Crew-robot complementarity in missions

Scale effects: structural observability & controllability

САМАРСКИЙ УНИВЕРСИТЕТ
SAMARA UNIVERSITY

Future Space Technologies and Experimentsin Space
Samara University
Russian Academy of Cosmonautics
The International Summer Space School

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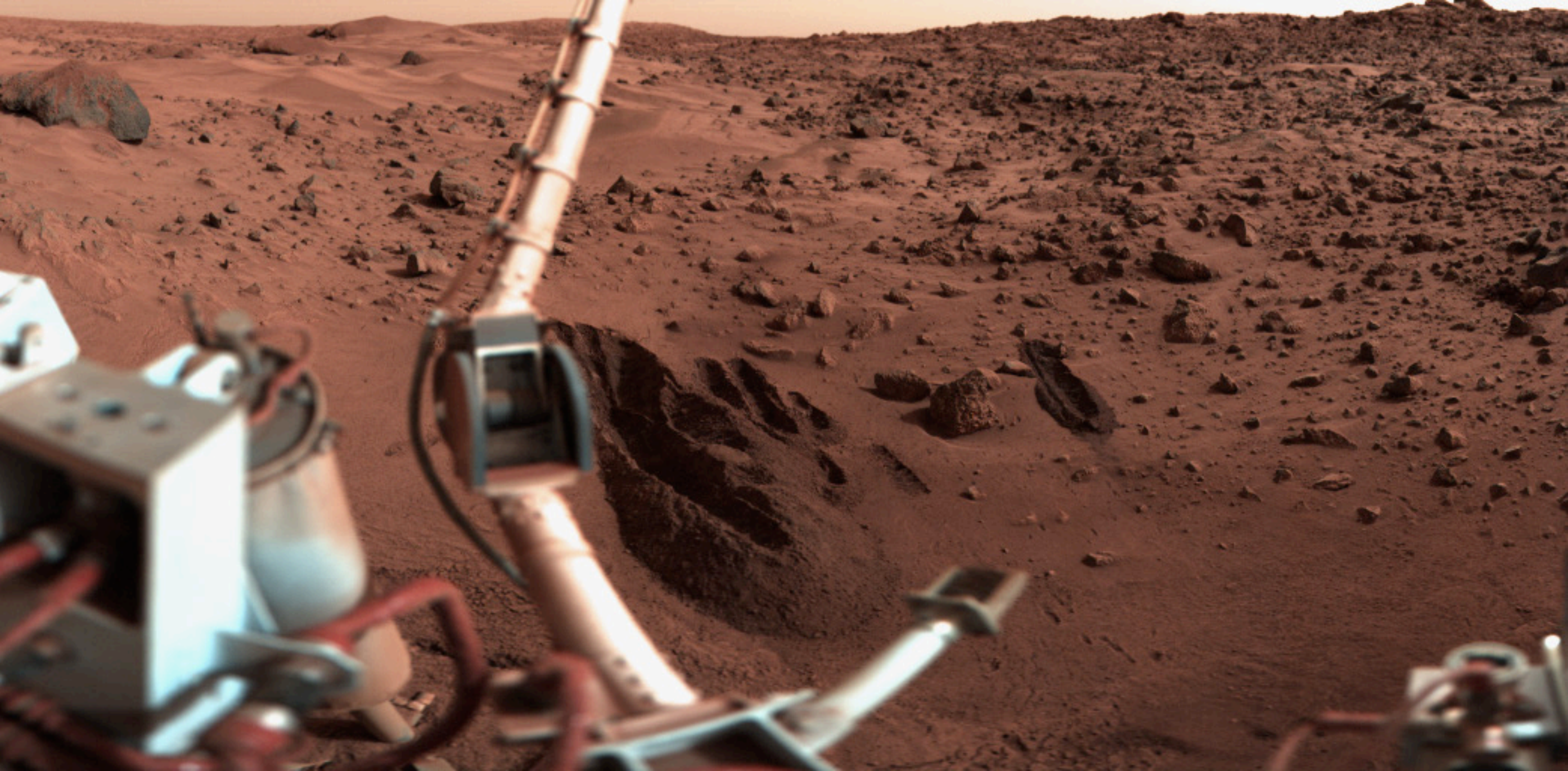
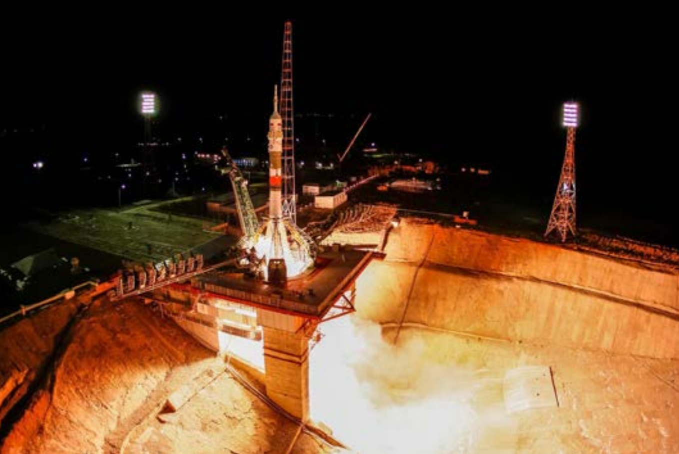
Institut Supérieur de l'Aéronautique et de l'Espace
SUPAERO

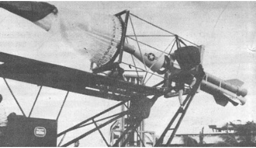
Pr.Yves Gourinat

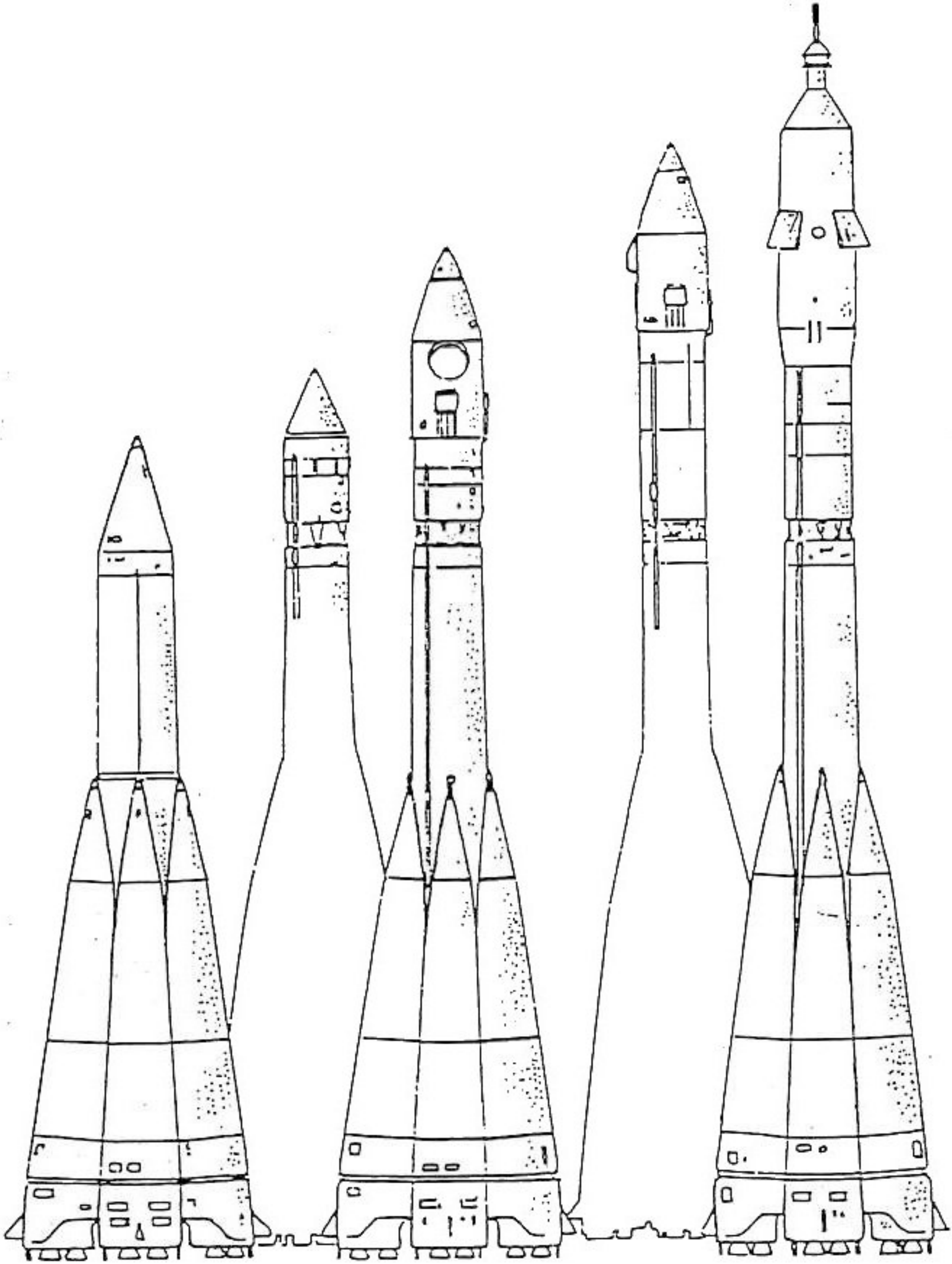
SUPAERO - Université de Toulouse

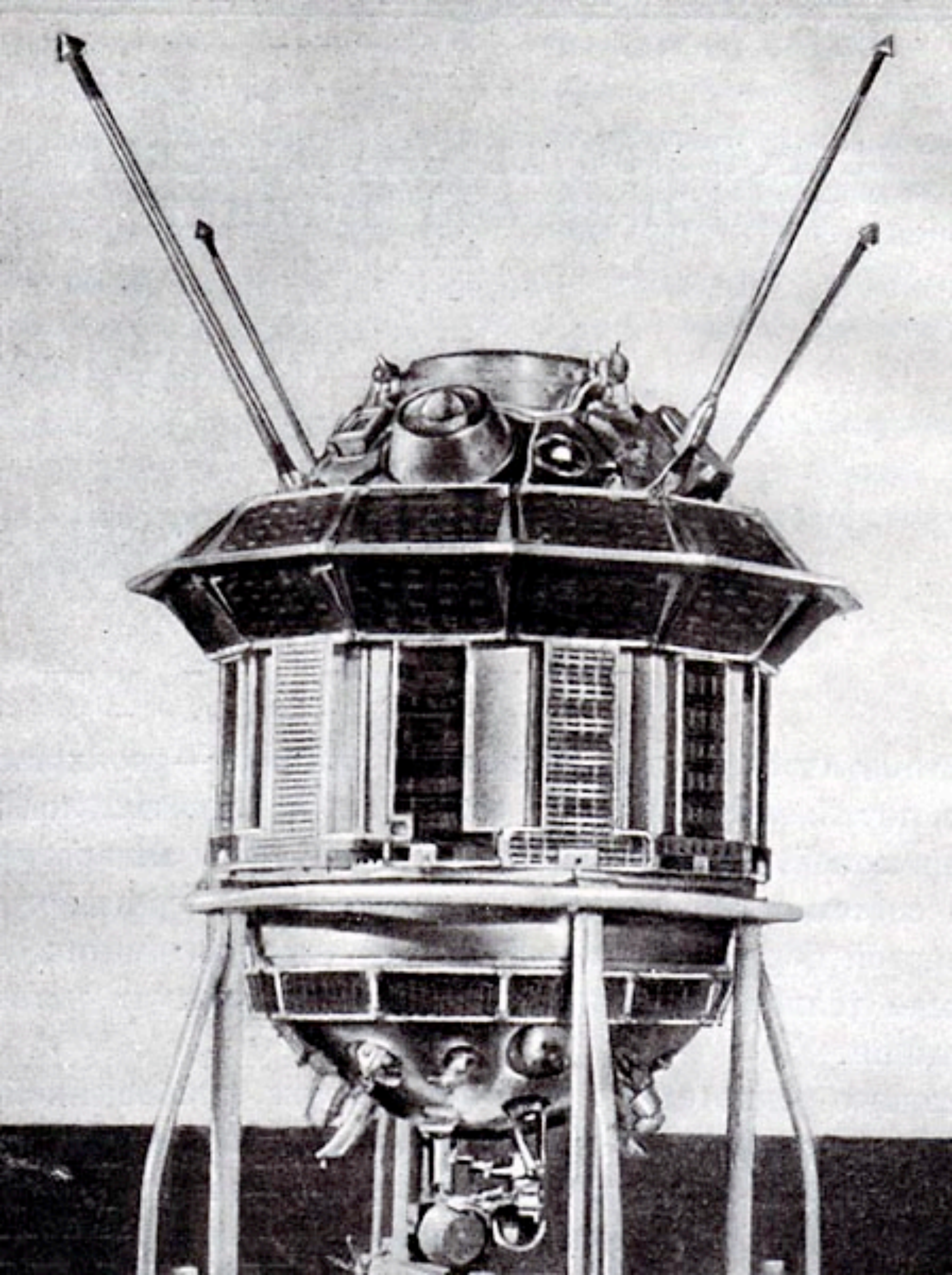
August 31st 2021

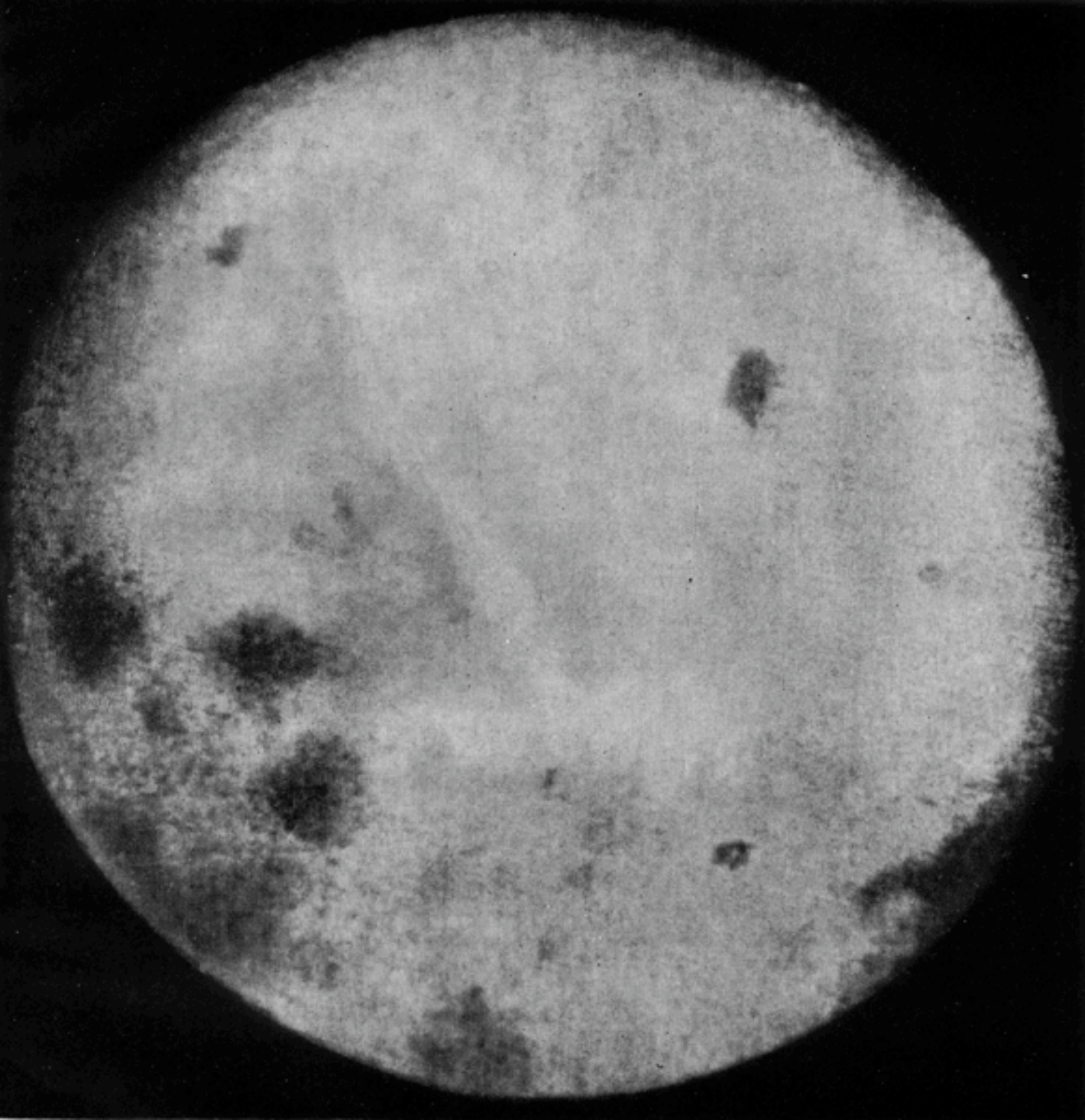


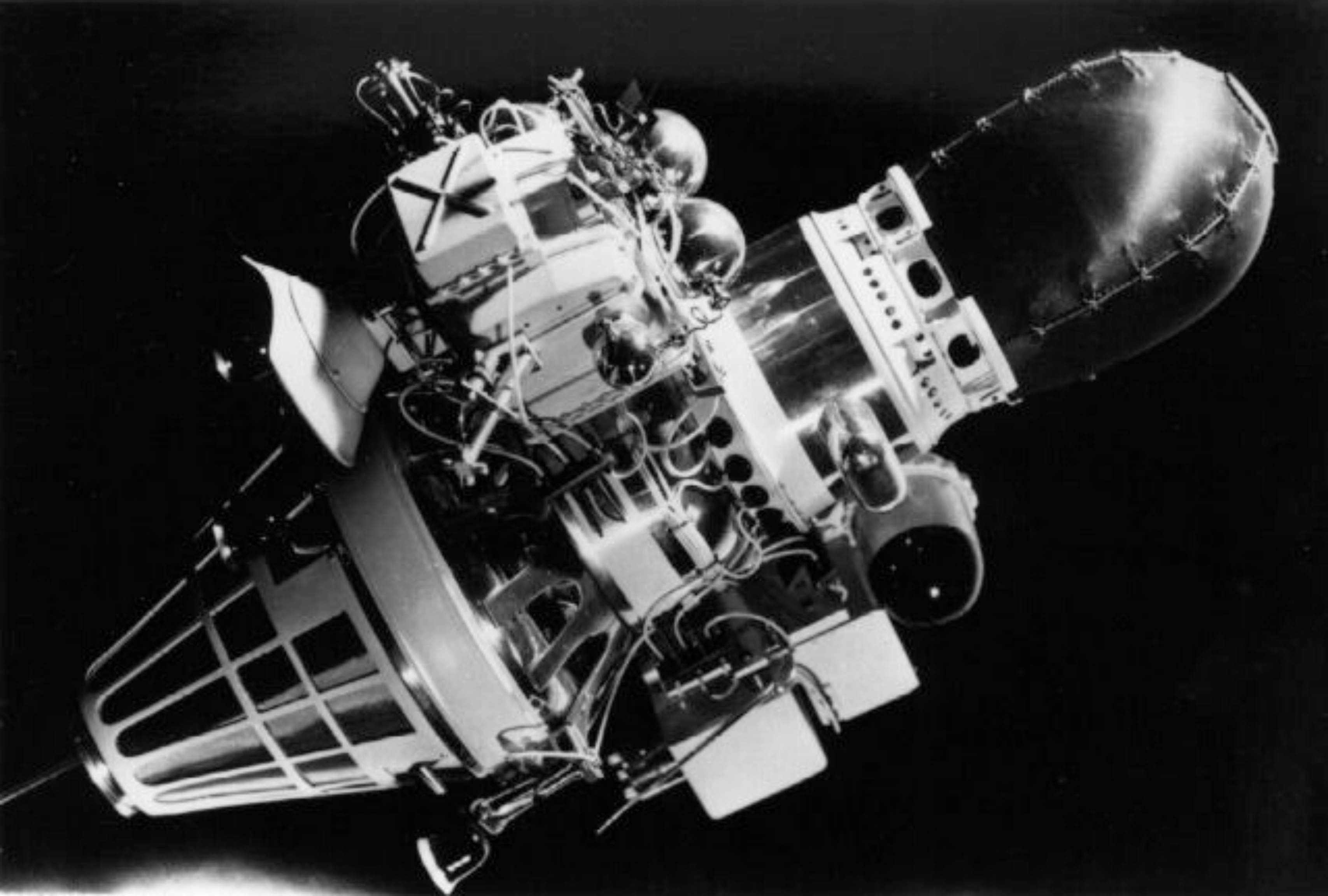


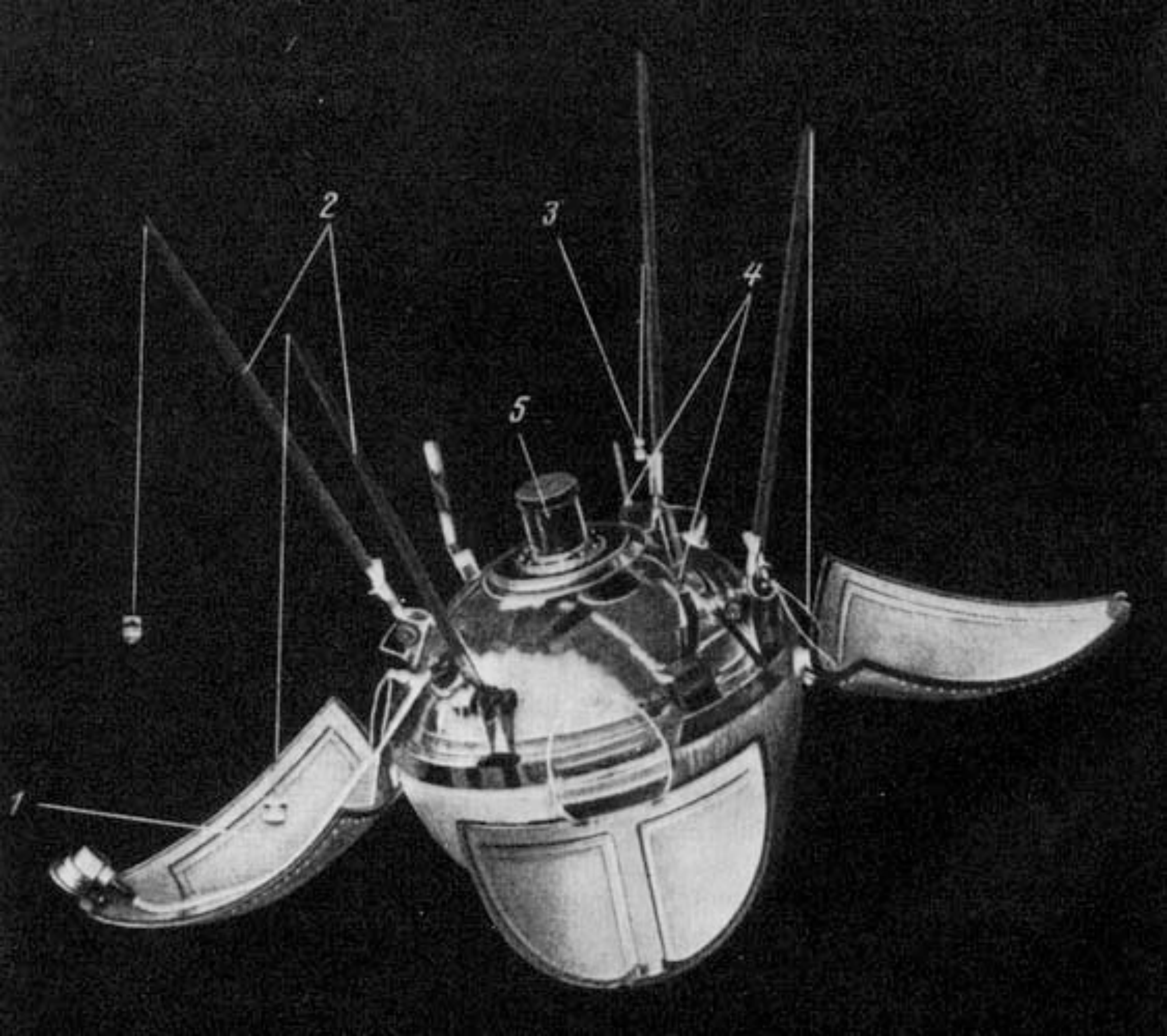








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BELYAYEV, PAVEL I.
CHAFFEE, ROGER B.
DOBROVOLSKY, GEORGI T.
FREEMAN, THEODORE C.
GAGARIN, YURI A.
GIVENS, EDWARD G. Jr.
GRISSOM, VIRGIL I.
KOMAROV, VLADIMIR M.
PATSAYEV, VIKTOR I.
SEE, ELLIOT M. Jr.
VOLKOV, VLADISLAV N.
WHITE, EDWARD H. II
WILLIAMS, CLIFTON C. Jr.


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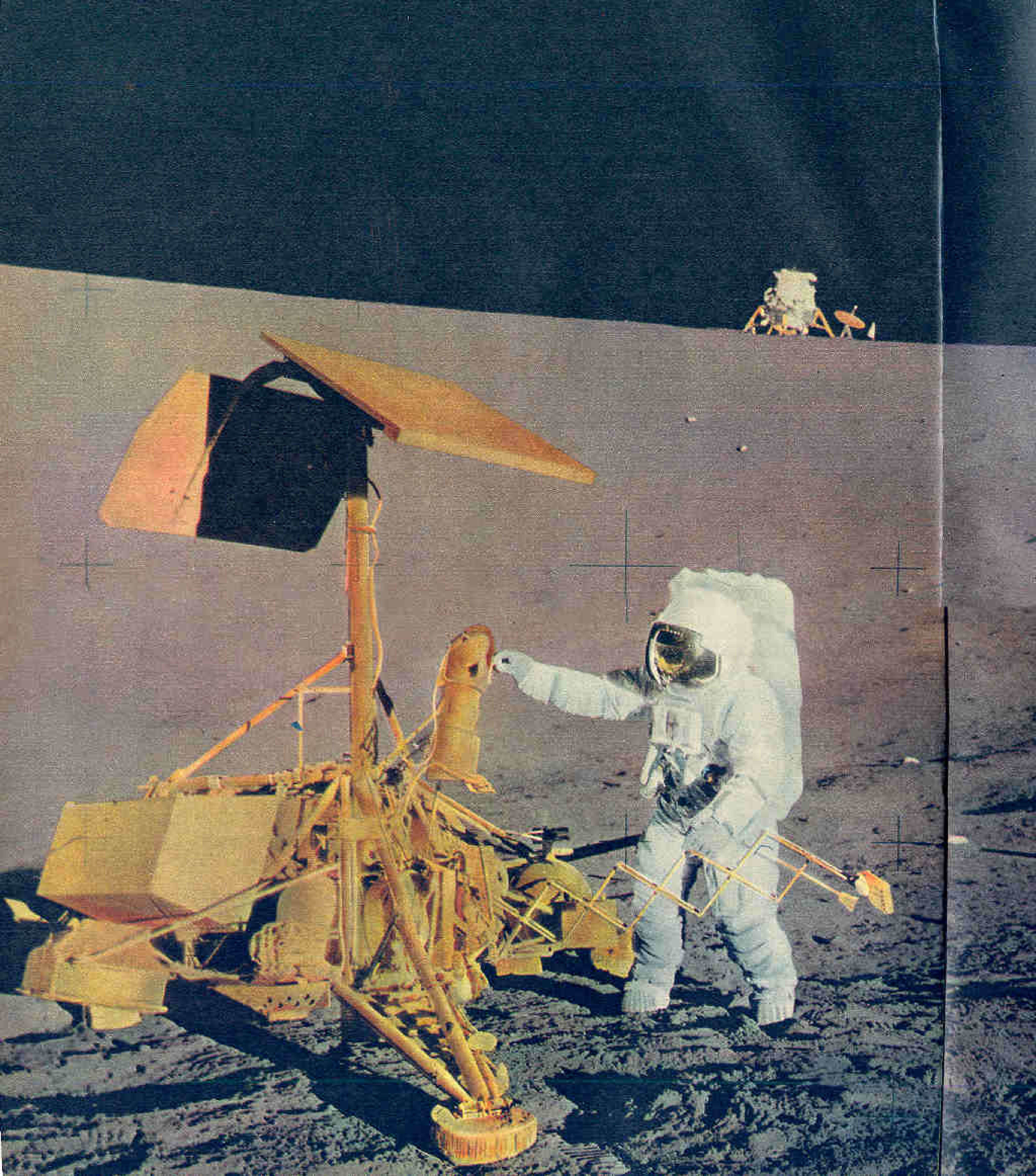
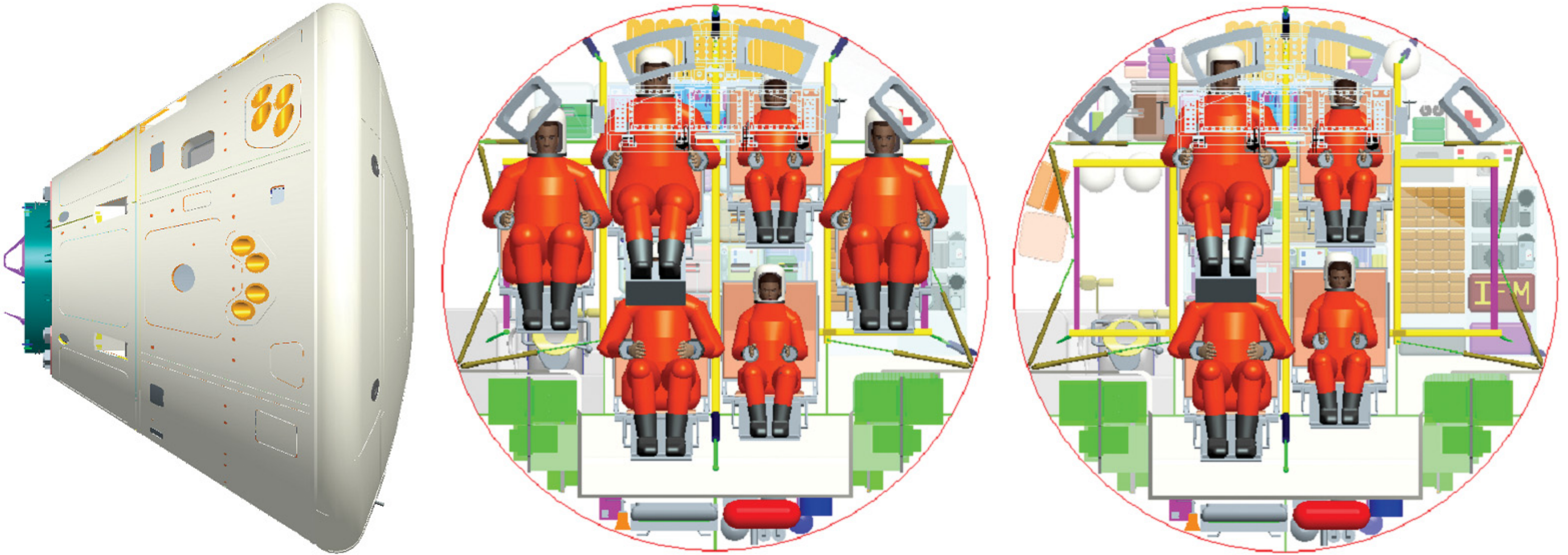
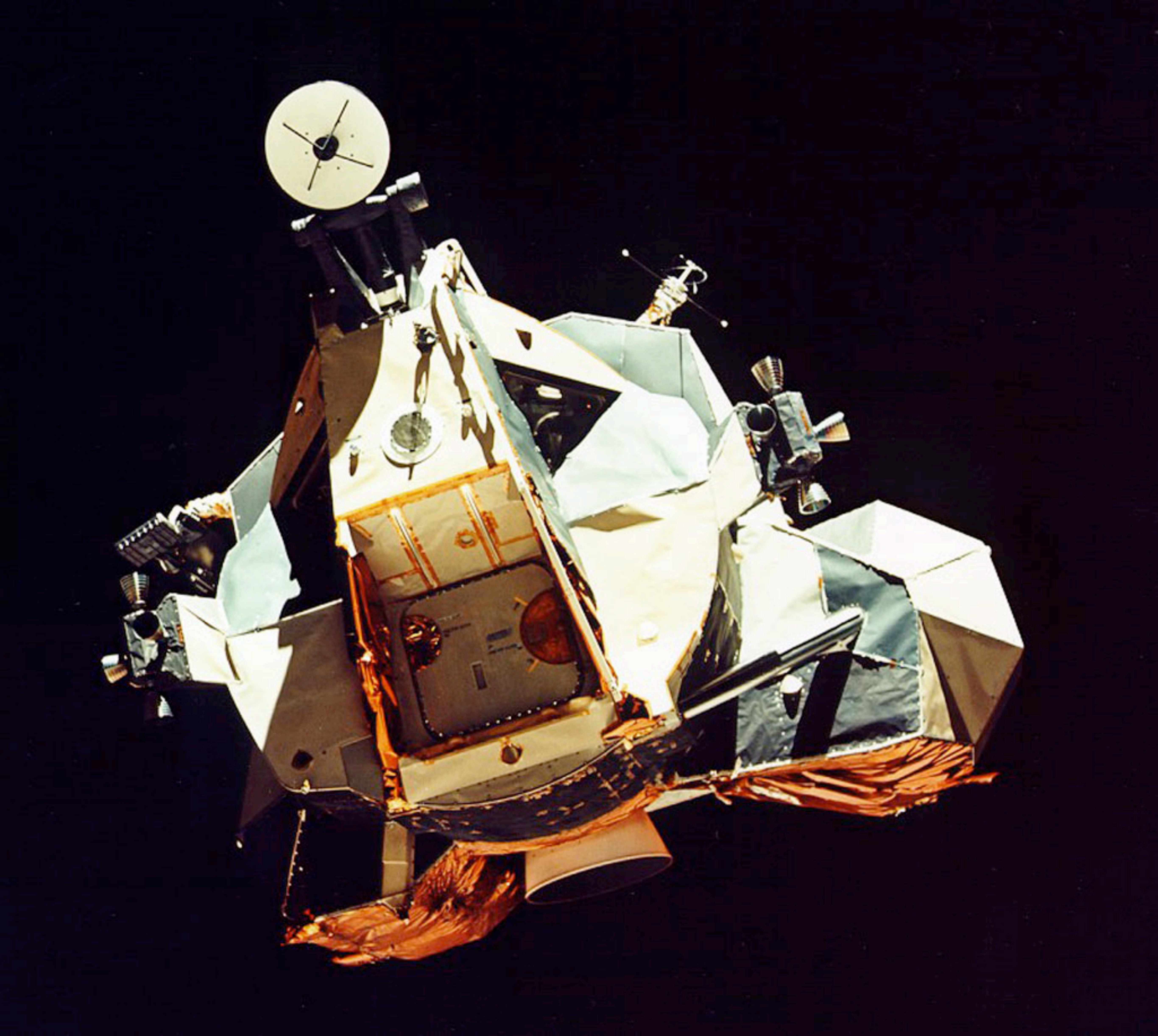



esa

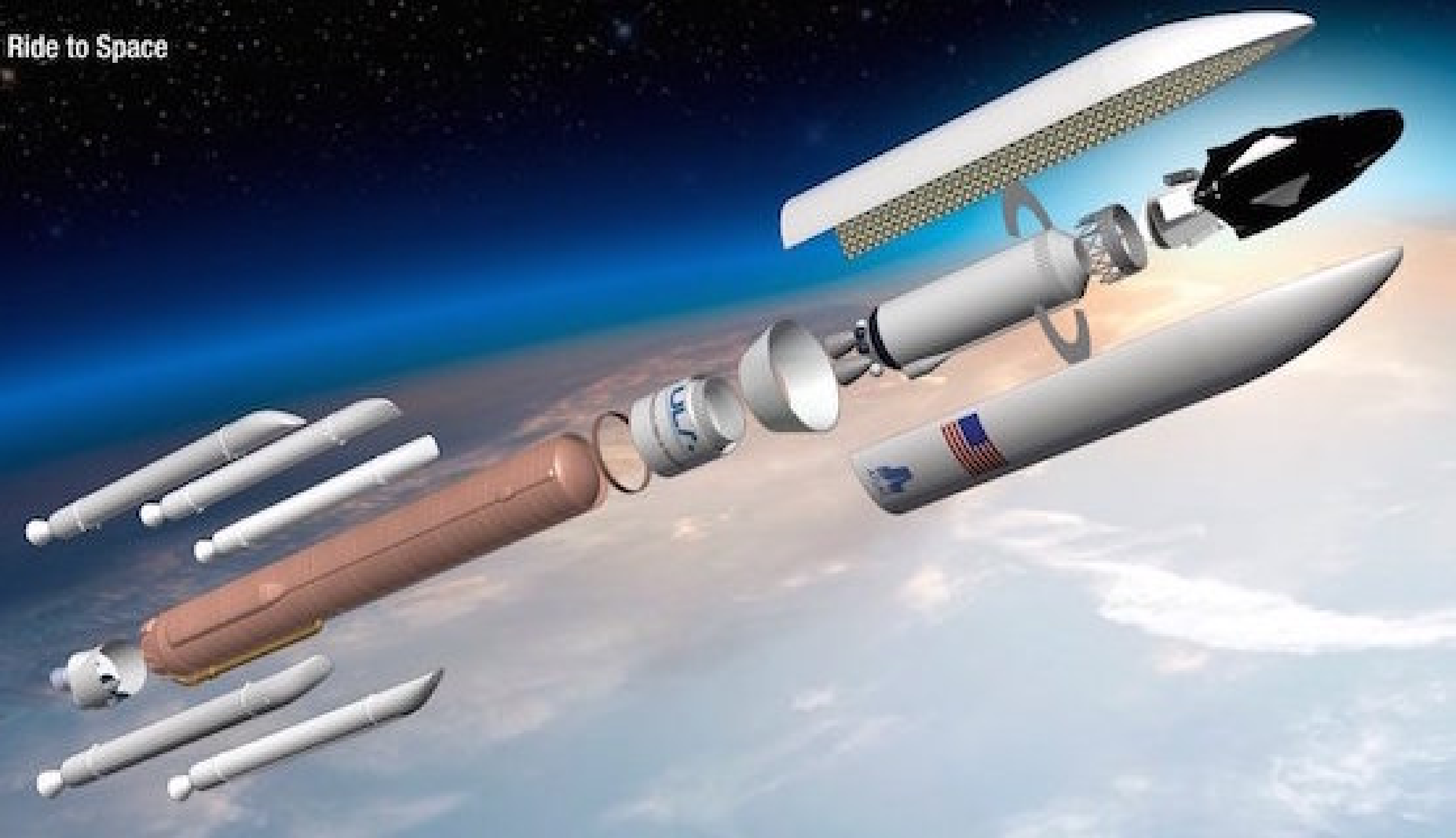





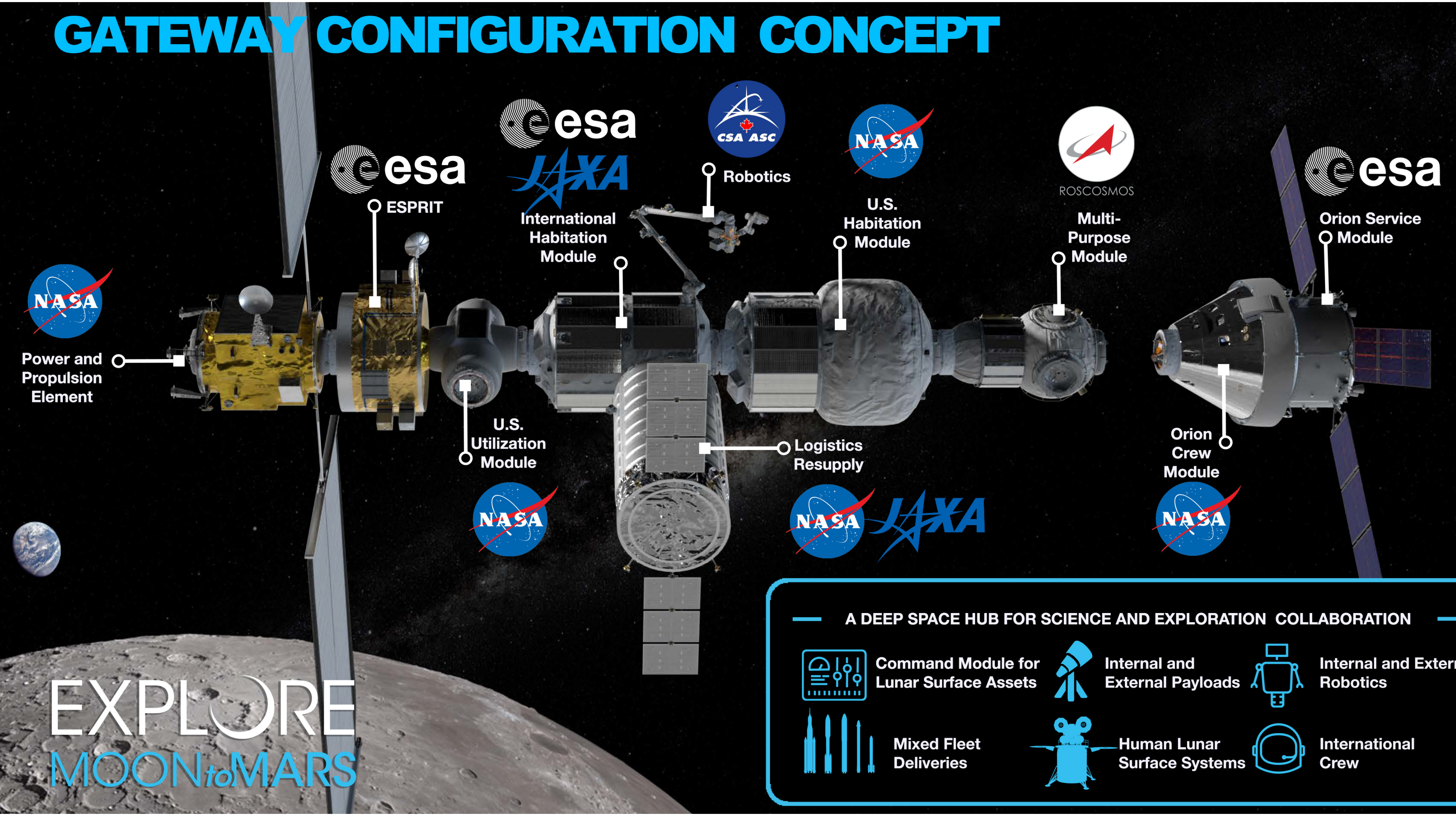

Virgin
N348MS
N202VG
Virgin
Virgin
N348MS
V1RG1N GALACTIC

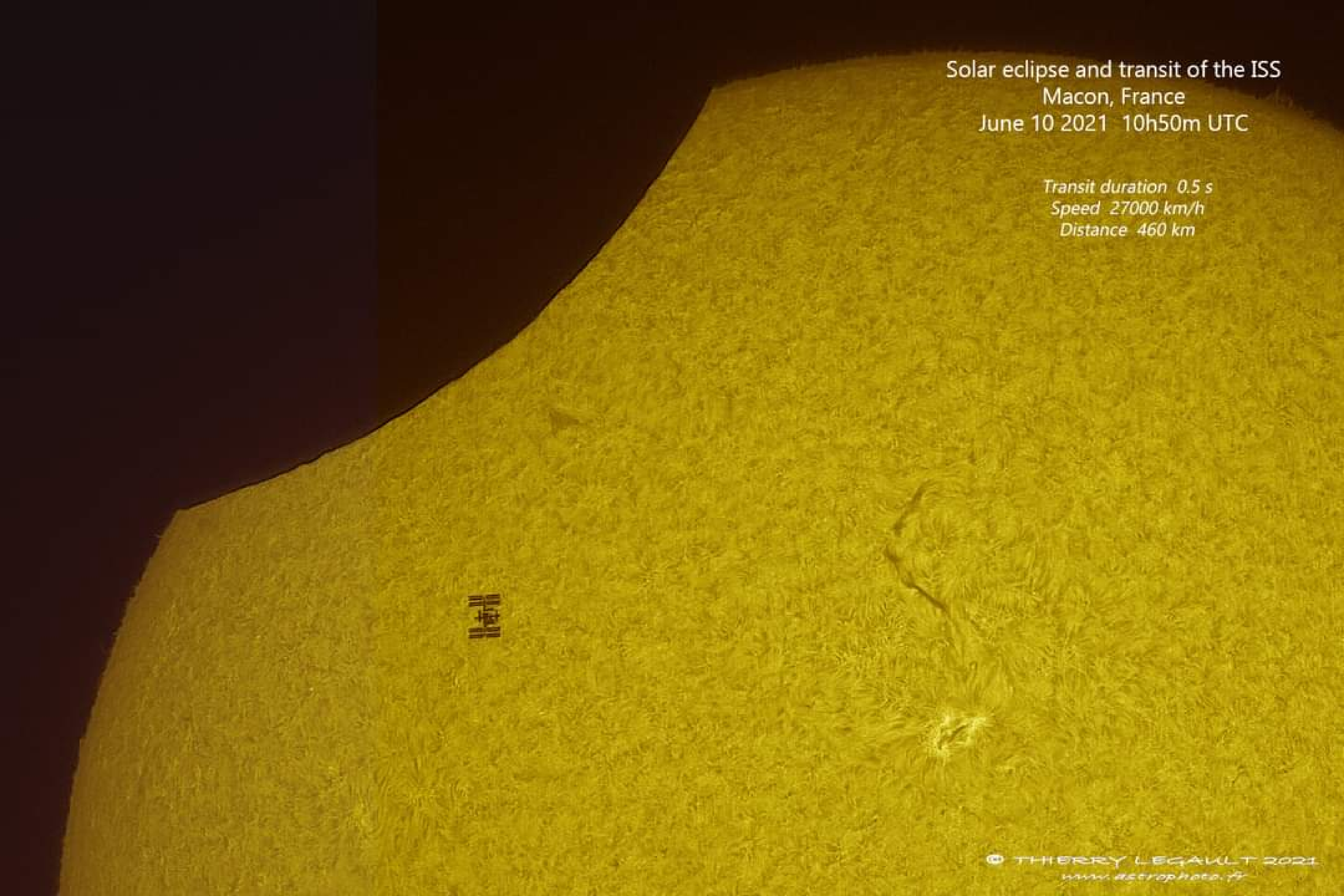

esa
ThalesAlenia
APCO


SNC
Dream Chaser


Ride to Space

- *Contemporary astronautical strategical chronologies*



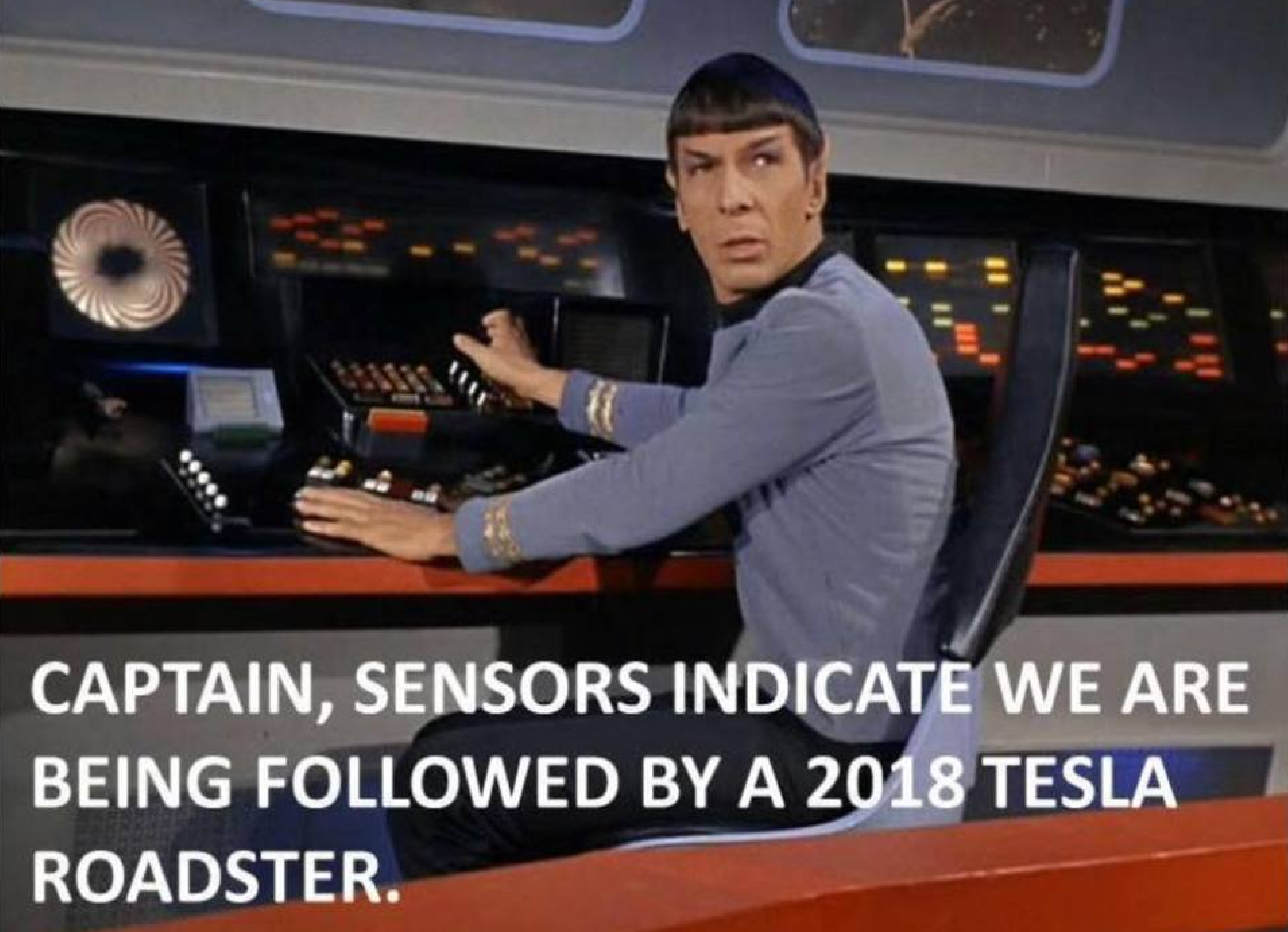

Solar eclipse and transit of the ISS
Macon, France
June 10 2021 10h50m UTC
Transit duration 0.5 s
Speed 27000 km/h
Distance 460 km
© THIERRY LEGAULT 2021
www.astrophoto.fr

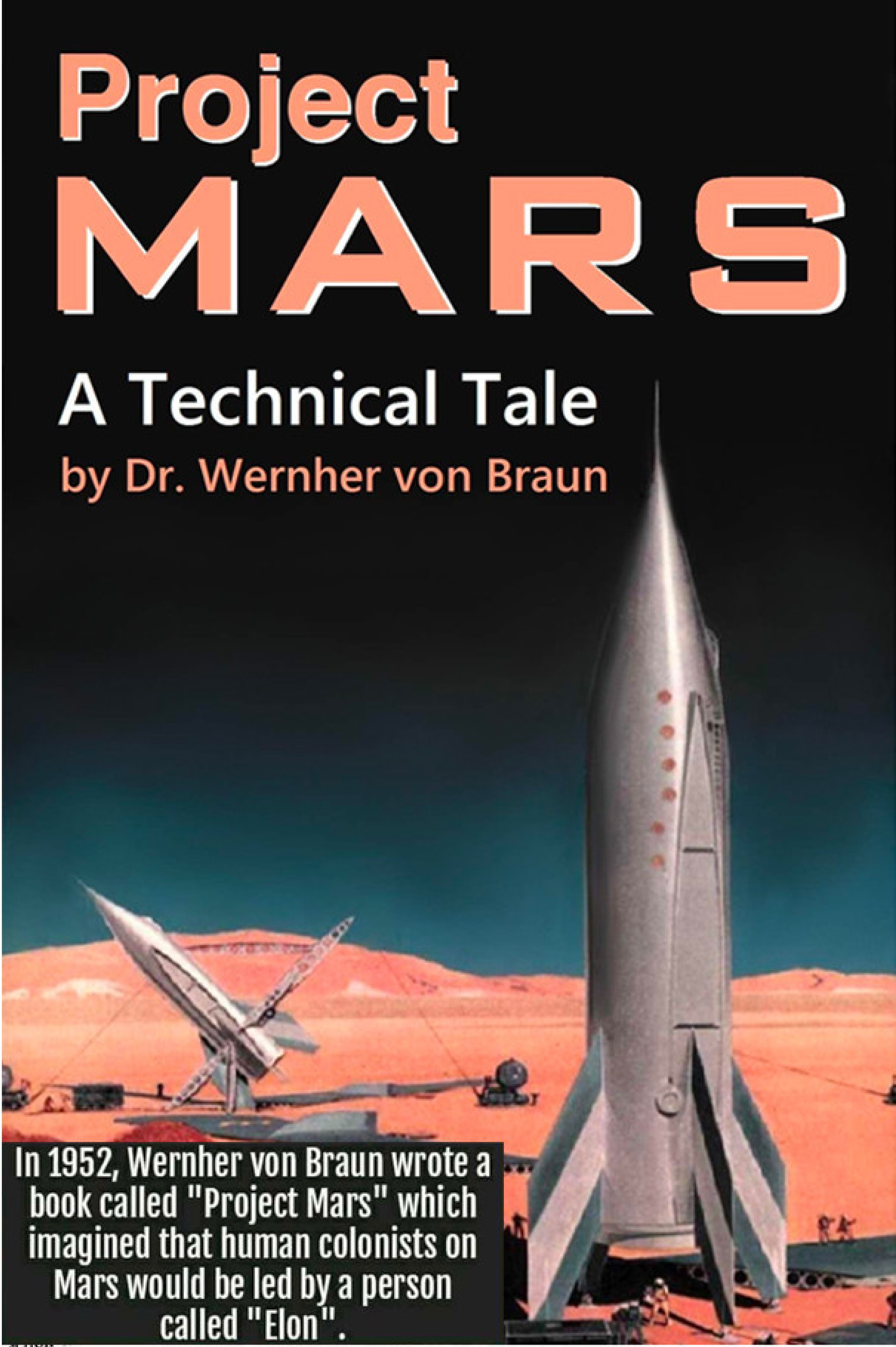

SOLARSTRATOS


FELIX BAUMGARTNER
ZENITH


NO MATTER WHERE YOU ARE
THERE'S ALWAYS A BMW TRYING
TO OVERTAKE
AC AC 3400

Disclose.tv
YOUR UBER DRIVER WILL
ARRIVE IN 6 MONTHS


CAPTAIN, SENSORS INDICATE WE ARE BEING FOLLOWED BY A 2018 TESLA ROADSTER.

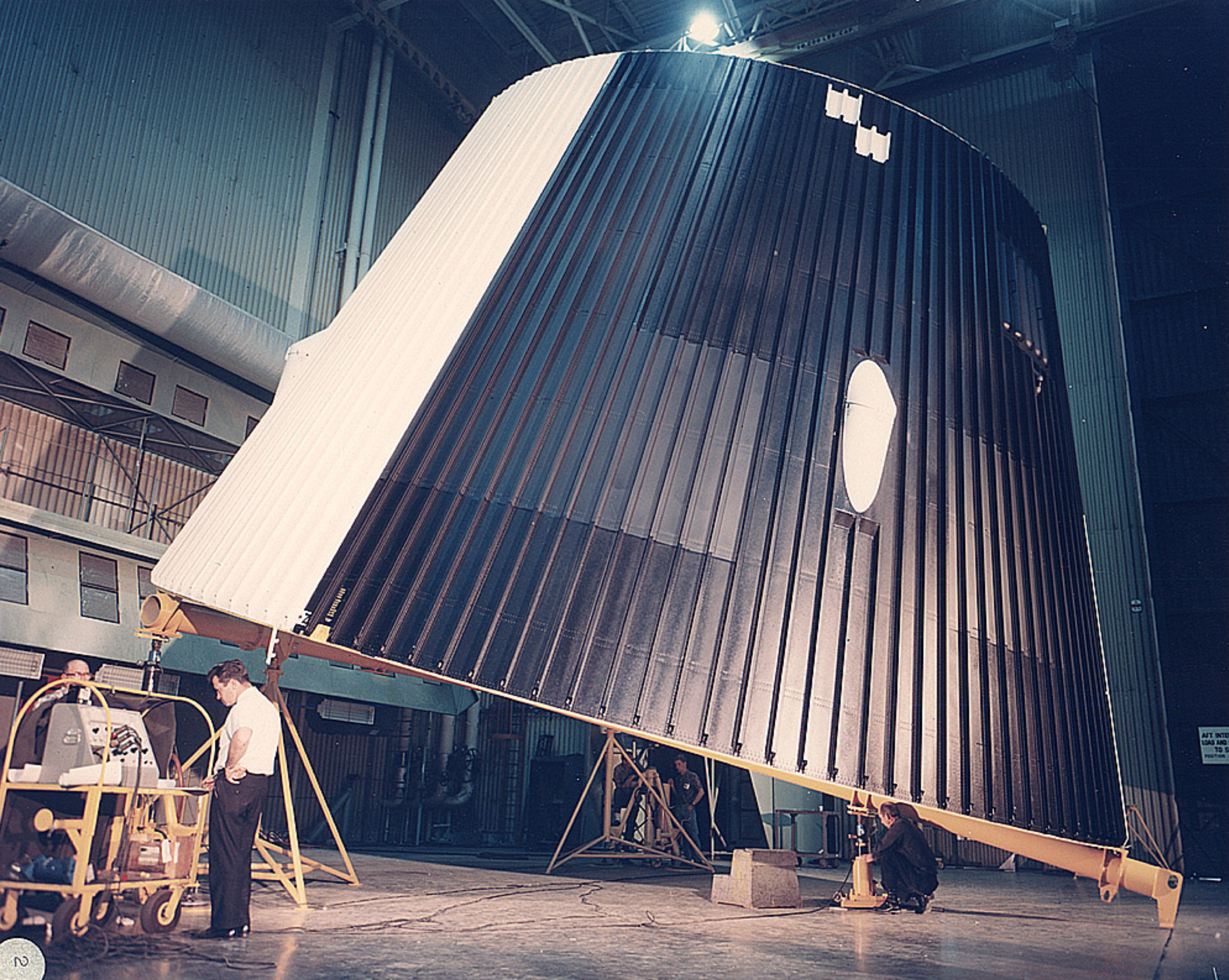

Project
MARS
A Technical Tale
by Dr. Wernher von Braun
In 1952, Wernher von Braun wrote a book called "Project Mars" which imagined that human colonists on Mars would be led by a person called "Elon".

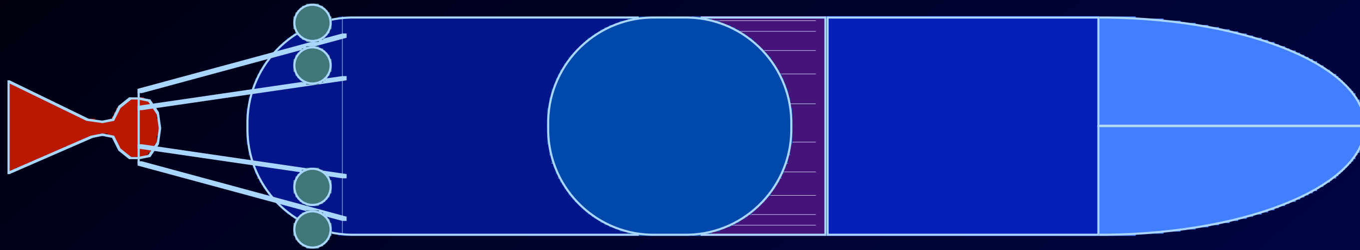
mit jener inneren Verpflichtung zur Tat verbunden war, die auch die treibende Kraft in der Entwicklung der Marszivilisation gewesen war.

Die Regierung des Mars bestand aus zehn Maennern. An ihrer Spitze stand ein von der Gesamtbevoelkerung fuer jeweils fuenf Jahre erwaehlter Mann, den die Martianer den "Elon" nannten. Dem Elon und seinem Kabinett aber stand ein Parlament gegenueber, das die Gesetze beschloss, nach denen das Kabinett zu regieren hatte,

Das Marsparlament hatte zwei Haeuser.

Das Oberhaus nannte sich der "Rat der Alten". Sein Umfang war auf sechzig Personen beschraenkt, die von dem jeweils amtierenden "Elon" auf Lebenszeit berufen wurden, sobald ein bisheriges Mitglied verstorben war, Das hier angewandte Prinzip aehnelte in vieler Hinsicht der Auswahl fuer das Kardinalskollegiums der katholischen Kirche. Gewoehnlich griff der "Elon" bei diesen Berufungen auf Historiker, Kirchenfuehrer, fruehere Kabinettsmitglieder oder erfolgreiche Wirtschaftsfuehrer zurueck, die in einem langen Leben auf wichtigem Posten wertvolle Erfahrungen gesammelt hatten. Der "Rat der Alten" hatte jedoch nur eine beschraenkte Zustaendigkeit:

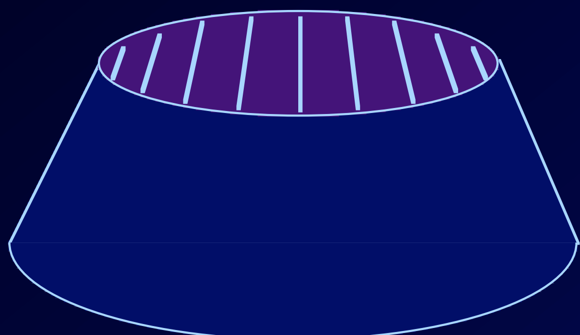


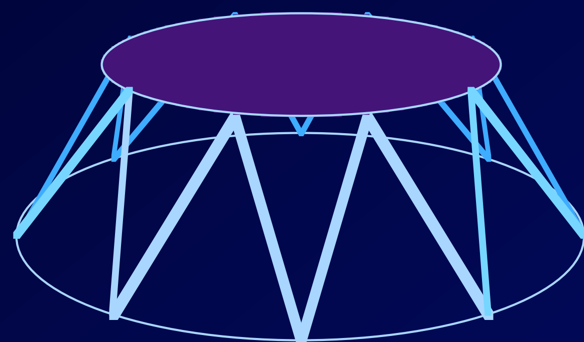


- *Réservoirs :* Ballons (membrane gonflée)

- *Structures intermédiaires :* *(inter-étages, baies de propulsion)*

Coques raidies et Treillis





- Sollicitations structurales :

-<u>Quasi-statiques</u> *(facteur de charge)* :

Longitudinal
(propulsion)

Flexion
(Aérodynamique)
(Pilotage tangage-lacet)

Torsion
(Pilotage roulis)

MODAL PROBLEMATICS WITHOUT DAMPING
(excellent approximation)

Homogeneous General Solution *(without excitation)*

$$[M]\{\ddot{q}\} + [K]\{q\} = \{0\} \quad \text{or} \quad [M_{ij}]\{\ddot{q}_j\} + [K_{ij}]\{q_j\} = \{0\}$$

Rather than direct solution, diagonalisation

M and K positive & defined (& symetrical)

$\Rightarrow$ principal base in which they are **both diagonal**

n DOF Coupled System $\Rightarrow$ n Independant 1DOF Systems

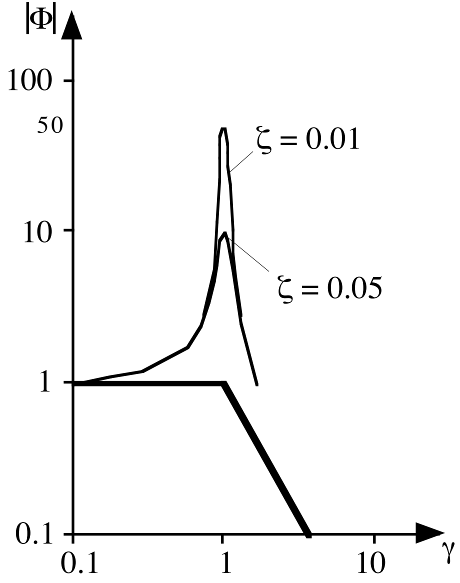
$$\begin{bmatrix} m_1 & 0 & 0 & 0 \\ & m_2 & 0 & 0 \\ & & . & 0 \\ & & & m_n \end{bmatrix} \begin{Bmatrix} \ddot{p}_1 \\ \ddot{p}_2 \\ . \\ \ddot{p}_n \end{Bmatrix} + \begin{bmatrix} k_1 & 0 & 0 & 0 \\ & k_2 & 0 & 0 \\ & & . & 0 \\ & & & k_n \end{bmatrix} \begin{Bmatrix} p_1 \\ p_2 \\ . \\ p_n \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ . \\ 0 \end{Bmatrix} \quad \text{with} \quad \{q\} = [P]\{p\} \Rightarrow \{p\} = [P]^{-1}\{q\}$$

$$\text{or} \quad [M]_{diag}\{\ddot{p}\} + [K]_{diag}\{p\} = \{0\} \quad \text{with} \quad [M]_{diag} = {}^t[P][M][P] \;;\; [K]_{diag} = {}^t[P][K][P]$$

As long as we consider result at same place than excitation, factor Φ will be equivalent.

It has sense at low-medium frequencies
(practically f < 500 Hz)

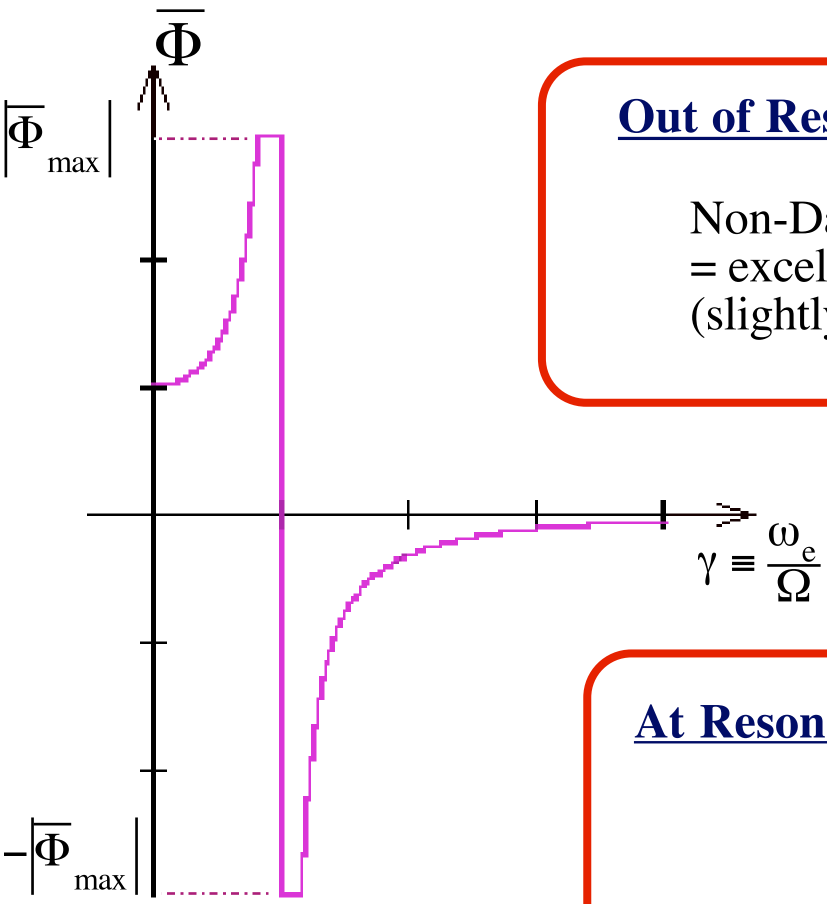
If spectral computation is required,
it is recommended to represent it
in log/log scale



NB : Transfers from one point to another one would induce slightly different function.

Simplified Fundamental Representation

(precision ~ 1% for aerospace structures)



Out of Resonance : $\gamma \in \left]-\infty \,;\, 1-\zeta\right] \cup \left]1+\zeta \,;\, +\infty\right[$

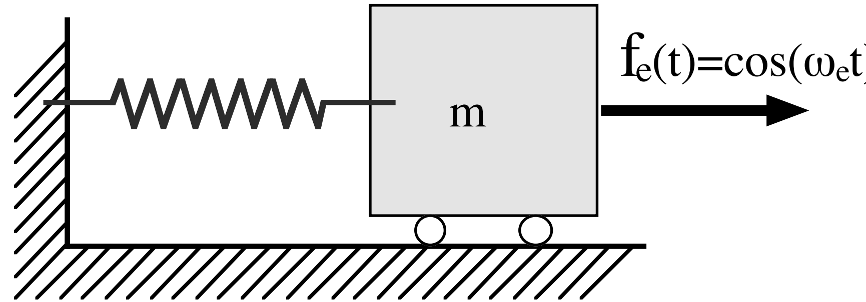
Non-Damped system
= excellent approximation
(slightly conservative)

$$\overline{\Phi}_{(\gamma)} \equiv \frac{1}{1-\gamma^2}$$

At Resonance : $\gamma \in [1-\zeta \,;\, 1+\zeta]$

$\left|\overline{\Phi}_{(\gamma)}\right|$ is limitated at $\left|\overline{\Phi}_{max}\right| \cong \frac{1}{2\zeta}$

DYNAMIC SYSTEM CANONIC REPRESENTATION



1 DOF Dynamic System $\Leftrightarrow$ $\left(m \;;\; \Omega\right) \quad \left(\Omega \equiv \sqrt{\frac{k}{m}}\right)$

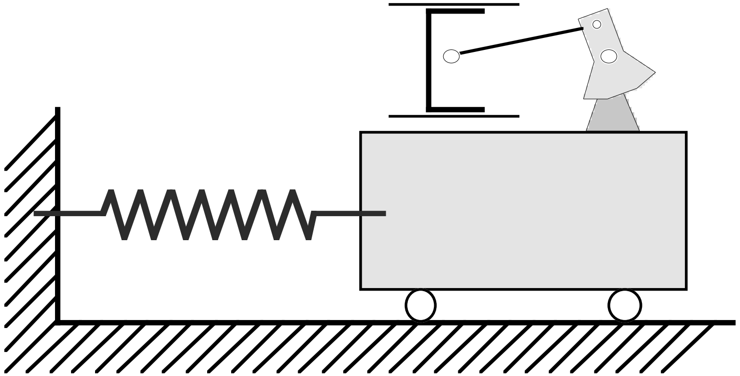
Non-Damped system is an excellent approach

ζ appears only as a perturbation which limitates $\left|\overline{\Phi}\right|$ at $\left|\overline{\Phi}_{max}\right| \cong \frac{1}{2\zeta}$ at resonance

For our Performing Space Structures, we will consider that $0.01 \leq \zeta \leq 0.015$

$$\Rightarrow \zeta \cong 0.01 \text{ or } 1\ \% \quad \Longrightarrow \quad \left|\overline{\Phi}_{max}\right| \cong 50$$

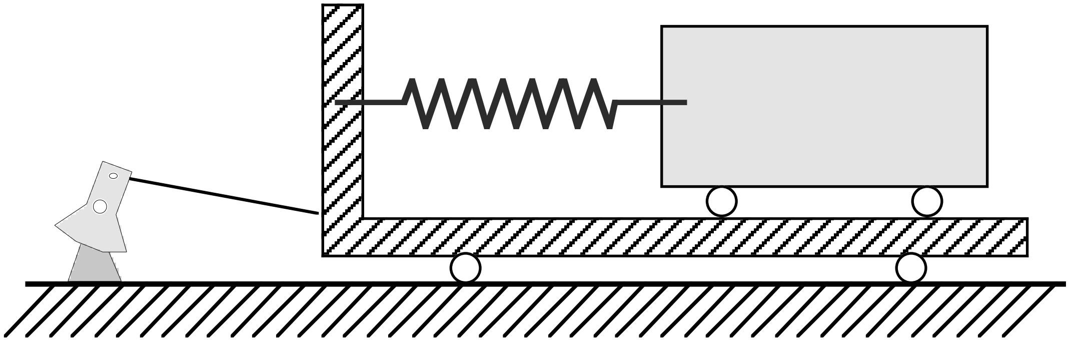
EQUIVALENT EXCITATIONS



Excitation = Applied force on Mass

Result = Motion of Mass (spring elongation)

Ratio Exc/Res ≡ Dynamic Flexibility



Excitation = Imposed Motion of Support

Result = Reaction (load) of Spring

Ratio Exc/Res ≡ Dynamic Mass

Launcher : **Imposed Motion ⇒ Vibrating Motion Tests** ⇒ Equivalent Computations

The two excitations are equivalent because of inertial (equivalence) principle (F=Ma)

NB1 : Equivalence deplacement / acceleration (in our reference sinus motion) :

$$x = \delta \cos\omega_e t \quad \Rightarrow \quad a \equiv \ddot{x} = -\omega_e^2 \delta \cos\omega_e t$$

NB2 : **Frequency f (Hz)** is deduced from angular **pulsation ω (rd/s)** by classical relation :

$$\omega = 2\pi f$$

ω is generally used for computations, and f for tests.

Low/medium Frequency :

Sinus for structure/model **identification** :

$a \cos(2\pi f\, t)$ (f=1 to 500 Hz) Generally in G ($1G \equiv 9.80665\ m/s^2$)

Random for **qualification** :

Continuous Spectrum imposed acceleration with **Spectral Density** $\mathbf{W_a(f)}$ **(G^2/Hz)**

At frequency f, **equivalent sinus** imposed acceleration :

Acceleration Amplitude (G)

$$a(f) \cong \alpha_a \times \sqrt{f \cdot W(f)} \{\times \gamma(f)\}$$

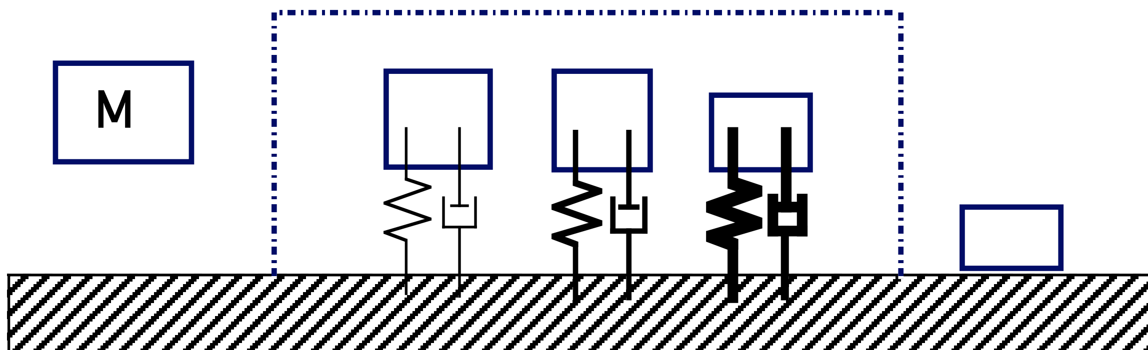
$\alpha_a \cong 3.76$ with "3σ" (99.7% confidence), $\alpha_a \cong 2.72$ with "2σ" (95% confidence)

EFFECTIVE MODAL MASSES & MODAL TRUNCATURE

Normalized eigenmodes : system ⇔ n effective modal parameters

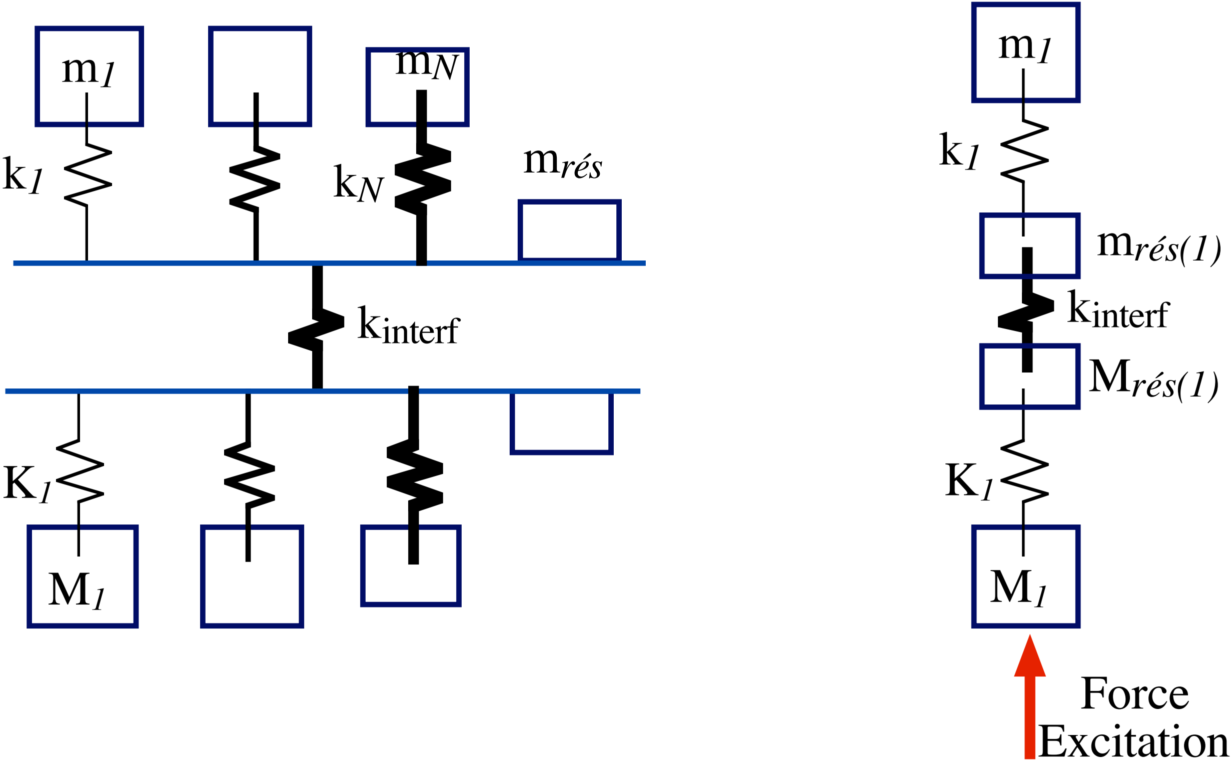
⇔ **n 1DOF effective modal systems** $(\mathbf{m}_k, \omega_k)$

Efficient Modes
(N modes)



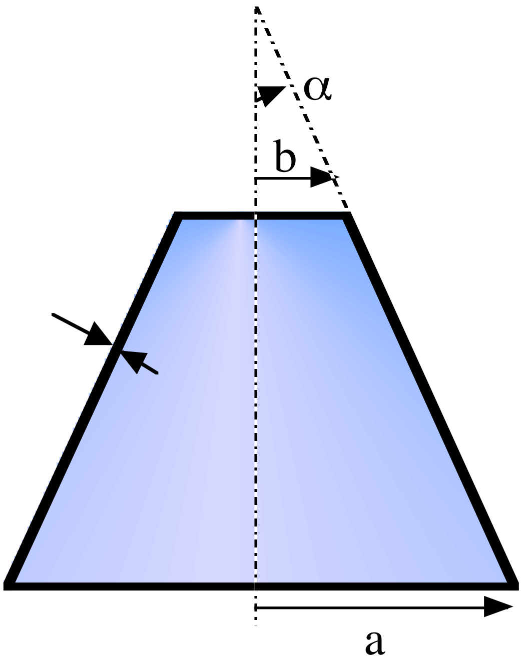
Hypostatic Truncature
rigid body modes
(non-structural)

High-Frequency Truncature
Excitation Spectrum
Modal Fusion
Rigididity and Damping Increasing



m_1
m_N
k_1
k_N
$m_{rés}$
k_{interf}
K_1
M_1
m_1
k_1
$m_{rés(1)}$
k_{interf}
$M_{rés(1)}$
K_1
M_1
Force
Excitation

STRUCTURAL STIFFNESS

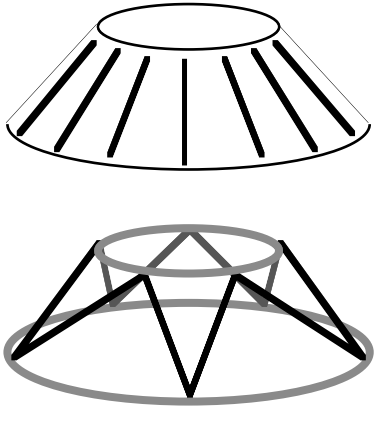


Conical Shell Longitudinal Stiffness :

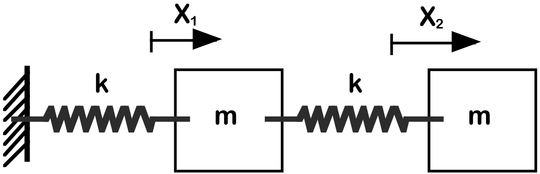
$$K_{zconic} = \frac{2\pi E h \sin\alpha \cos^2\alpha}{\mathrm{Log}\frac{a}{b}}$$

E : Longitudinal Young's Modulus
h : Average Longitudinal Thickness of Shell

Any Beam-Rod approach is envisageable...



On considère le système ci-contre, constitué de deux oscillateurs masse-ressorts identiques assemblés en série :



L'équation du mouvement s'écrit : $$[M]\ddot{\begin{pmatrix}x_1\\x_2\end{pmatrix}} + [K]\begin{pmatrix}x_1\\x_2\end{pmatrix} = \begin{pmatrix}0\\0\end{pmatrix}$$

Les matrices $[M]$ et $[K]$ sont directement tirées des expressions quadratiques des énergies

$$2\mathcal{E}_{cin} = m\left\{\left(\dot{x}_1\right)^2 + \left(\dot{x}_2\right)^2\right\} \quad \Rightarrow \quad [M] = \begin{pmatrix}m & 0\\0 & m\end{pmatrix} = m\begin{pmatrix}1 & 0\\0 & 1\end{pmatrix}$$

$$2\mathcal{E}_{pot} = k\left\{x_1^2 + \left(x_2 - x_1\right)^2\right\} = k\left\{2x_1^2 + x_2^2 - 2x_1x_2\right\} \quad \Rightarrow \quad [K] = \begin{pmatrix}2k & -k\\-k & k\end{pmatrix} = k\begin{pmatrix}2 & -1\\-1 & 1\end{pmatrix}$$

Pour expliciter les matrices diagonales, il faut utiliser la matrice de passage $P \cong \begin{pmatrix} 0.526 & -0.851 \\ 0.851 & 0.526 \end{pmatrix}$

Le changement de base donne :

$$\left| \begin{array}{l} [M]_{diag} = {}^t[P][M][P] = m\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = [M] \\ [K]_{diag} = {}^t[P][K][P] \cong k\begin{pmatrix} 0.382 & 0 \\ 0 & 2.618 \end{pmatrix} \end{array} \right.$$

$$\begin{pmatrix} m & 0 \\ 0 & m \end{pmatrix}\ddot{\begin{pmatrix} p_1 \\ p_2 \end{pmatrix}} + \begin{pmatrix} 0.382k & 0 \\ 0 & 2.618k \end{pmatrix}\begin{pmatrix} p_1 \\ p_2 \end{pmatrix} \equiv \begin{pmatrix} \mu_1 & 0 \\ 0 & \mu_2 \end{pmatrix}\ddot{\begin{pmatrix} p_1 \\ p_2 \end{pmatrix}} + \begin{pmatrix} \chi_1 & 0 \\ 0 & \chi_2 \end{pmatrix}\begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \text{avec} \begin{cases} \chi_1 - \omega_1^2\mu_1 \equiv 0 \\ \chi_2 - \omega_2^2\mu_2 \equiv 0 \end{cases}$$

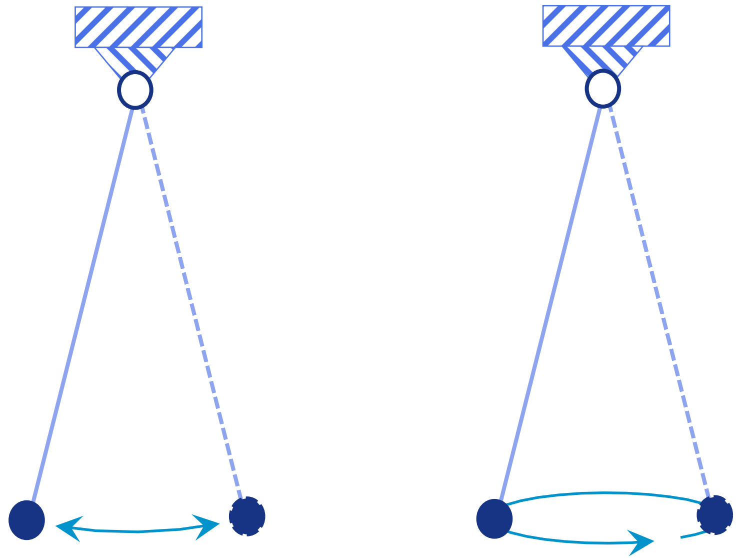
Ainsi, vu de O, le système initial est mécaniquement équivalent, autour de ω_1, à un système élémentaire masse-ressort dont la masse vaut 1.894m et de pulsation ω_1.

On peut tenir le même raisonnement pour le mode 2, autour de la pulsation ω_2. On obtient alors :

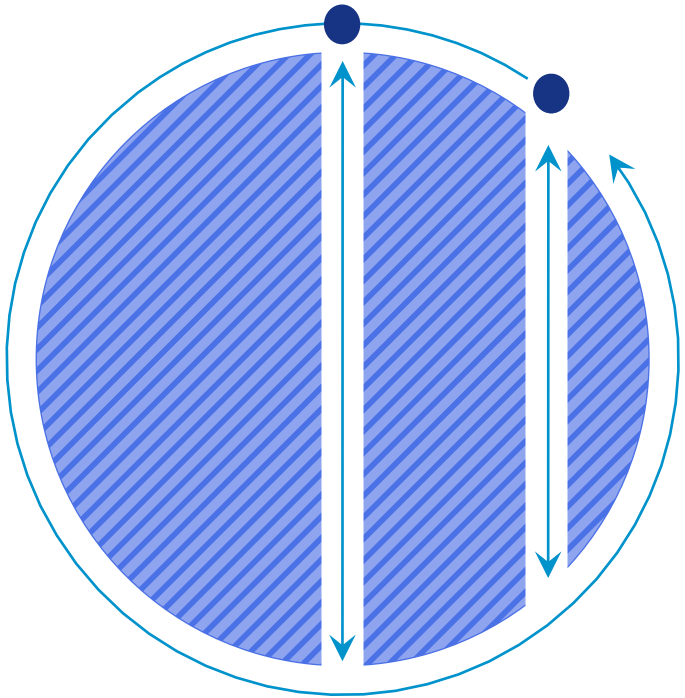
$$\mu_{II} \cong 0.106m$$

✧ Modes isochrones 1DDL

➢ *Plan & conique (Galilée)*



➢ *Sphérique interne & externe (Gauss)*



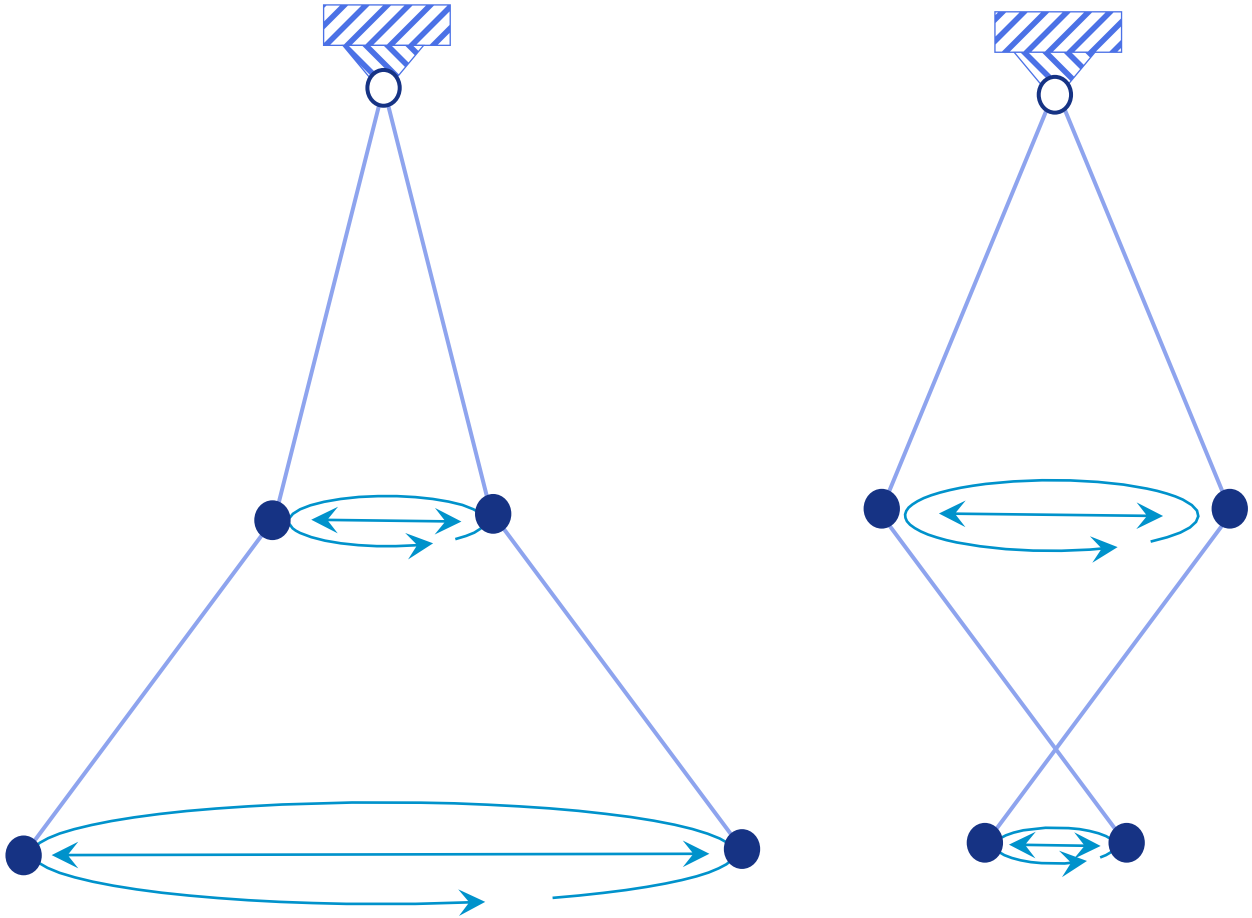
✧ Pendule double

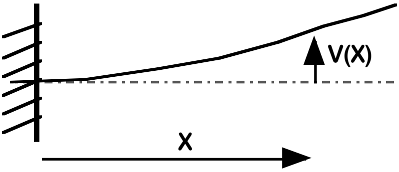
Paramétrage x_1, x_2
en translation absolue

$$\frac{\{\omega_I^2\,;\,\omega_{II}^2\}}{\frac{g}{L}} = \{2-\sqrt{2}\,;\,2+\sqrt{2}\}$$

$$\begin{cases} v_I = \begin{pmatrix} 1 \\ 1+\sqrt{2} \end{pmatrix} \\ v_{II} = \begin{pmatrix} 1 \\ 1-\sqrt{2} \end{pmatrix} \end{cases}$$

$$\Rightarrow \quad [P] \cong \begin{bmatrix} .383 & -.924 \\ .924 & .383 \end{bmatrix}$$





$M_Z(X)$

$$\begin{cases} M_Z' + T_Y = 0 \\ EI_Z V'' - M_Z = 0 \end{cases}$$

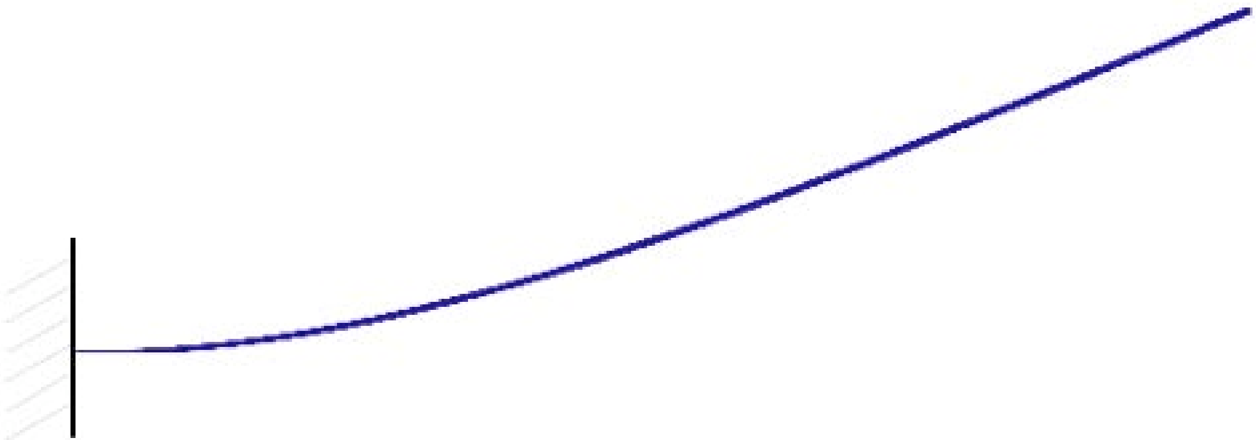
$$EI_Z V'''' - \lambda_Y - \rho \ddot{V} = 0$$

$V(X;t)$

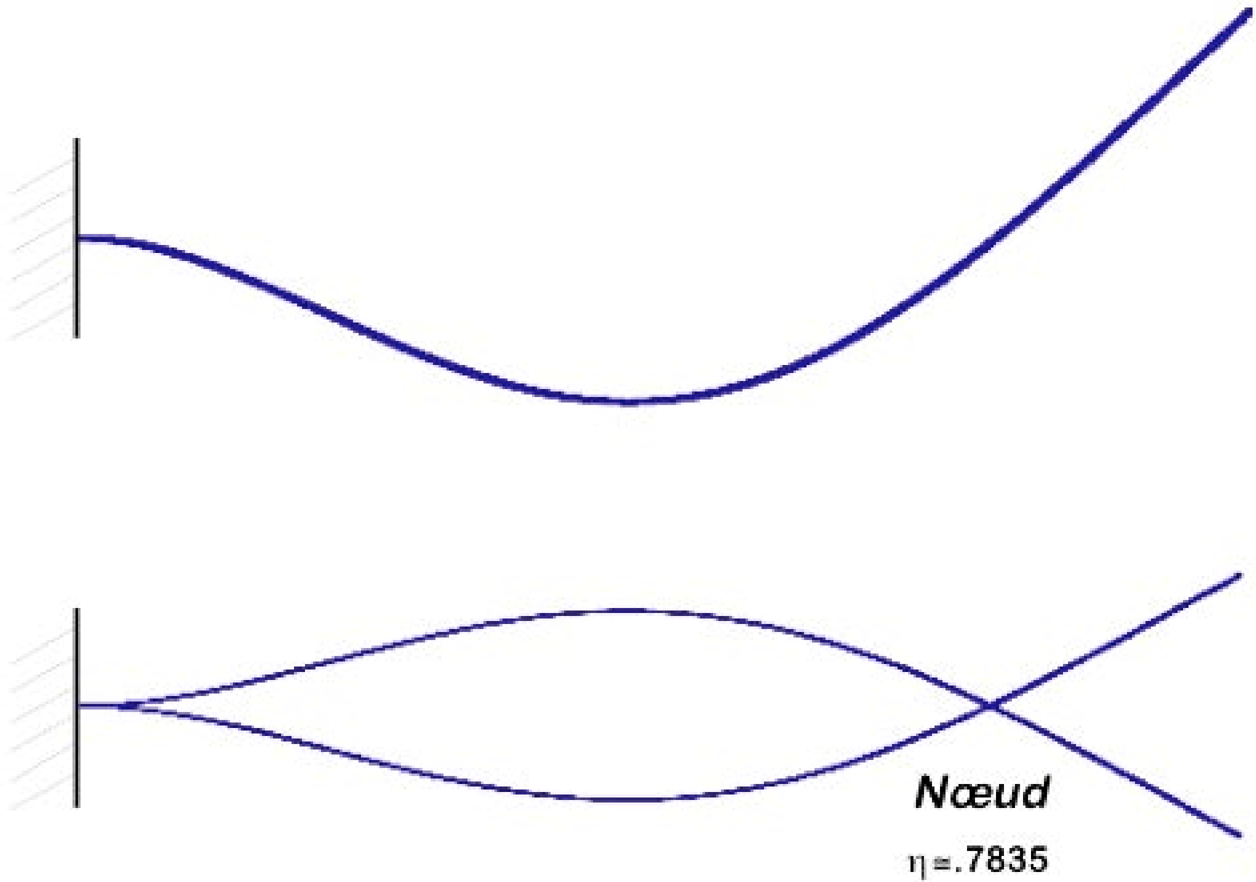
Pulsation : $\omega_1^2 \equiv \Omega_1^4 \frac{EI_z}{\rho S} \cong 12.36 \frac{EI_z}{\rho S L^4}$

Forme : (II) $\Leftrightarrow 3.038\, A_1 + 4.138\, B_1 = 0 \Rightarrow (A_1, B_1)$ normé à $\sqrt{.5}$: $\begin{cases} A_1 \cong -.5700 \\ B_1 \cong +.4184 \end{cases}$ et une forme $f_1(X)$

$$f_1(X) \cong -.5700\left\{\cos(1.875\eta) - ch(1.875\eta)\right\} + .4184\left\{\sin(1.875\eta) - sh(1.875\eta)\right\} \quad \text{avec} \quad \eta \equiv \frac{X}{L} \in [0;1]$$



$$\omega_2^2 \cong 485.5\frac{EI_Z}{\rho SL^4}\ ;\ \ 54.63\ A_2 + 53.64\ B_2 = 0 \quad \Rightarrow \quad f_2(X) \cong .4954\left\{\cos(4.694\eta) - ch(4.694\eta)\right\} - .5046\left\{\sin(4.694\eta) - sh(4.694\eta)\right\}$$



3 enjeux majeurs

<u>Modèle Lagrange-Euler</u>

Gaz-Membrane & Fluide-Coque

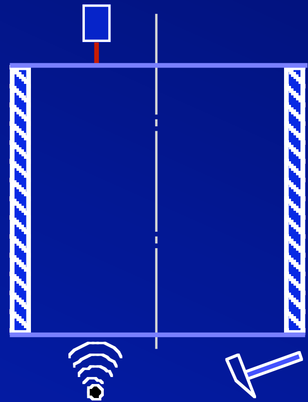
Métamodes

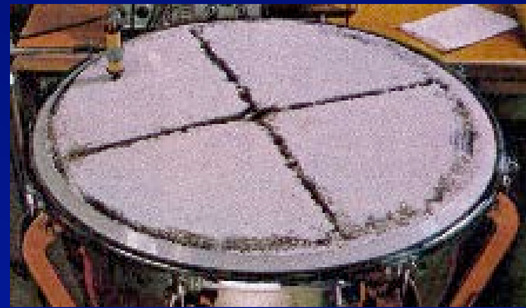
Milieux granulaires & cryogénie

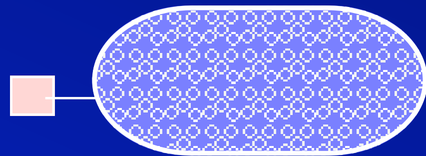
Contrôle

Vibro-IFS

Programme Région-Europe 2015-18

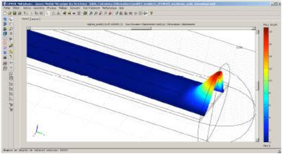




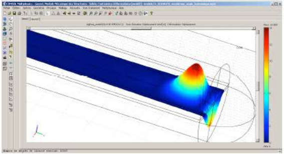


$$\left|\begin{array}{l}[z(\omega)](q)=(0)\\ [y(\omega)](\sigma)=(0)\end{array}\right. \xrightarrow{\textit{coques}} \left|\begin{array}{l}[Z](\overline{W})=(0)\\ [Y](\overline{p})=(0)\end{array}\right.$$

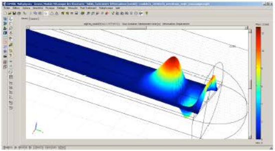
$$\xrightarrow{\textit{coques / fluides}} \begin{bmatrix} \{\ Z\ \} & \{\ C\ \} \\ \{\ {}^{t}C\ \} & \begin{Bmatrix} y_1 & 0 & 0 \\ 0 & y_i & 0 \\ 0 & 0 & y_p \end{Bmatrix} \end{bmatrix} \begin{pmatrix} (\overline{W}) \\ (\delta p) \end{pmatrix} = \begin{pmatrix} 0 \end{pmatrix}$$



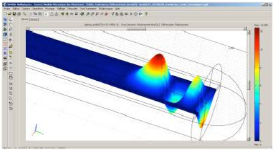
Mode 1 (87 Hz)



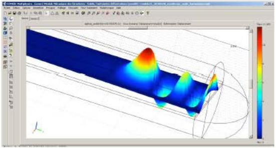
Mode 2 (100 Hz)



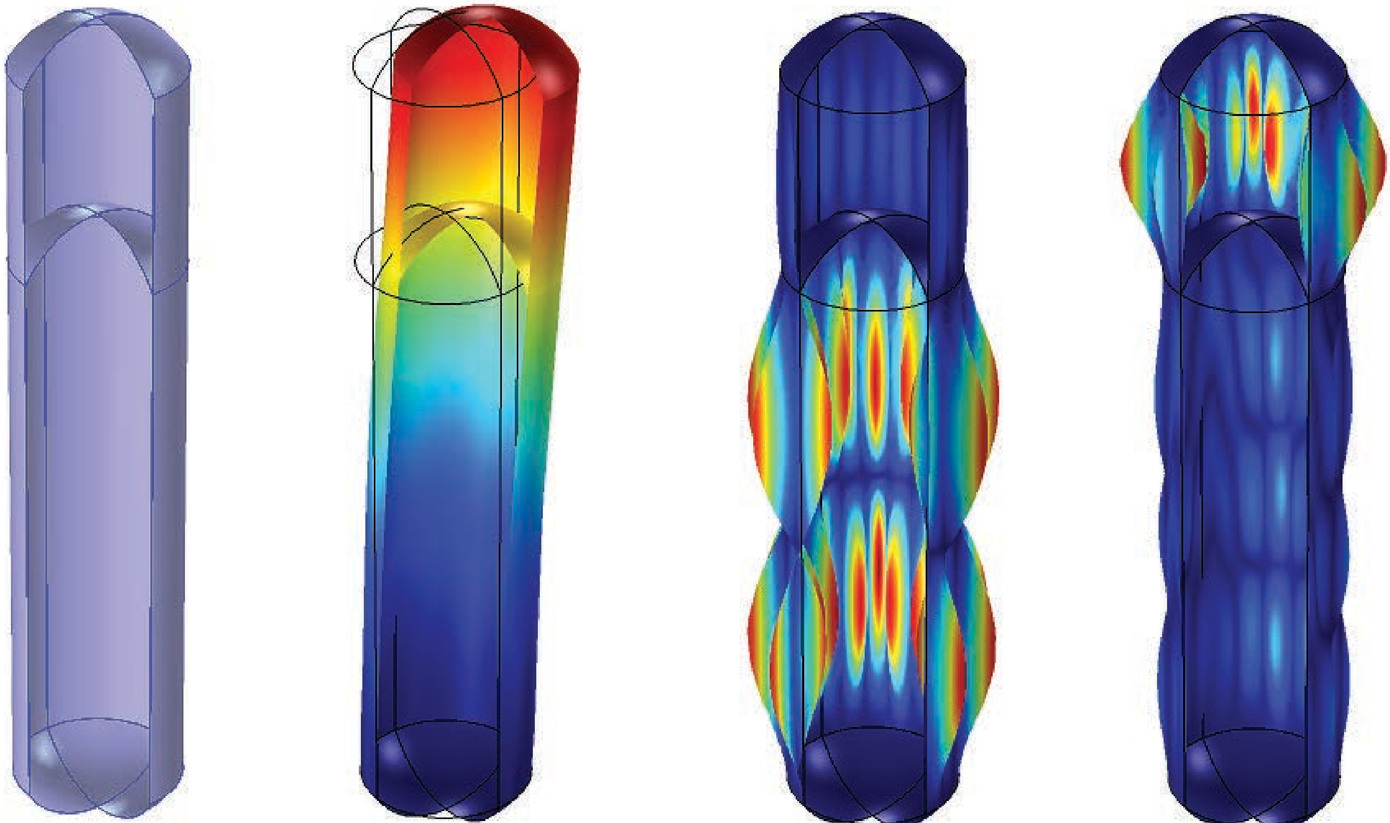
Mode 3 (111 Hz)



Mode 4 (122 Hz)



Mode 5 (132 Hz)



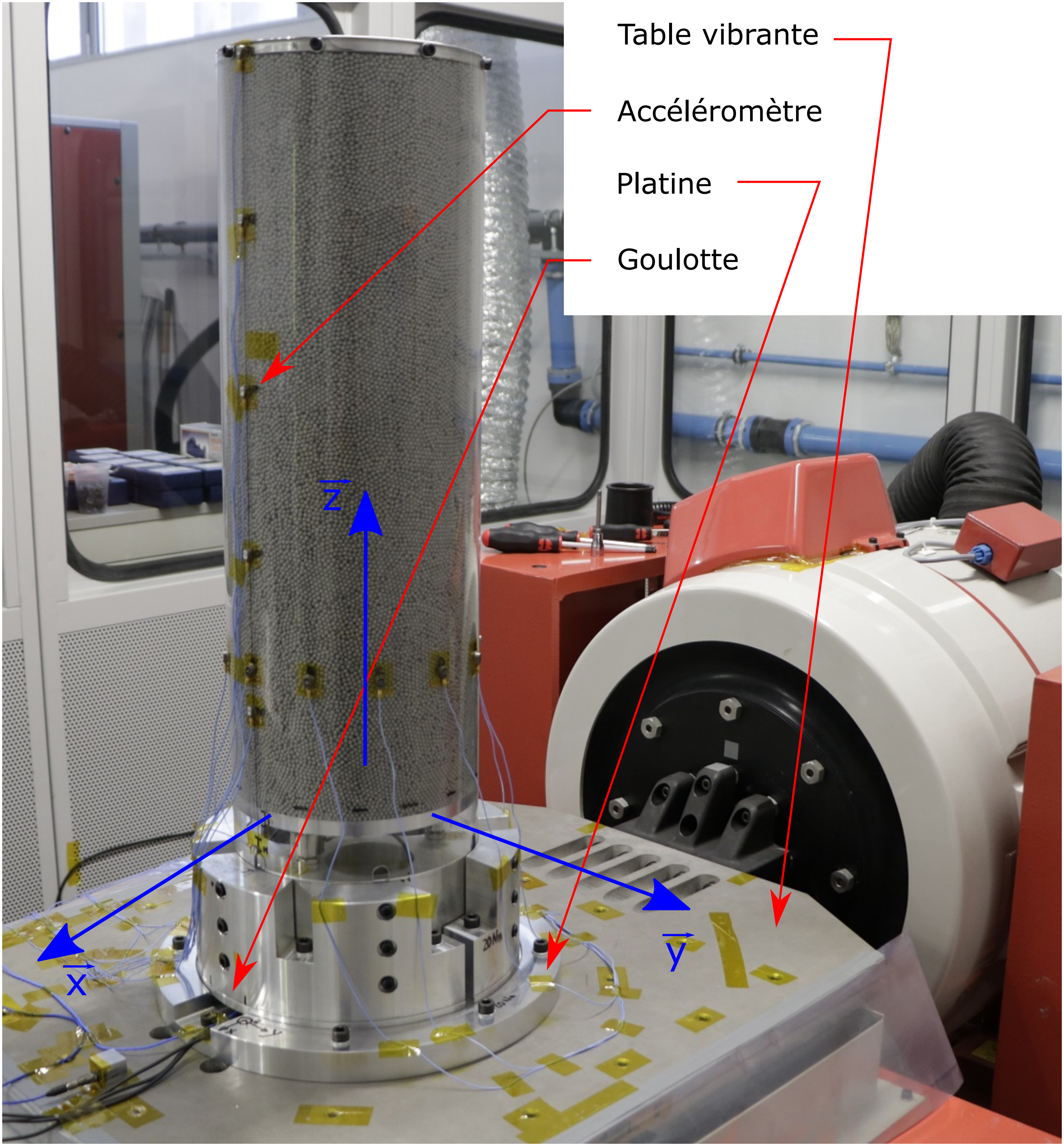


Table vibrante
Accéléromètre
Platine
Goulotte
z
x
y

$$m\overrightarrow{\boldsymbol{OP}}^{\circ\circ} - \vec{\boldsymbol{f}} \equiv \vec{\boldsymbol{O}} \Rightarrow \left[M_{ij}\right]\left(q_j\right)^{\circ\circ} + \left[K_{ij}\right]\left(q_j\right) \equiv \left(O\right) \quad \text{(Feynman)} \qquad (1)$$

where

m: punctual mass (particle);

O: affine Galilean origin (euclidian);

P: point associated with m (trajectory);

°: particle derivative with respect to time;

$\vec{f}$ force associated with *m*;

$\left(q_j\right)$: column vector of n Lagrange displacement parameters ($j = 1, \cdots, n \in N$);

$\left[M_{ij}\right]$: $n \times n$ matrix of system inertias, associated with the q_j parameters ($i, j = 1, \cdots, n$);

$\left[K_{ij}\right]$: $n \times n$ matrix of system stiffnesses, associated with the q_j parameters.

Mechanics

$\vec{V}^{\circ} - \vec{g} \equiv \vec{0}$; $\boldsymbol{m}\overrightarrow{\boldsymbol{OP}}^{\circ\circ} - \vec{\boldsymbol{f}} \equiv \vec{\boldsymbol{0}} \Rightarrow [M](q)^{\circ\circ} + [K](q) = (0)$

(*Newton-Feynman*, *pr*. 1-2) (1.1)

Kinetic constant $\dfrac{\partial E_{lag}}{\partial q_k} \equiv 0 \Rightarrow \dfrac{\mathrm{d}}{\mathrm{d}t}\left(\dfrac{\partial E_{lag}}{\partial \overset{\circ}{q}_k}\right) \equiv 0$

(*Lagrange-Routh*, *pr*. 2) (1.2)

Control energy $\dfrac{\partial E_{lag}}{\partial t} \equiv 0 \Rightarrow \dfrac{\mathrm{d}}{\mathrm{d}t}\left(E_{ham} - \sum_j \dfrac{\partial E_{pot}}{\partial \overset{\circ}{q}_j}\overset{\circ}{q}_j\right) \equiv 0$

(*Hamilton-Painlevé*, *pr*. 3) (1.3)

Dynamic digital system $\langle \mathcal{L} \rangle_j \left(E_{lag}\right) - Q_{j\,feyn} \equiv Q_{j\,stat}$

(*Lagrange-Feynman*, *pr*. 1-4) (1.4)

Continuous **1*D solid*** $U^{\circ\circ} - c_N^2 U'' \equiv 0\,,\quad c_N^2 \equiv \dfrac{E}{\rho}$

(*Hooke-Mach*, *pr.* 1-2) (2.1)

Continuous **1.5*D solid*** $\rho S V^{\circ\circ} + EIV'''' \equiv \lambda_{Ystat}$

(*Bresse-Lagrange*, *pr.* 1-2) (2.2)

Continuous **2.5*D euclidian*** $\rho h W^{\circ\circ} + D\Delta\Delta W \equiv p_{Zstat}\,,\quad D \equiv \dfrac{Eh^3}{12\left(1-\nu^2\right)}$

(*Kirchoff-Lagrange*, *pr.* 1-2) (2.3)

Cont. **2.5*D non-euclidian*** $\mathcal{D}_{X,Y,Z} - \mathcal{F}_{X,Y,Z} = p_{X,Y,Zstat}; \mathcal{T}_{Y,X} + Q_{YZ,XZ} = 0$

(*Reissner-Mindlin*, *pr.* 1-3) (2.4)

Solid **3*D*** $\rho \vec{\boldsymbol{v}}^{\circ} - \overrightarrow{div}\overline{\overline{\boldsymbol{\Sigma}}} - \vec{\boldsymbol{f}}_{voldyn} = \vec{\boldsymbol{f}}_{volstat}$

(*Navier-Lamé*, *pr.* 1-4) (2.5)

Newtonian fluid

$$\begin{cases} \rho^{\circ} + \overrightarrow{div}\left(\rho\vec{\boldsymbol{v}}\right) = 0 \\ \left(\rho\vec{\boldsymbol{v}}\right)^{\circ} + \overline{\overline{\boldsymbol{grad}}}\left(\rho\vec{\boldsymbol{v}}\right)\cdot\vec{\boldsymbol{v}} + \rho\vec{\boldsymbol{v}}div\vec{\boldsymbol{v}} - \overrightarrow{div}\overline{\overline{\boldsymbol{\Sigma}}} - \vec{\boldsymbol{f}}_{vol} = \vec{\boldsymbol{O}} \\ \left(\rho e_{tot}\right)^{\circ} + div\left(\rho e_{tot}\vec{\boldsymbol{v}} - \overline{\overline{\boldsymbol{\Sigma}}}\vec{\boldsymbol{v}} - \lambda_T\,\overrightarrow{\boldsymbol{grad}}T\right) - \vec{\boldsymbol{f}}_{vol}\cdot\vec{\boldsymbol{v}} = q_{vol} \end{cases}$$

(*Navier-Stokes pr.* 1-3) (3.1)

Newtonian gas

$$\begin{cases} e_g \equiv c_v T \\ h \equiv e_g + \dfrac{p}{\rho} \equiv c_p T \\ T ds_g \equiv de_g + pd\left(\dfrac{1}{\rho}\right) \end{cases}$$

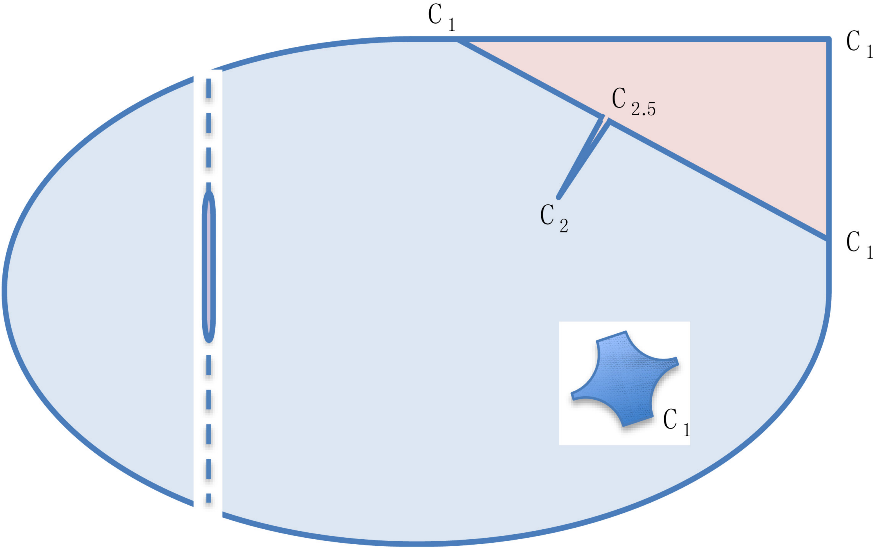
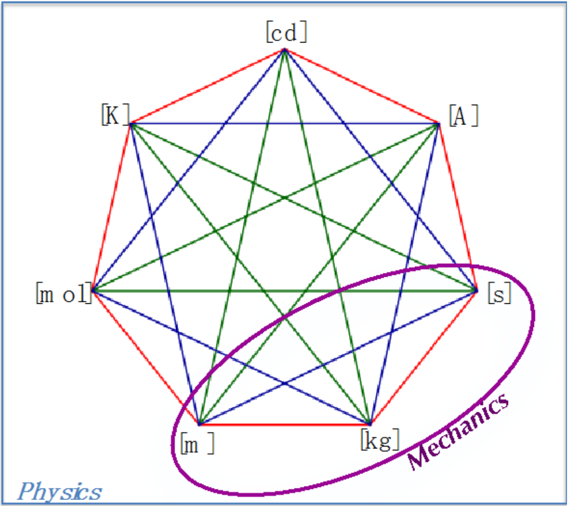


Figure 7. Interfaces and singularities in a complex shell.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Mechanics
Physics


Буран
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Crew-robot complementarity in missions

Scale effects: structural observability & controllability

Pr.Yves Gourinat

SUPAERO - Université de Toulouse

August 31st 2021