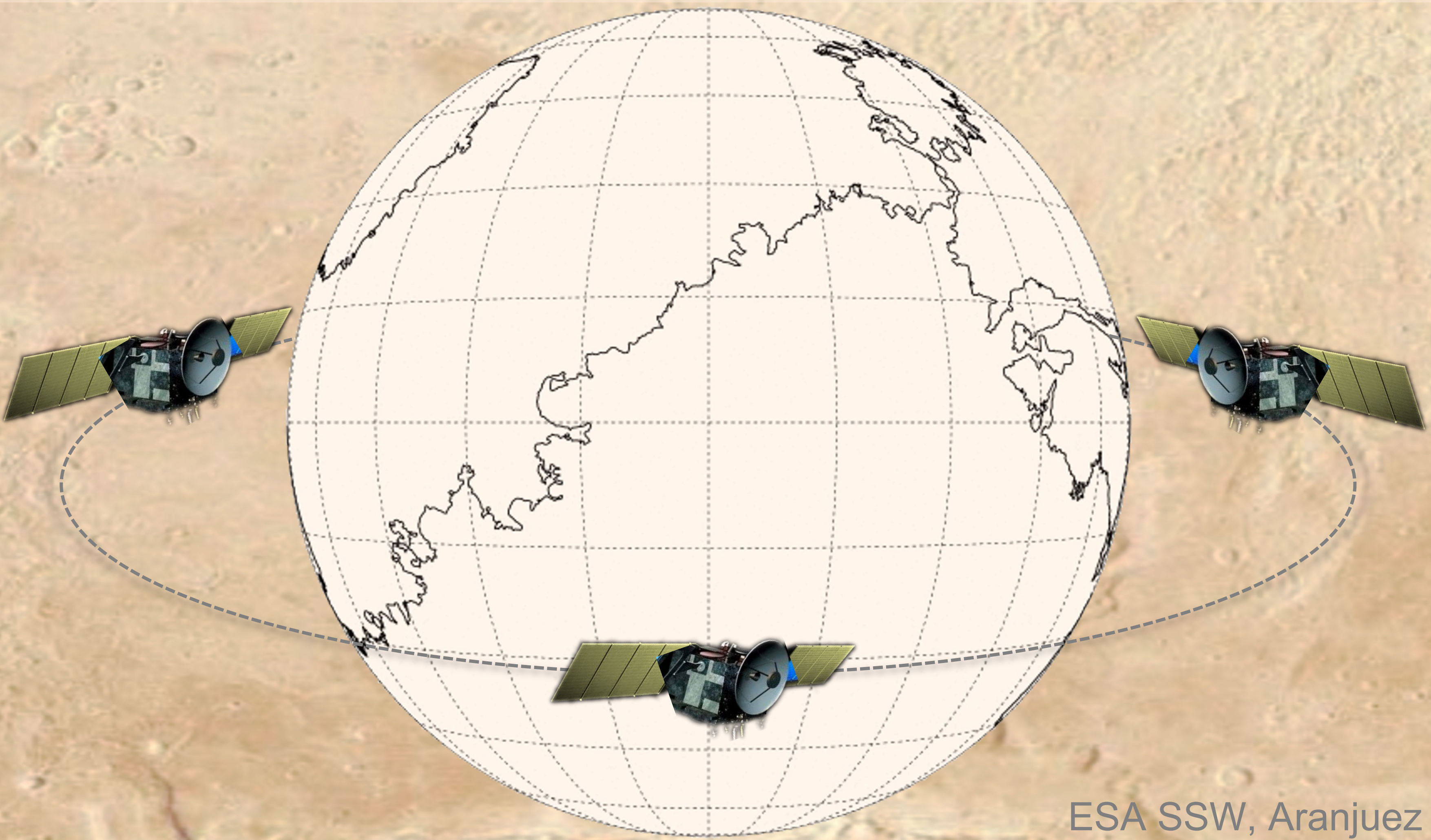


Requirements have been established.

The feasibility study is ongoing to develop small payload.

Mars Smallsat Mission & Instrumentation Studies for Global Meteorology & Space Weather Monitoring

A. Cardesin-Moinelo, L. Montabone + international science consortium



A Paradigm Shift in Mars Meteorology:
Towards Monitoring and Forecasting with Areostationary SmallSats

Luca Montabone, Michel Capderou, Alejandro Cardesin-Moinelo, Lorenzo Feruglio, François Forget, Sandrine Guerlet, Nicholas Heavens, Robert Lillis, Ehouarn Millour, Claire Parfitt, Francesco Topputo, Sanjay Vijendran, and Roland Young

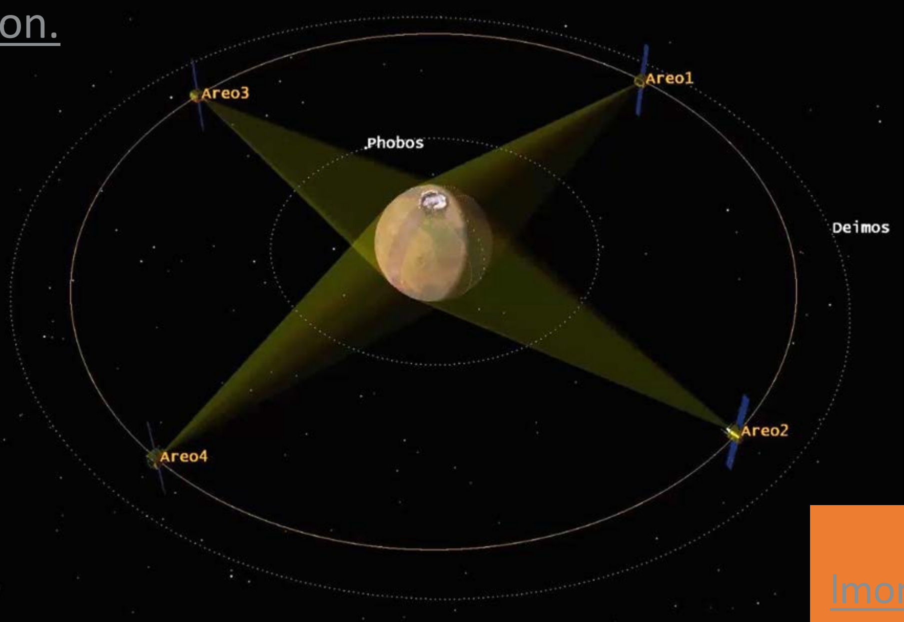
A poster presentation for EPSC 2021

EPSC abstract, Vol. 15, EPSC2021-625

The significance of diurnal meteorological variability at Mars argues for orbital observations that span the diurnal cycle. The rapid dynamics of meteorological phenomena such as dust storms and water/CO2 ice clouds, together with their spatial extension and duration/repeatability, argue for continuous and simultaneous observations across the planet. As it happened for the study of meteorology on Earth in the 1970s, now is the right time to introduce monitoring to the observation paradigm for the martian atmosphere, so far almost exclusively focused on mapping. Quasi-global monitoring (except the polar regions) can be achieved by a constellation of areostationary platforms, i.e. satellites in equatorial, circular orbits in which the orbital period of the satellite matches the rotational period of Mars. We present an orbital mission concept with the rationale to close knowledge gaps in preparation for future human exploration.

Areostationary Orbit Key Characteristics

- Planet-synchronous (T = one sidereal day)
- Circular (radius: 20,428 km)
- Equatorial
- Stationary footprints
- 4 equilibrium points, 2 stable (17.92°W, 167.83°E)
  2 unstable (75.34°E, 105.55°W)
- ± 80.4° latitude coverage (nominal)



Click on the figure for an animation by R. C. Woolley (JPL/Caltech)

Contact:
lmontabone@spacescience.org

SPP Mother/Daughter SC guidelines (F-Mission Technical Annex II)

Potential target orbit from SEL2	Max. distance to Sun	Indicative number of daughtercraft (constrained for mass and/or cost reasons)	Indicative Science Payload Mass allocation and distribution	Science Payload Maximum Power in the daughtercraft	Remark
Venus	<1.1 AU	2	4-8 kg in Mothercraft 6-8 kg per daughter	~90W	Assumes high impulse (~3600 s) electrical propulsion system. S/C design assumptions to be confirmed by dedicated study.
Mars	<1.67 AU	2-3	4-8 kg in Mothercraft 6-8 kg per daughter	~40W	Assumes high impulse (~3600 s) electrical propulsion system. S/C design assumptions to be confirmed by dedicated study.
Phobos	<1.67 AU	0-2	4-8 kg in Mothercraft 6-8 kg per daughter	~40W	Assumes high impulse (~3600 s) electrical propulsion system. S/C design assumptions to be confirmed by dedicated study.
L2	~1 AU	3	~50 kg in Mothercraft 6-8 kg per daughter	~90W	Overall payload mass is a cost/schedule driver
Heading/trailing heliocentric orbits and Sun-Earth L4/L5	<1.2 AU short transfer, <1.1 AU long transfer	4	4-8 kg in Mothercraft 6-8 kg per daughter	~90W	Long transfer reduces DV, adds +1 year. No Moon-Earth gravity assist assumed to leave L2. S/C design assumptions to be confirmed by dedicated study.
Moon orbit	~ 1 AU	4	4-8 kg in Mothercraft 6-8 kg per daughter	~90W	1500x60000 km capture orbit, then reduction to 300 km LLO considered. S/C design assumptions to be confirmed by dedicated study.
HEO	1 AU	4	4-8 kg in Mothercraft 6-8 kg per daughter	~90W	S/C design assumptions to be confirmed by dedicated study.

SPP Mother/Daughter SC guidelines (F-Mission Technical Annex I)

Potential target orbit from SEL2	Max. distance to Sun	Indicative number of daughtercraft (constrained for mass and/or cost reasons)	Indicative Science Payload Mass allocation and distribution	Science Payload Maximum Power in the daughtercraft	Remark
Main asteroid belt (inner ring)	<2.5 AU	2	Total P/L mass typically 20-25 kg e.g. 4-8 kg on Mothercraft, and 6-8 kg per daughter	~ 20 W	Overall mass highly constrained by the DV. Mass figures assume high impulse electrical propulsion for the Mothercraft (3600 s); A small surface package could also be considered, subject to mass compatibility (see also 4.3.3). Power constrained by distance to the Sun.
Near Earth Object	<1.5 AU	2-4	Total P/L mass typically 30-40 kg, e.g. 4-8 kg in Mothercraft and 6-8kg per daughter	~90 W	A small surface package could replace one of the daughtercraft (see also 4.3.3)
Multi target for Near Earth Object up to 3km/s	<1.5 AU	2-3 (one of which is assumed "explorer" to the second target)	Total P/L mass typically 20-25 kg e.g. 4-8 kg in Mothercraft ~ 6 kg per daughter	~90 W	P/L mass assumes 3 daughtercraft, one of which is exploring a second target. The explorer daughter needs 7-8 kg extra mass for the electric propulsion (DV < 1 km/s) and for enabling the communication with the mothercraft (staying at the first target). Other concepts/combinations are possible, e.g. 2 daughtercraft only, but both visiting the second target.
Multi target for Near Earth Object up to 5km/s	<1.5 AU	2 (one of which is an "explorer" to the second target)	Total P/L mass typically < 20 kg e.g. 4-8 kg in Mothercraft ~ 6 kg per daughter	~90 W	Comparable to previous case, with higher mass constraint induced by the DV to reach the first target.