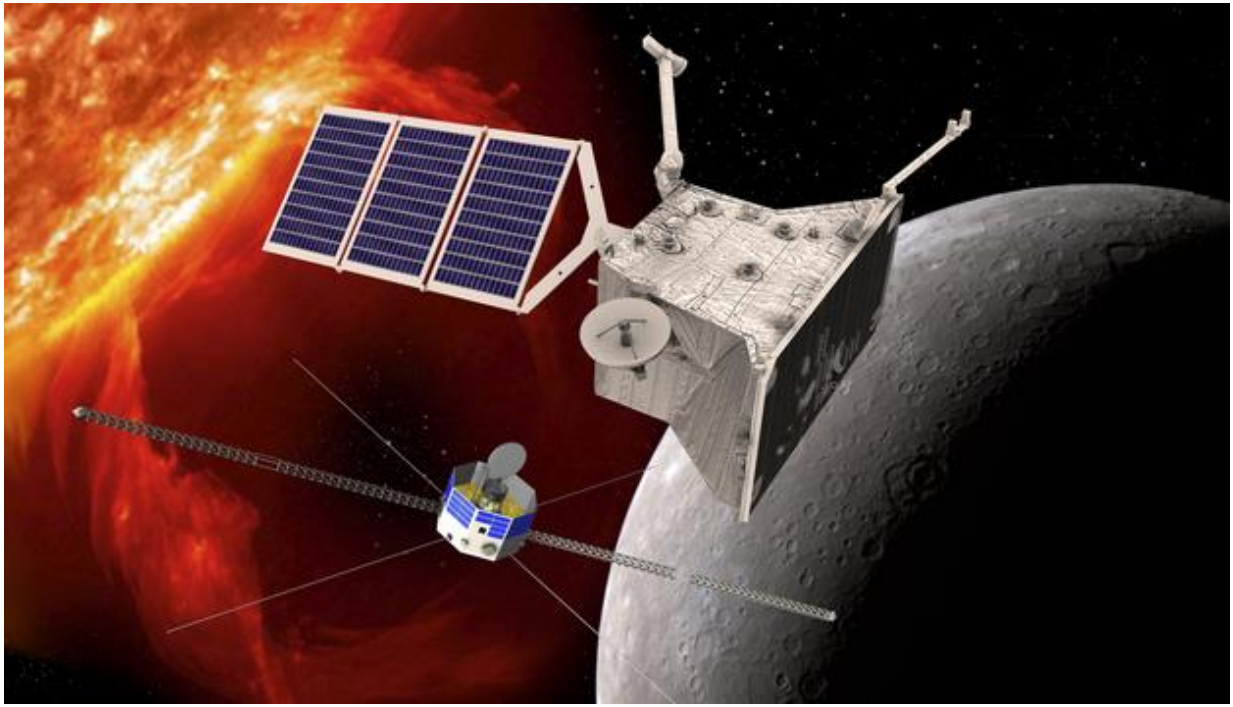
Communications and Radio Science

Joseph Lazio

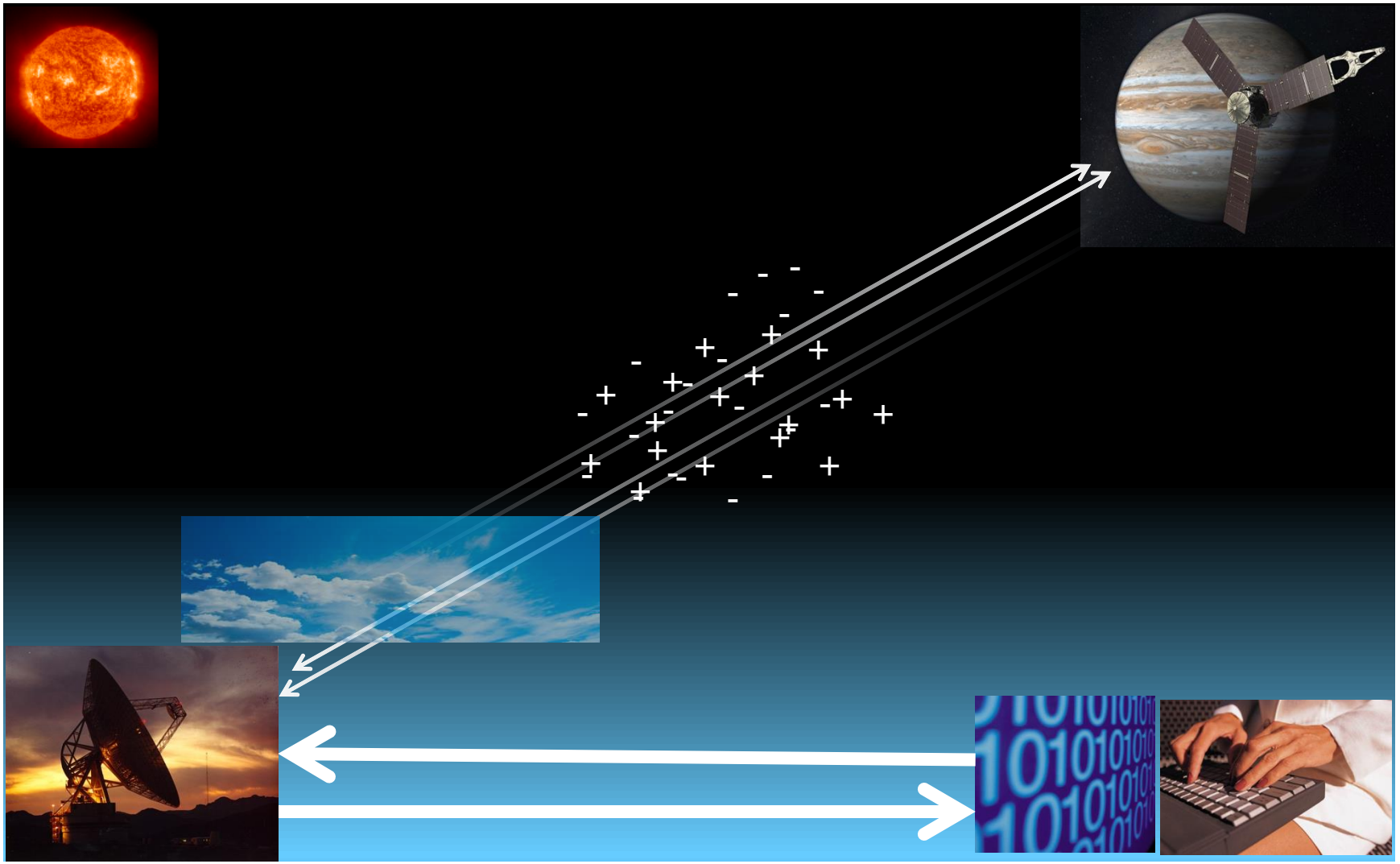
Jet Propulsion Laboratory
California Institute of Technology

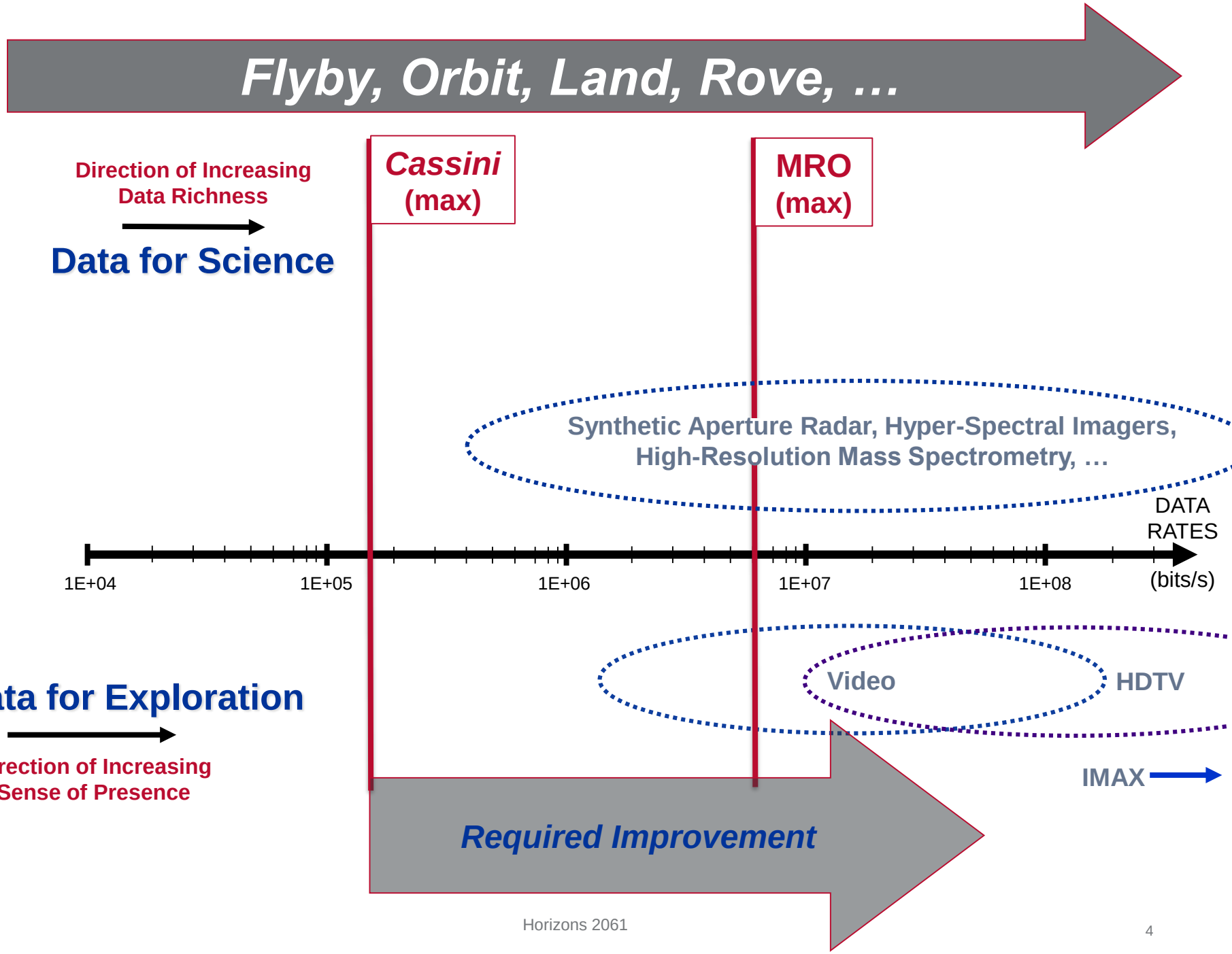
Mars InSight



BepiColumbo - Mercury

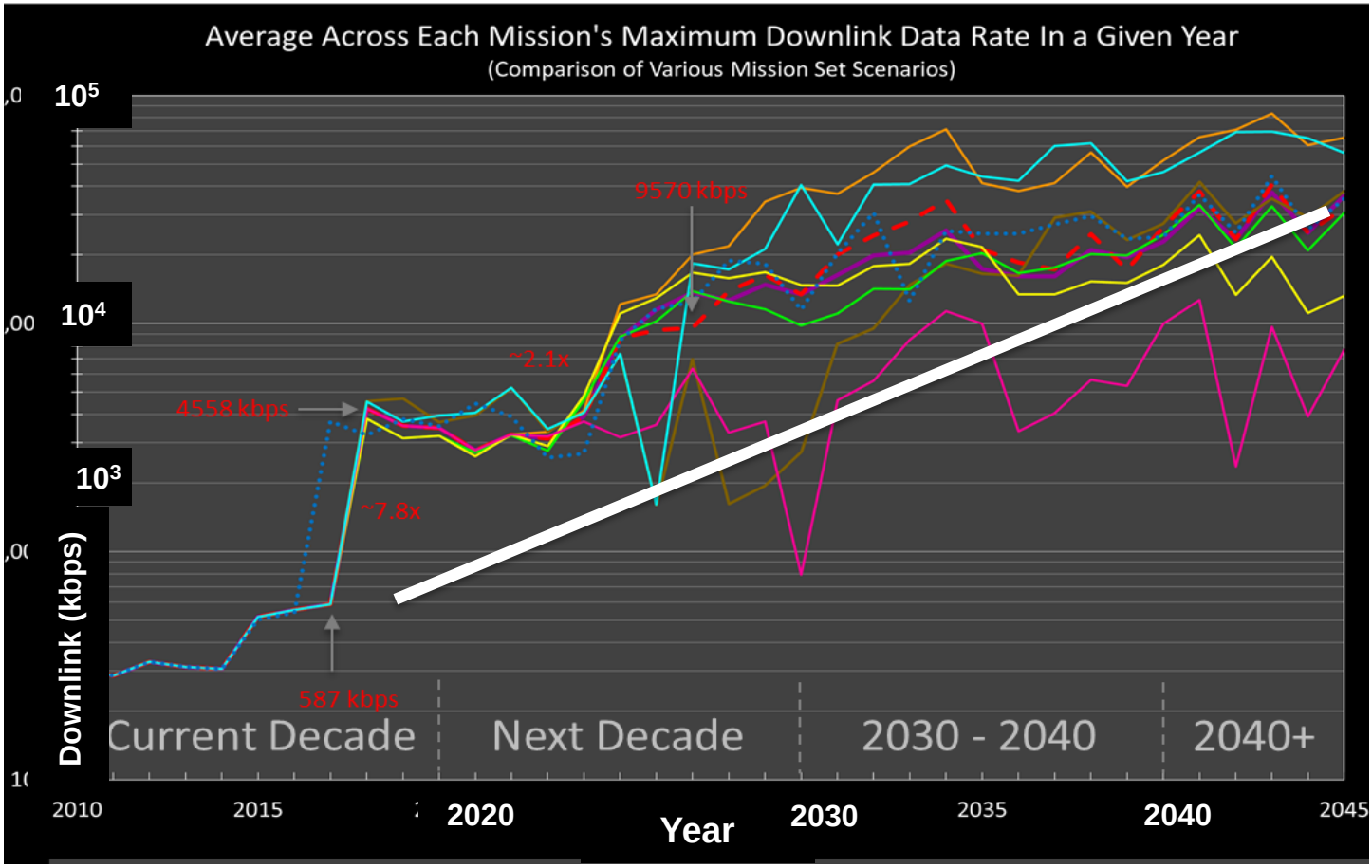
The End-to-End View




Flyby, Orbit, Land, Rove, …
Direction of Increasing
Data Richness
Data for Science
Cassini
(max)
MRO
(max)
Synthetic Aperture Radar, Hyper-Spectral Imagers,
High-Resolution Mass Spectrometry, …
DATA
RATES
1E+04
1E+05
1E+06
1E+07
1E+08
(bits/s)
Video
HDTV
IMAX
Data for Exploration
Direction of Increasing
Sense of Presence
Required Improvement

Future Mission Data Rate Trends

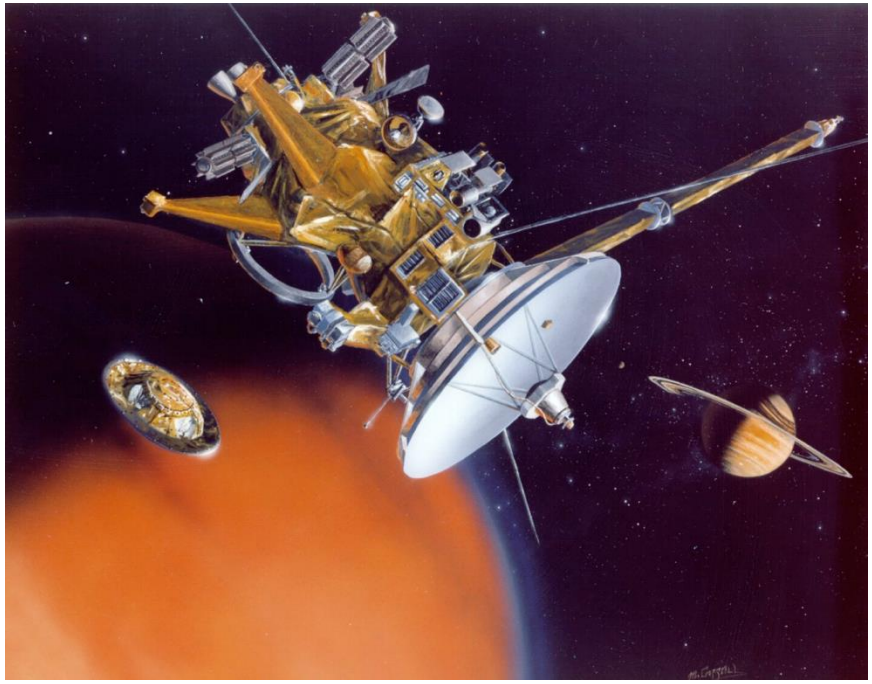
Have visited all major objects in Solar System, continuous presence on Mars since 2004



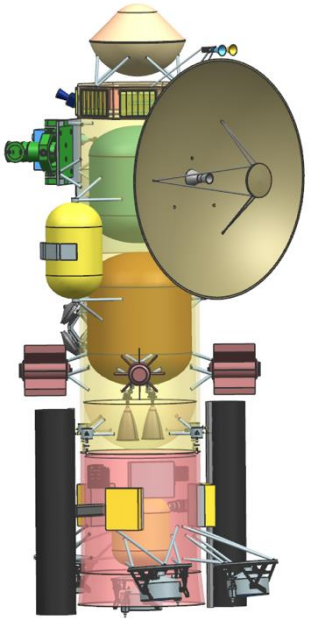
- **Trends: Revisit for more intense study, smaller spacecraft and constellations, Humans beyond LEO**

Mission modeling indicates desire for ~ 10× data improvement per decade (at least) through 2040

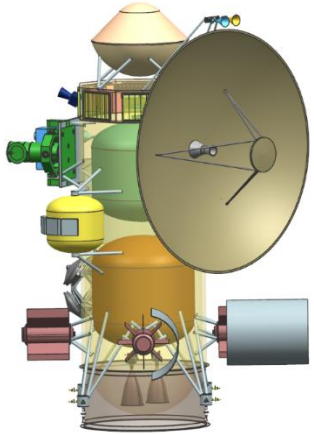
Ice Giant Mission Concepts



***Cassini* with Huygens Probe**



Neptune Orbiter with Probe, SEP, and 50 kg payload

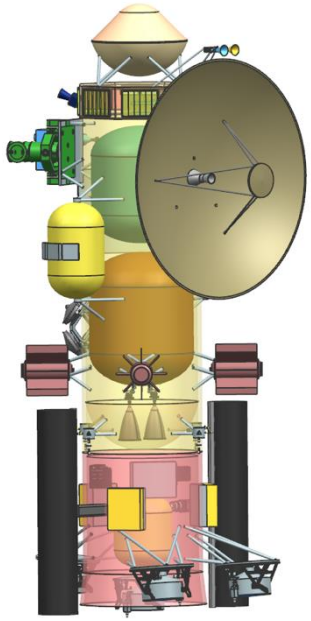


Uranus Orbiter with Probe and 50 kg payload

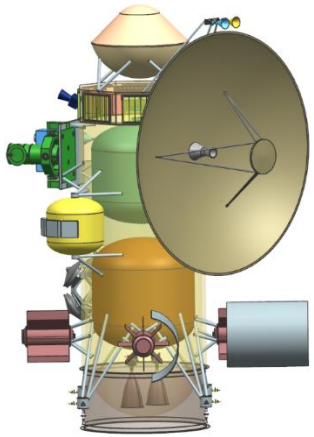
Why Do I Care?

Ice Giant Mission Concepts

- **More capable instruments**
  - **Higher spectral resolution spectrometers, higher spectral resolution mass spectrometers, higher angular resolution imager**
    - **30 km spatial resolution on a moon vs. 100 km spatial resolution**
- **More capable missions**
  - **Stereo vision on a moon via multiple looks**

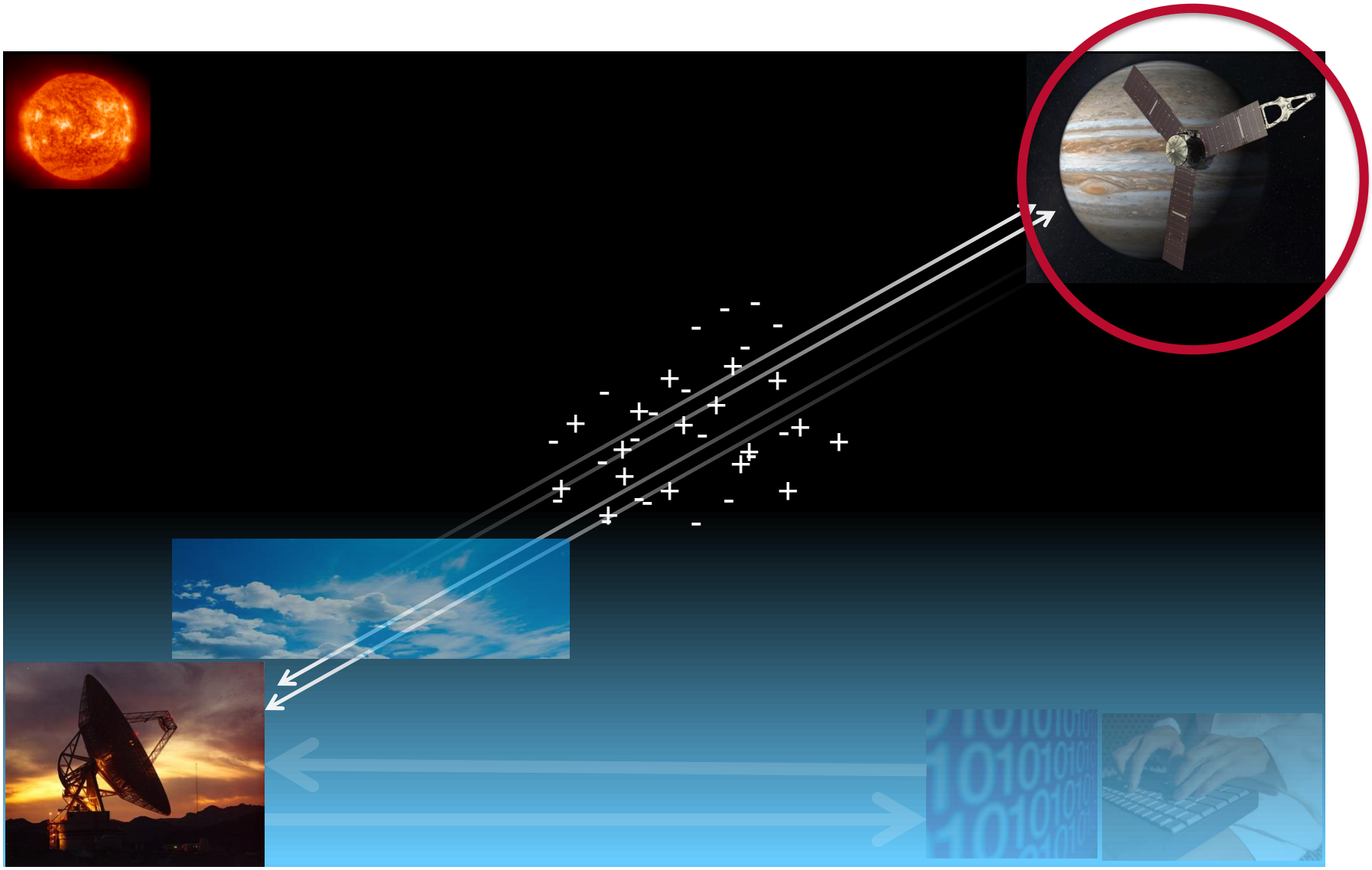


Neptune Orbiter with Probe, SEP, and 50 kg payload



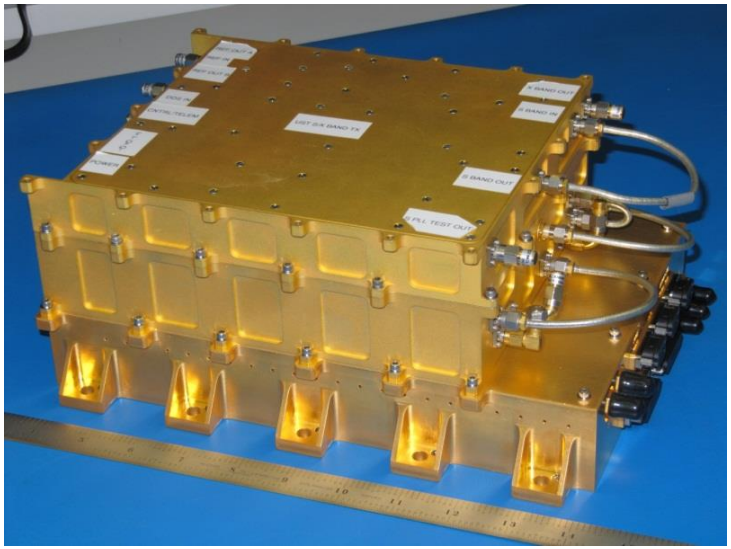
Uranus Orbiter with Probe and 50 kg payload

The End-to-End View

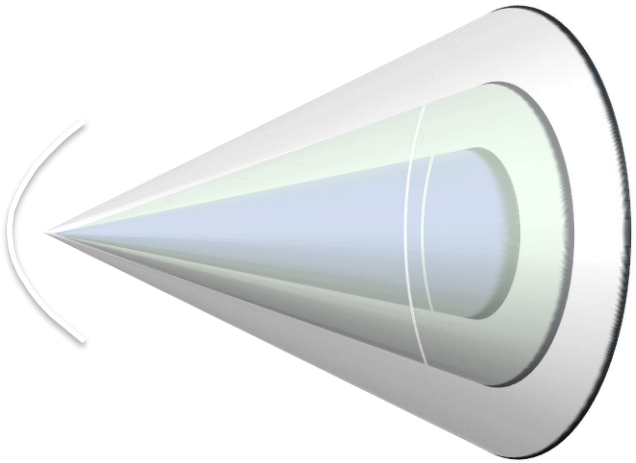


Spacecraft: 10× Improvement over Today

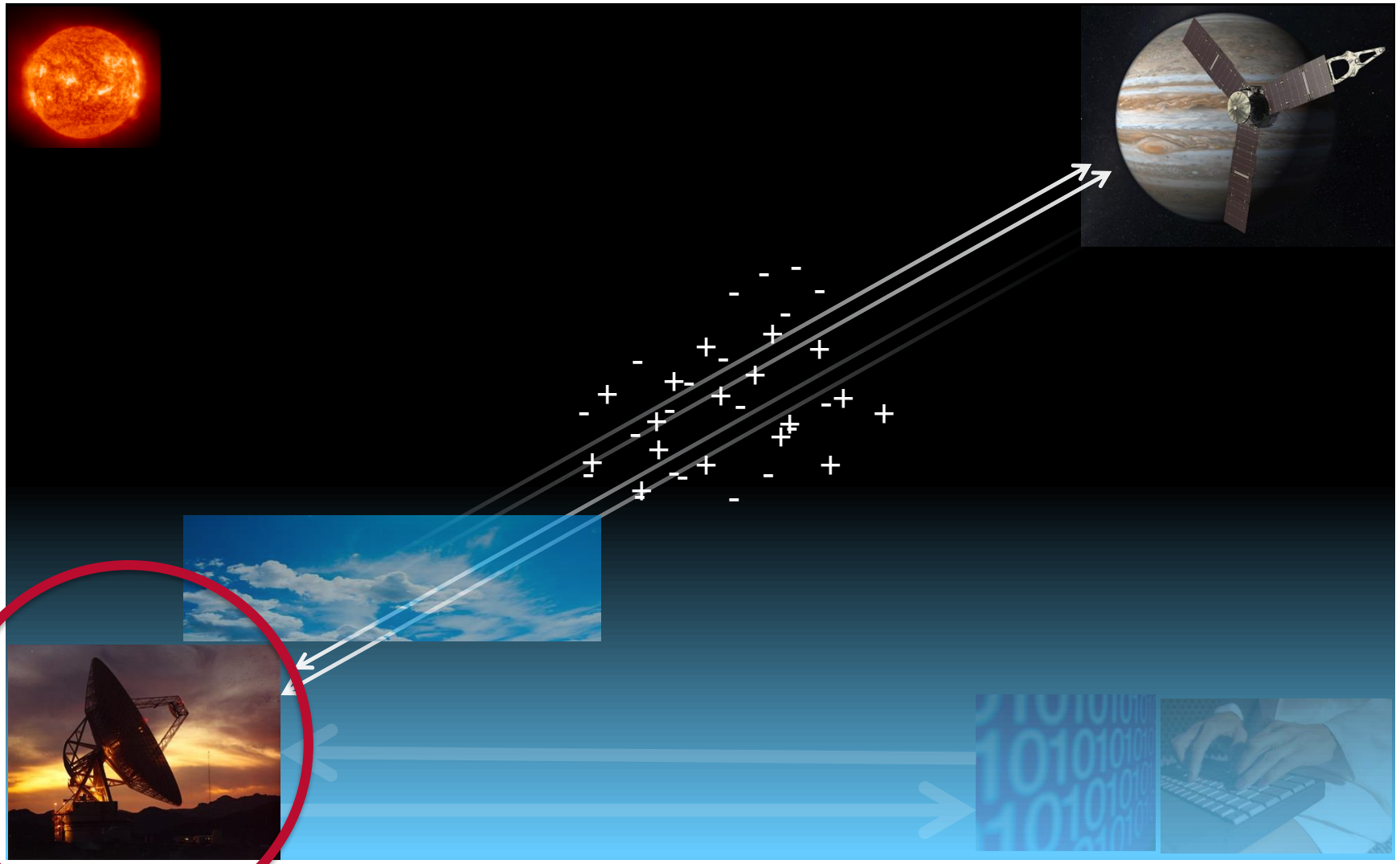
- **Remove bottlenecks on spacecraft**
  - **e.g., Universal Space Transponder (UST)**
  - **Modular approach ….**



- **Increase use of Ka band over X band**
  - **Factor of ~ 4× improvement**
  - **viz. *Cassini* Radio Science, Juno Radio Science**

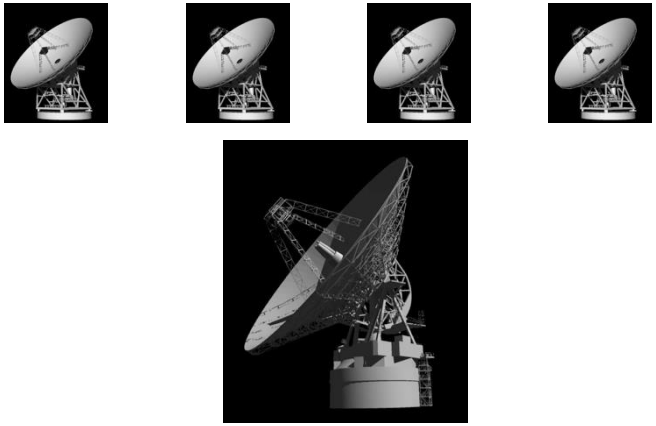


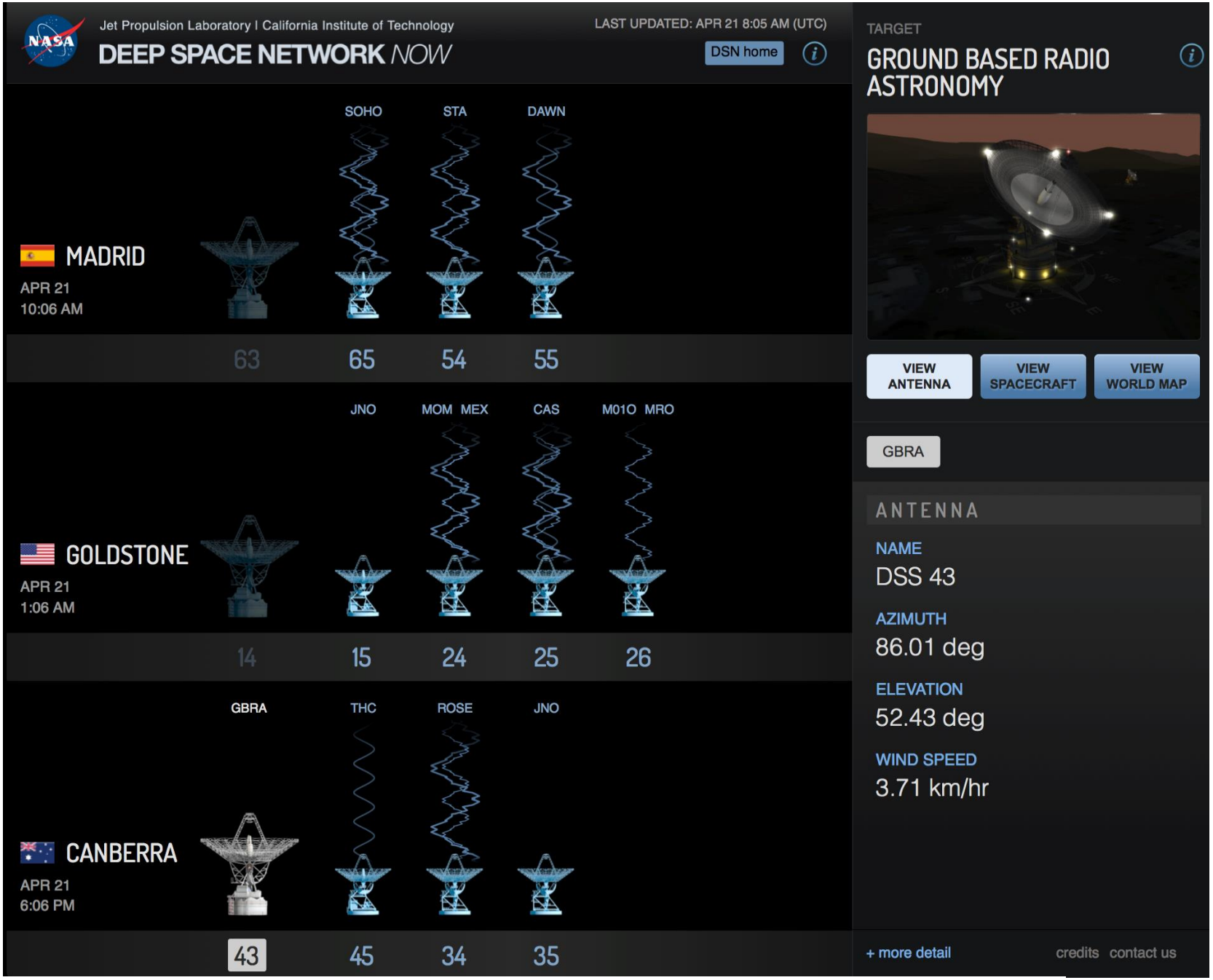
The End-to-End View



Ground Systems: Improvements over Today

- **Antenna arraying**
  - **DSN Aperture Enhancement Project emplacing additional 34m antennas**
  - **Provides backup for 70m capability as well as arraying beyond 70m**



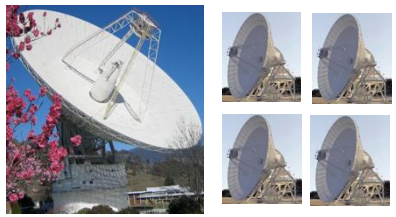


http://eyes.nasa.gov/dsn/dsn.html

Deep Space Network

DSN Aperture Enhancement Project (through 2025)

+ backend digital signal processing

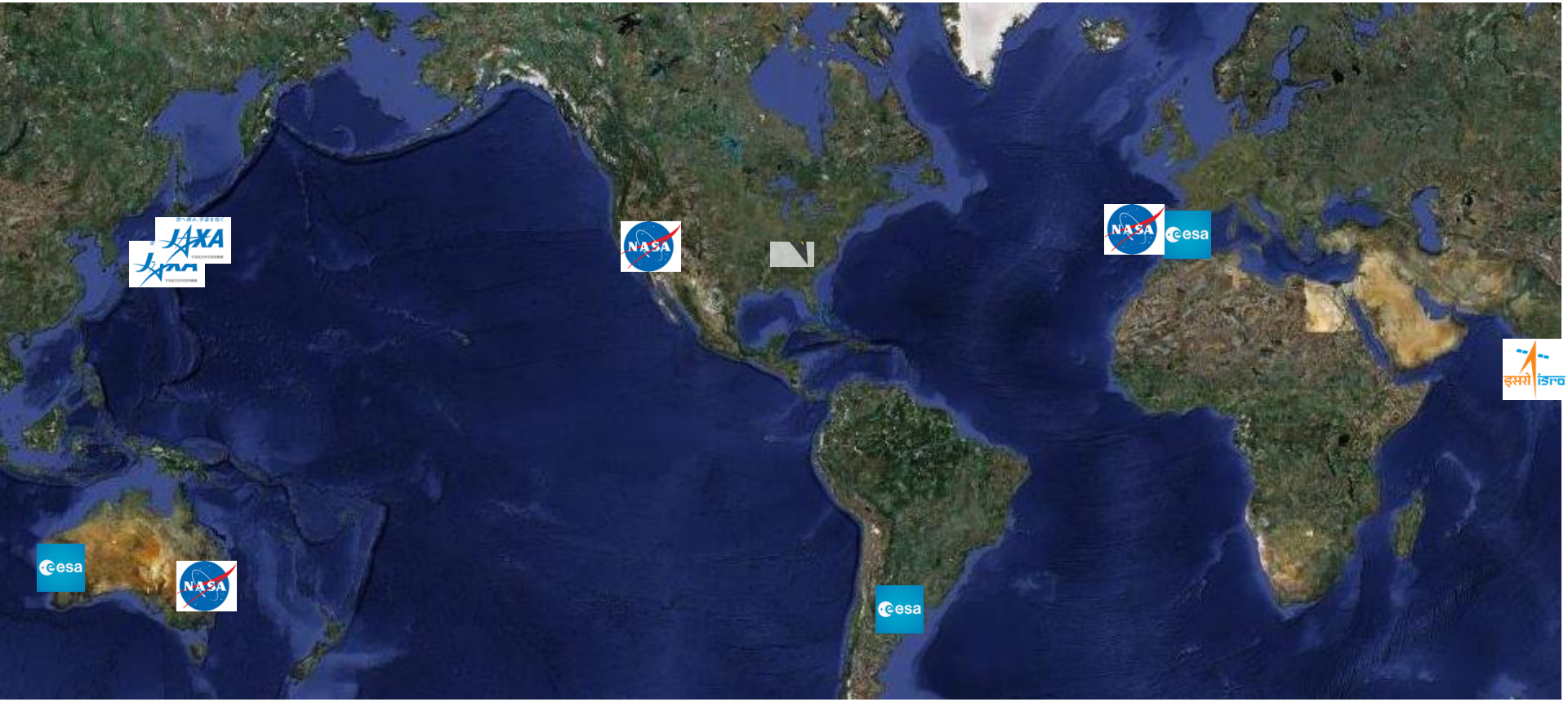


Canberra

Goldstone

Madrid

International Deep Space Network



Usuda
Uchinoura

Canberra
Goldstone
Madrid

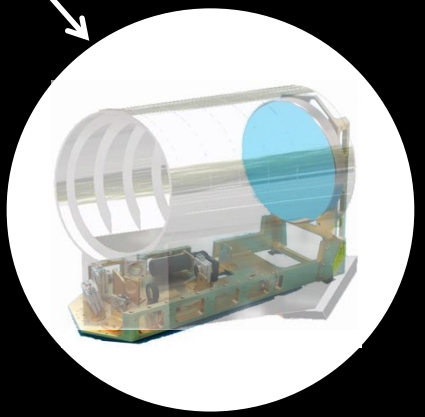
New Norcia
Cebreros
Malargüe

Byalalu

Laser Communications: 100x Today

Dedicated Comm Relays
Extend the Internet to Mars and enable public engagement

Human and robotic users
100× today's data rates from Mars – up to 1 Gbps

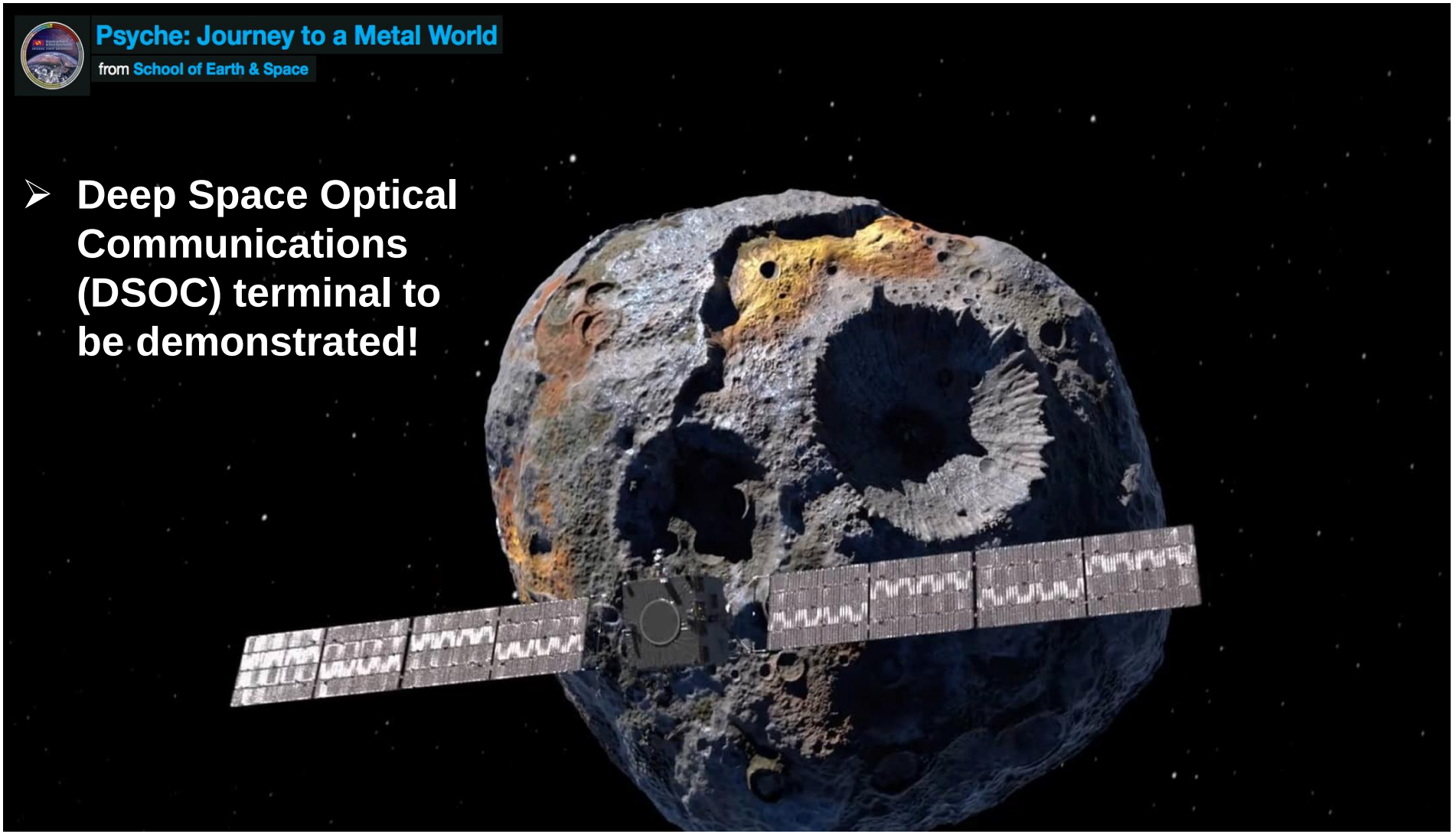


Dedicated 12m Stations
NASA + International partnerships

Hybrid RF/Optical Antenna
Potential reuse of existing infrastructure, in development today

High Performance Optical Terminal:
To be demonstrated on Pysche

Laser Communication

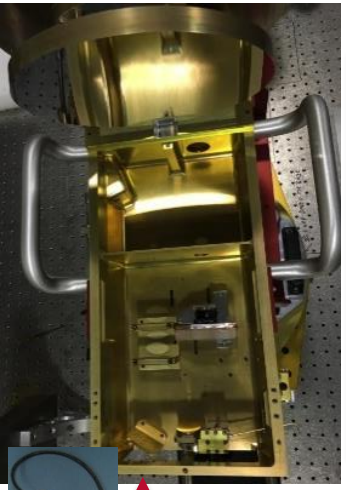


- **Deep Space Optical Communications (DSOC) terminal to be demonstrated!**

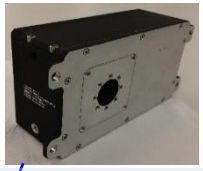
DSOC Technologies & Advances

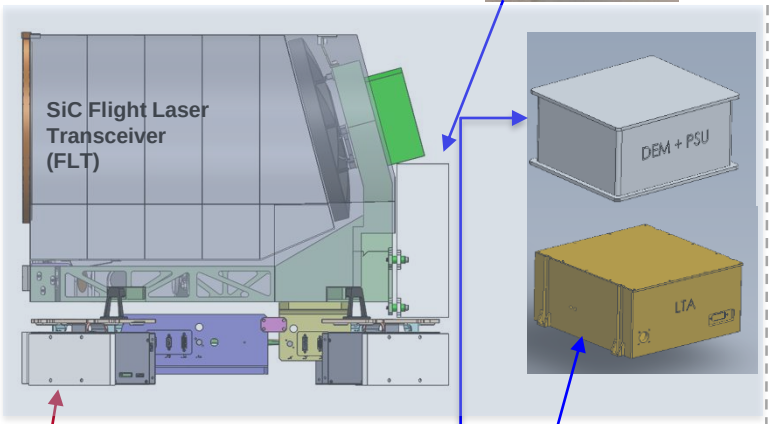
FLIGHT LASER TRANSCEIVER (FLT)

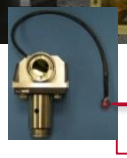
Aluminum Optical Transceiver Assembly



Photon-Counting Camera

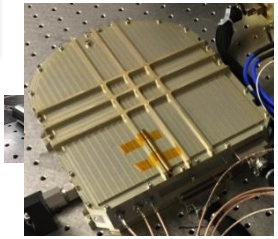




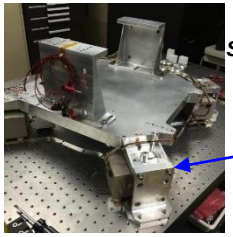


Point-Ahead Mirror

flight-like electronics



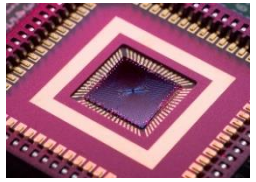
Laser Transmitter Average Power 4 W



Single strut photo

Isolation Pointing Assembly

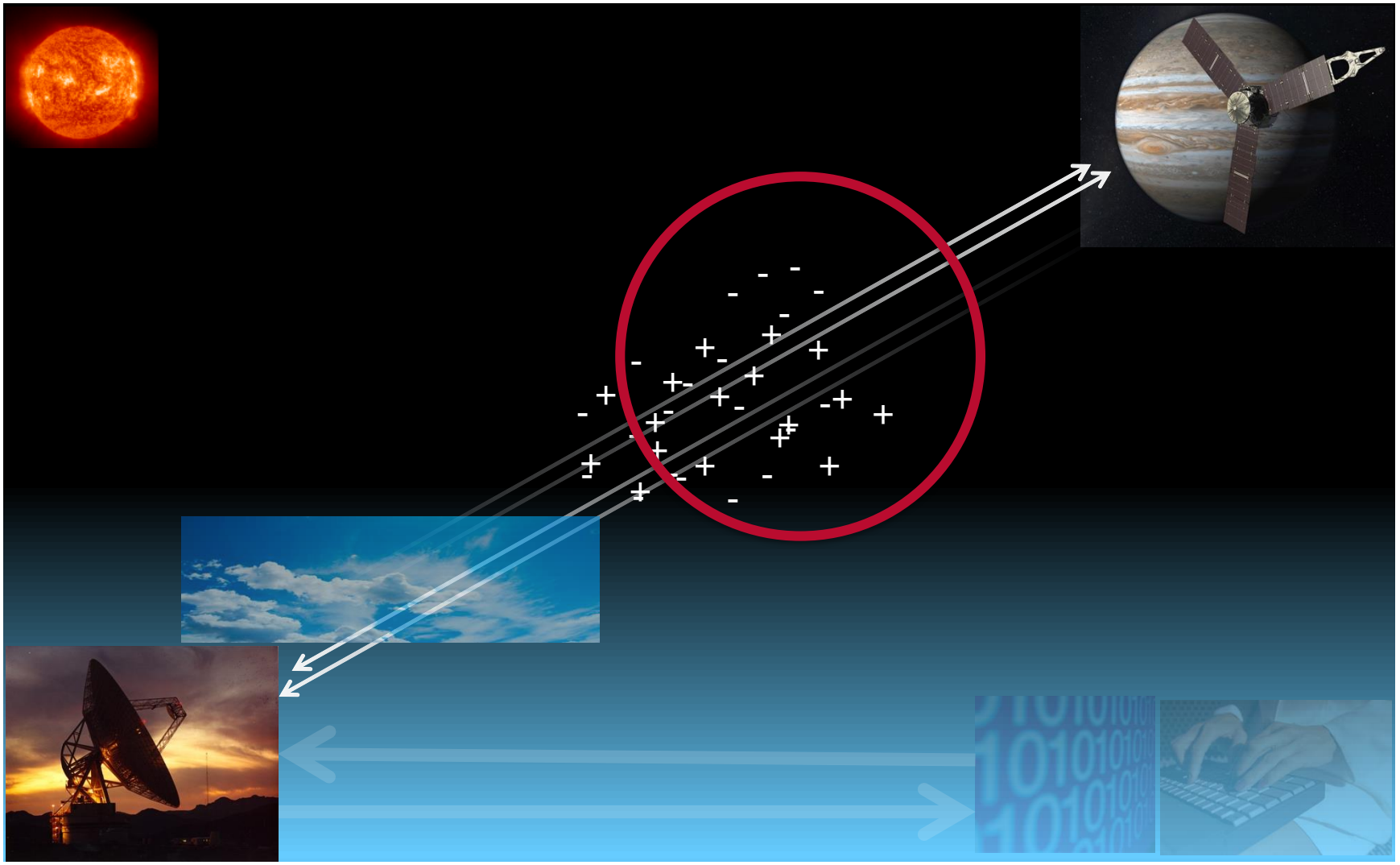
GROUND TECHNOLOGY



Packaged Nanowire Array

Electron microscope detail of 320 µm active area tungsten silicide (WSi) superconducting nanowire single photon detector (SNSPD) array

The End-to-End View

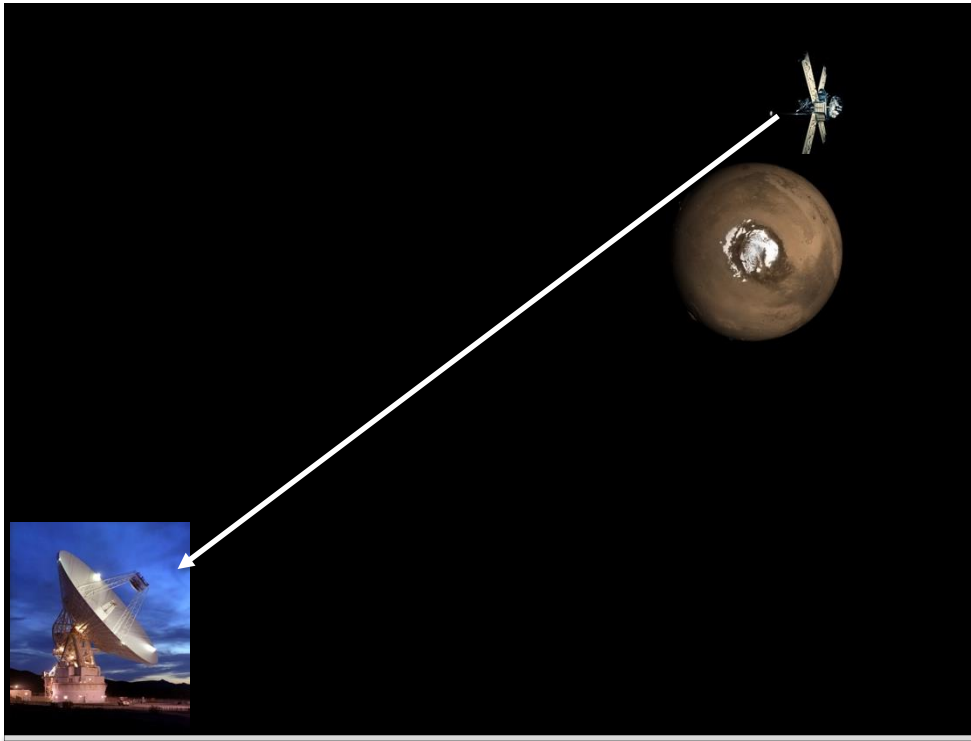


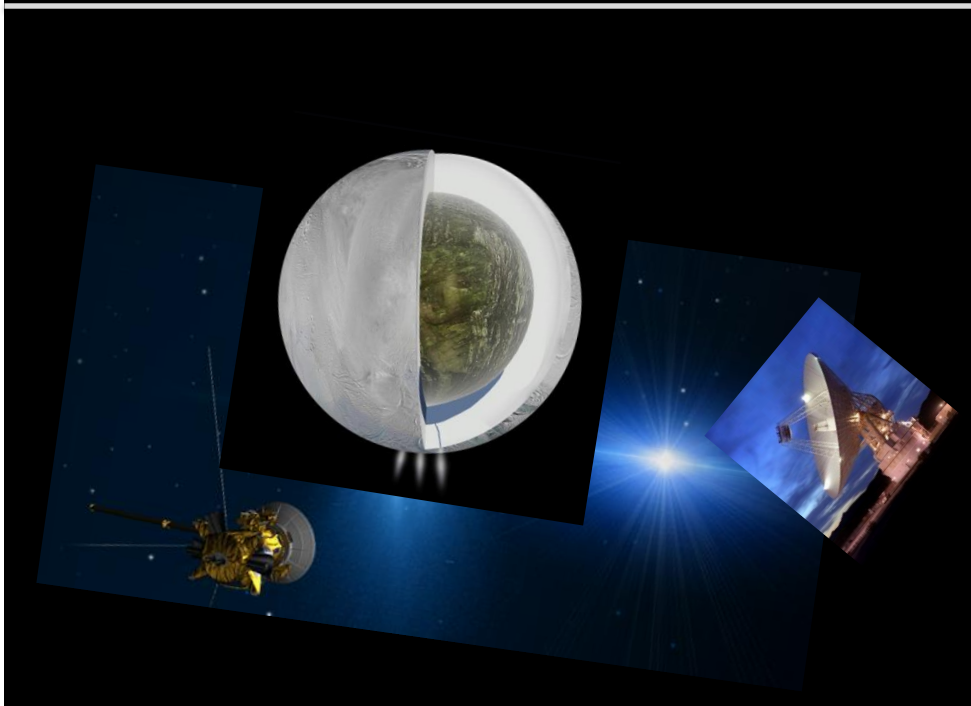
Radio Science

Apparent even with early missions that occultations by planetary atmospheres would affect radio communications

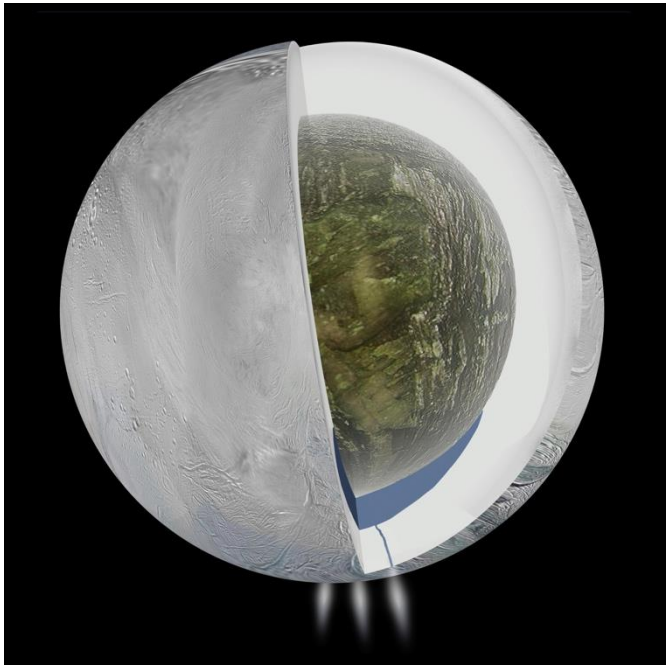
- **Mio dio! Tragedy!**
- **Or one person's annoyance is another's data --- Study atmospheric properties!**
  - **"Occultation Experiment: Results of the First Direct Measurement of Mars's Atmosphere and Ionosphere" (Kliore et al. 1965, *Science*)**
- **Can also study planetary interior!**

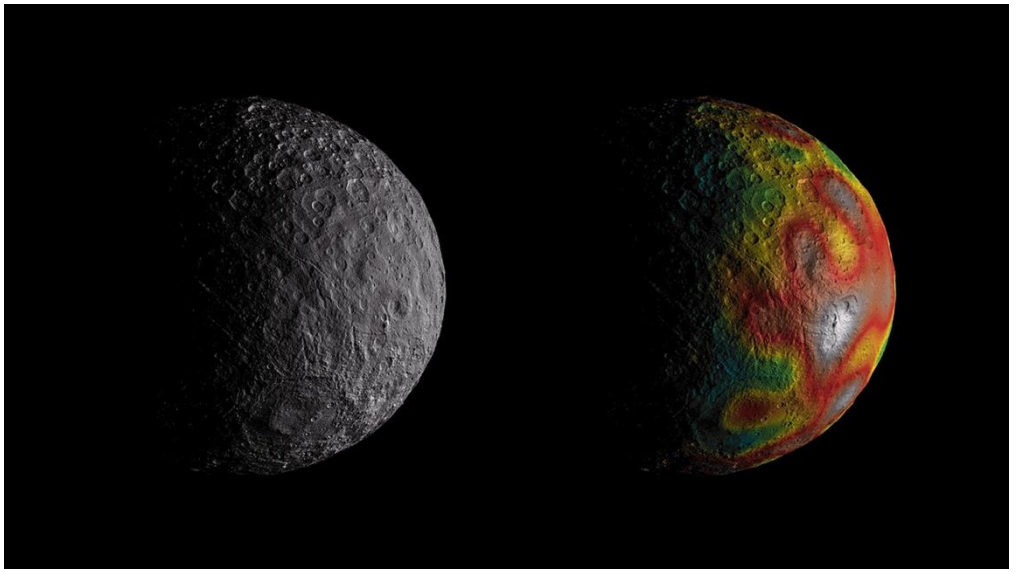
➢ **Turn the DSN+spacecraft into one giant science instrument**

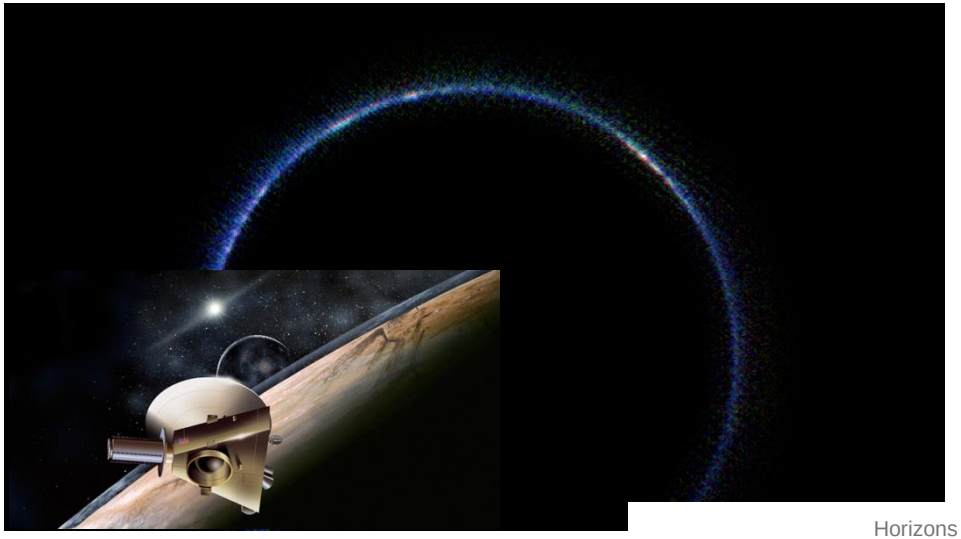


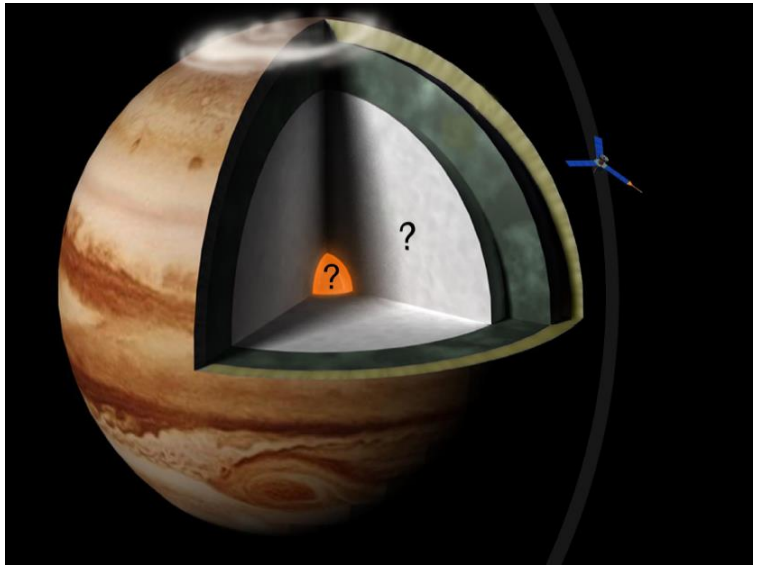


Radio Science in the Solar System Today

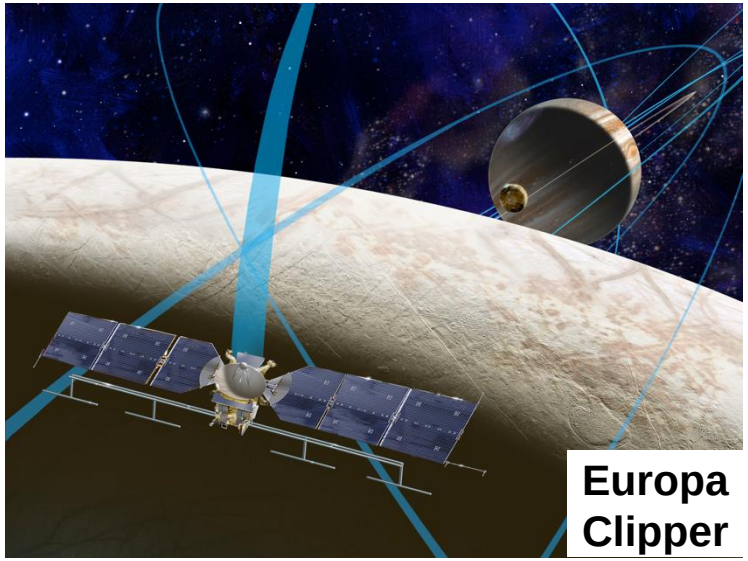




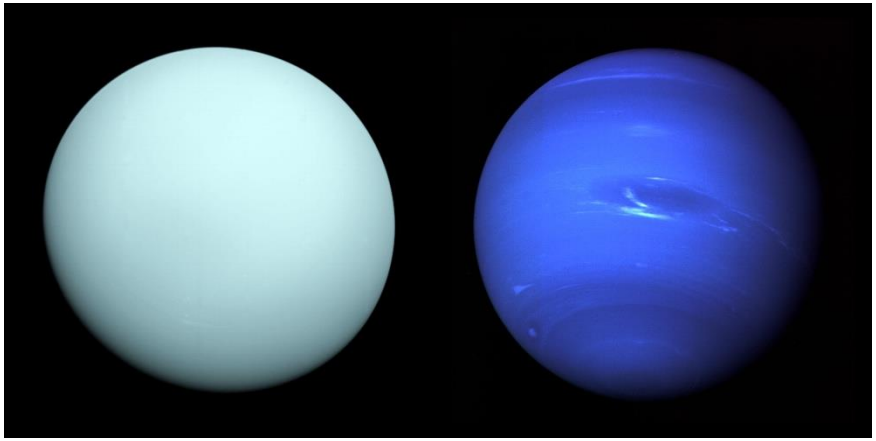




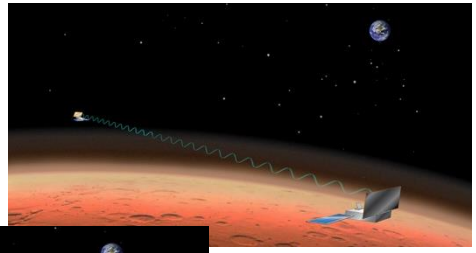
Radio Science to 2061

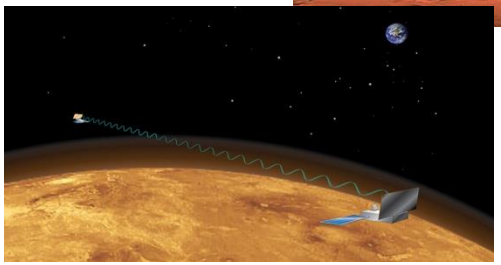


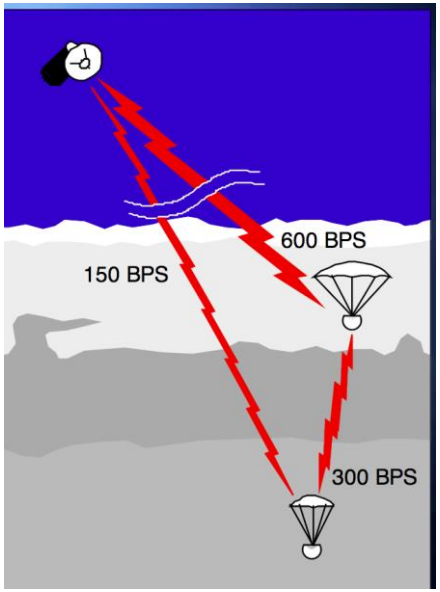
Europa Clipper



Ice Giant Mission Concept

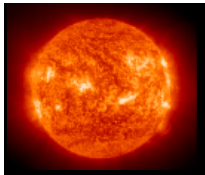






Deep Atmosphere Telecommunications Staged Probe Relay (Simon, Atkinson, Spilker, et al.)

Conclusions



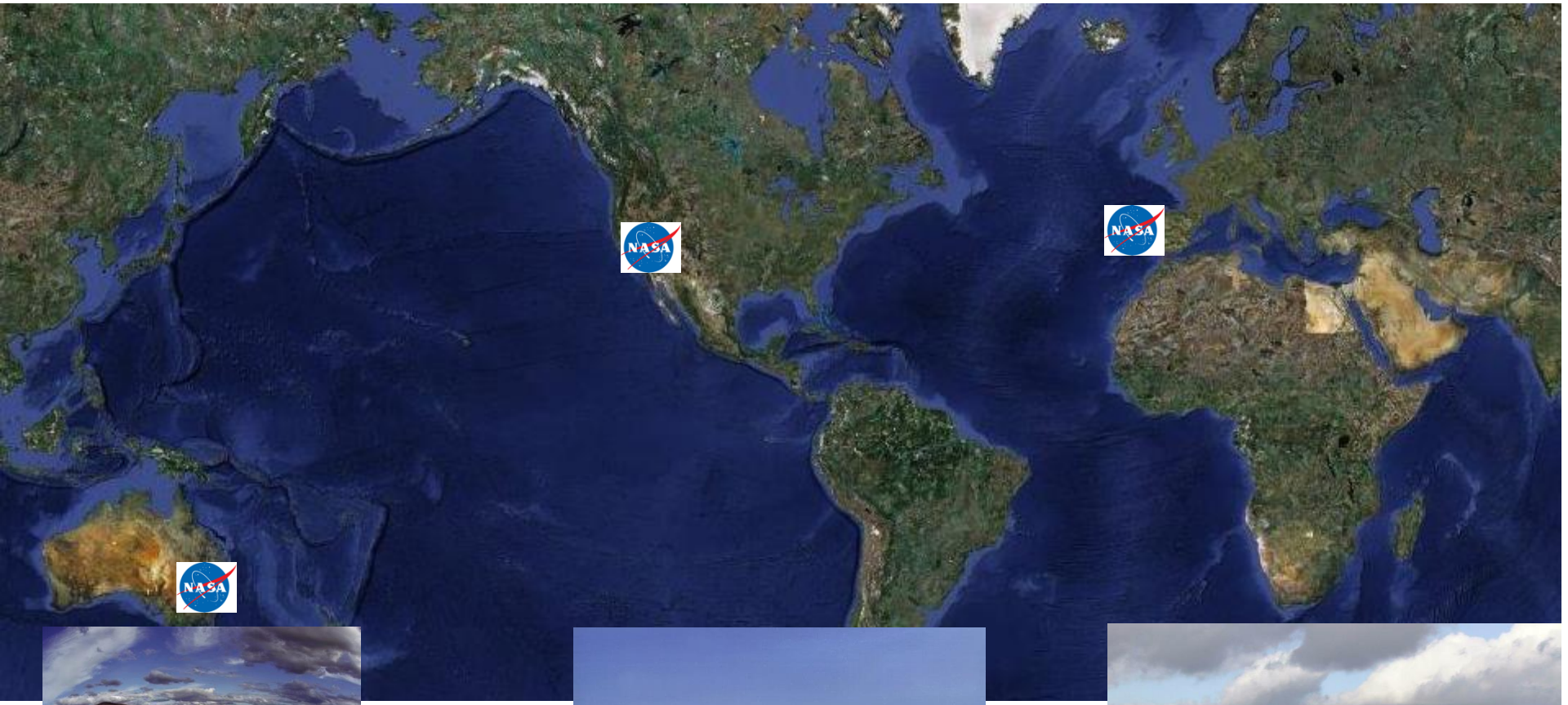
Ambitious science missions realized iff sufficient data returned

Deep Space Network technologies in hand or nearly so for significant improvements in data transport

- **More antennas, Ka band, laser communication, …**

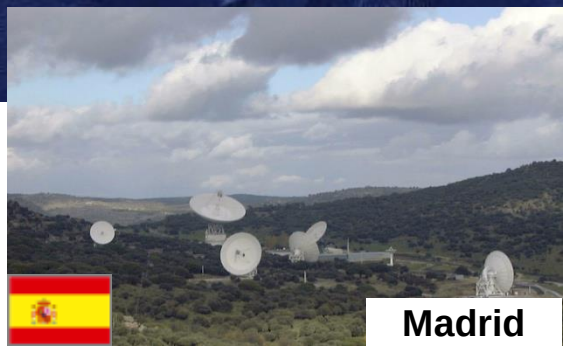
BACKUP

Deep Space Network



Canberra

Goldstone



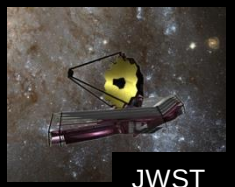
Madrid

Planetary Sciences-DSN Partnership

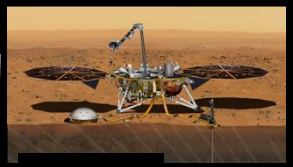
Don’t Leave Earth Without Us!


Solar Probe Plus

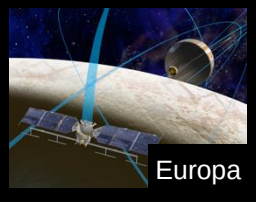

TESS


JWST


BepiColumbo


InSight

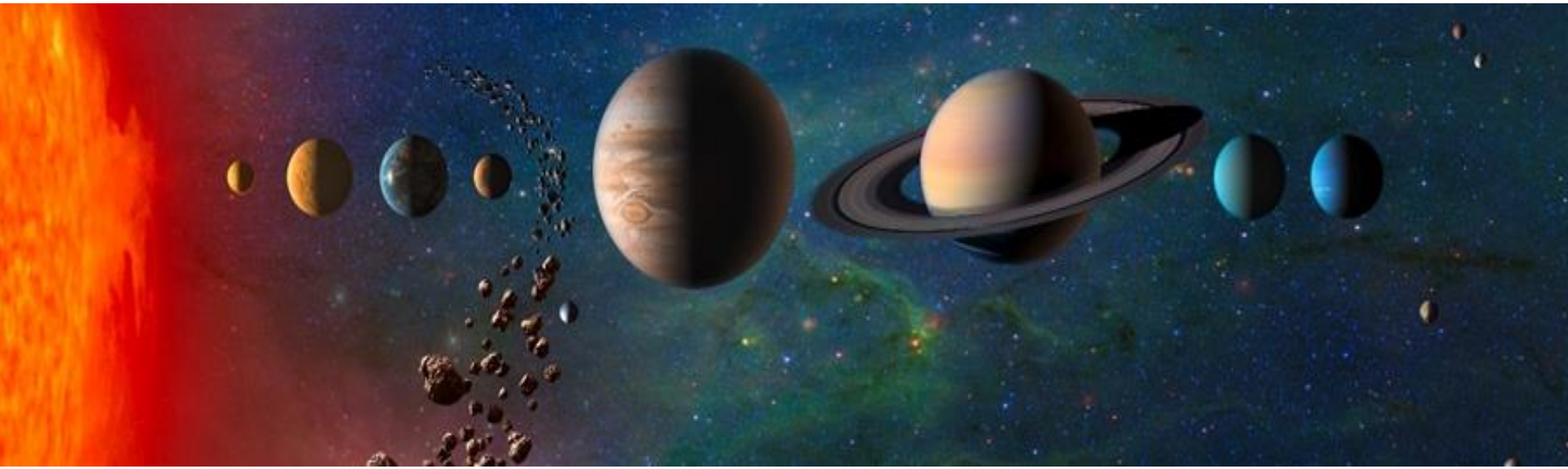

Mars 2020


Europa


GSSR

Exciting and Ambitious!

We Have a Problem …



Higher Data Rates; Better Remote Sensing

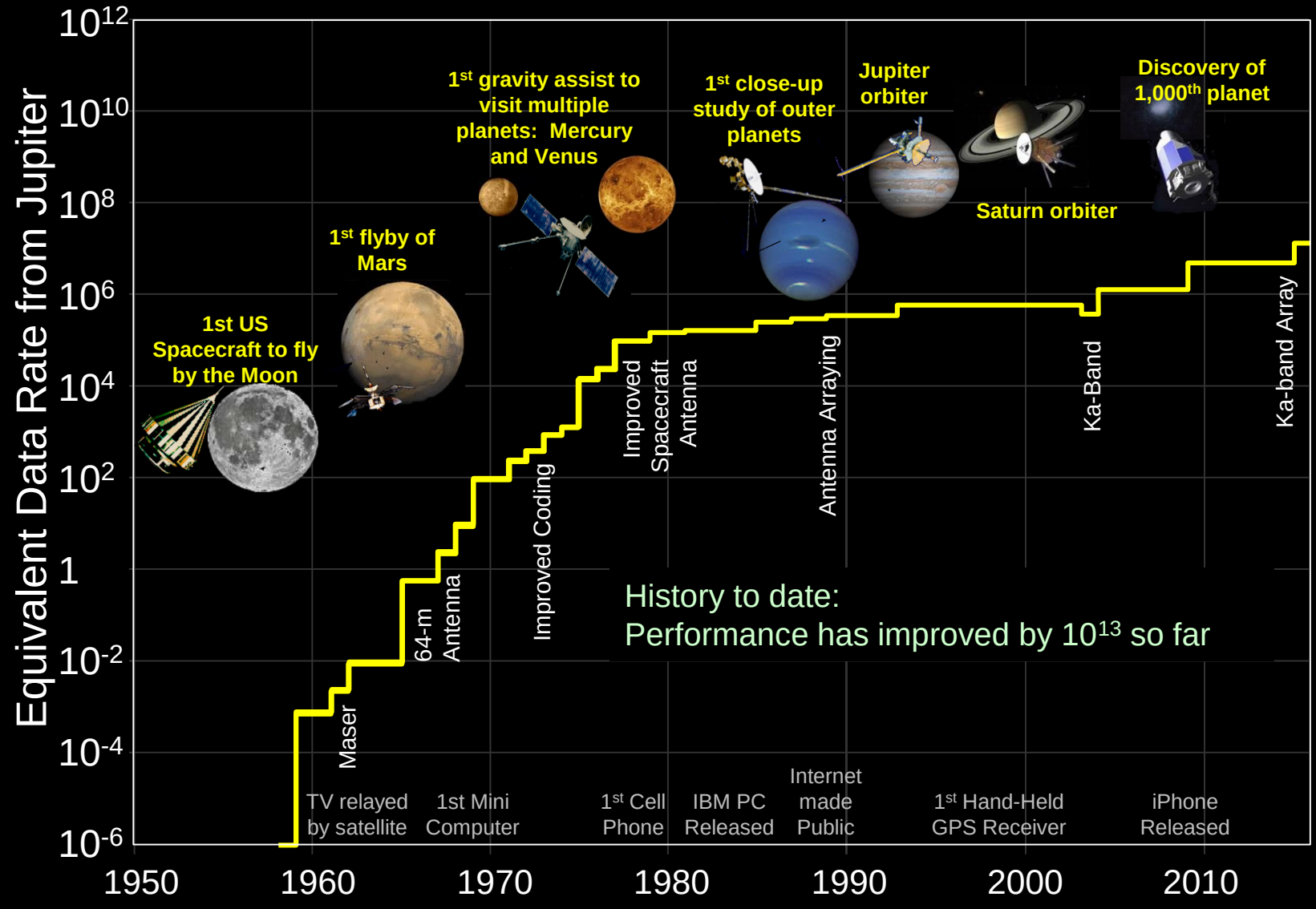
- Martian geology and climatology, life? (MEPAG)
- Exoplanets
  - LUVOIR (Domagal-Goldman et al.; Harris et al.)
  - OST (Milam & Hammel)
  - exoplanet remote sensing (Bains & Schulze-Makuch; Quick et al.)
- Outer solar system
  - Ice giants (Hofstader et al.)
  - Ocean Worlds (Hand et al.)
  - Kuiper Belt and Oort Cloud (Stern et al.)
  - Solar gravity lens point (Alkalai et al.)
  - Outer solar system (Rymer et al.)
- Small sats (Quinn et al.)
- Instruments: high-resolution mass spectrometry (Cleaves & Giri)

- **Ocean Worlds**
  - **under ice (Hendrix et al.; Schmidt)**
  - **chase plane (Owen & Bolton; Rymer et al.)**
- **Constellations**
  - **Ice giants (Hofstader et al.)**
  - **Asteroids (McFadden et al.; Bolton et al.)**
  - **Comets (Bauer et al.)**
  - **Mars (Ehlmann et al.)**
  - **Magnetospheres (Crary et al.)**
- **Challenging terrains (Boston; Rymer et al.)**
- **Atmospheric probes (Bolton et al.)**
- **Aerial vehicles**
  - **Titan (Lorenz et al.; Pauken et al.)**
  - **Venus (Cutts et al.)**
- **Triton (Oleson & Landis)**
- **Multiple surface assets**
  - **Mercury (Chabot et al.)**

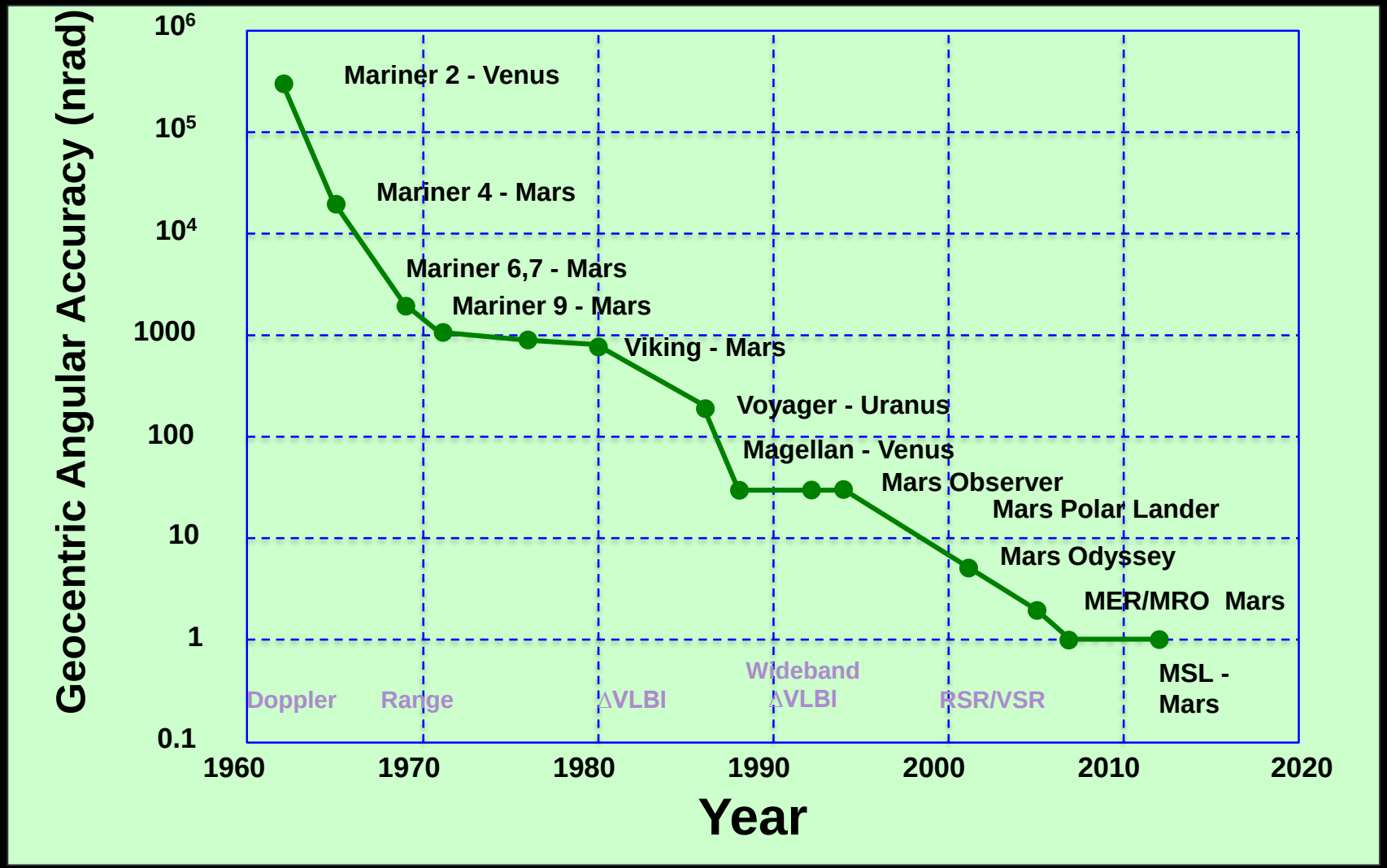
Networks and Relay Communications

- Others
- In situ asteroid tracking (Rivkin et al.)
- Radio Science (Asmar et al.)

History of Downlink Difficulty

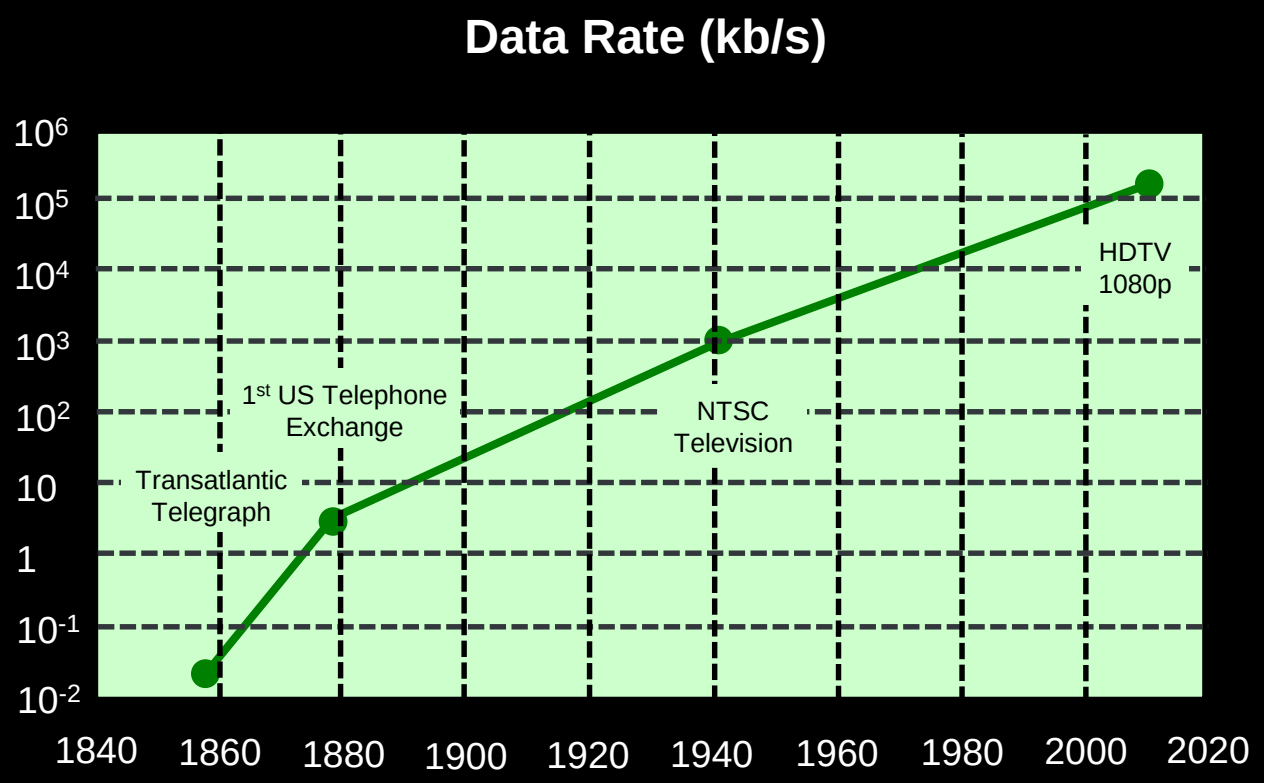


History of Navigational Angular Accuracy



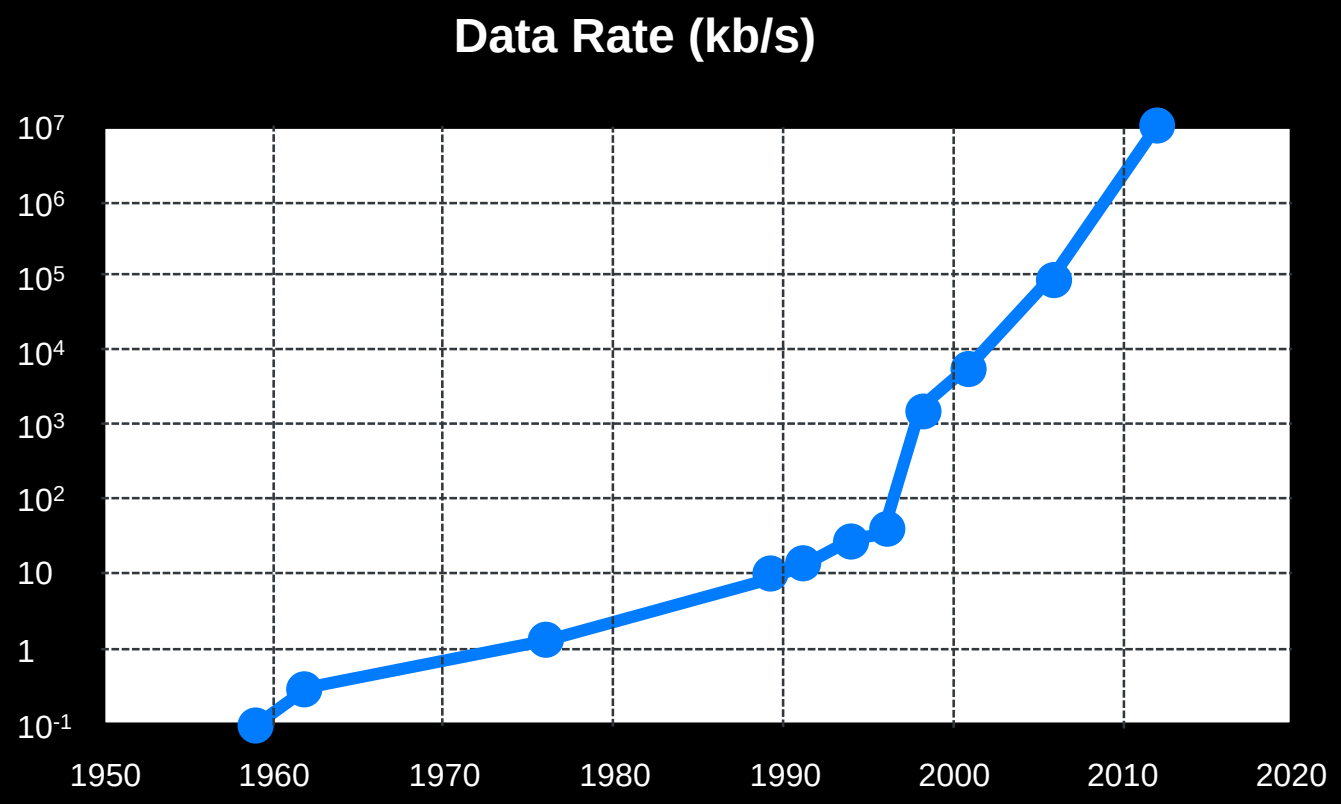
Long Term Communications Trend

- We can look at long term trends for communications in general
- Data gleaned from the Internet leads to ~0.34 orders of magnitude per decade
- But we all know (feel?) the information age has changed this



Internet Communications Trend

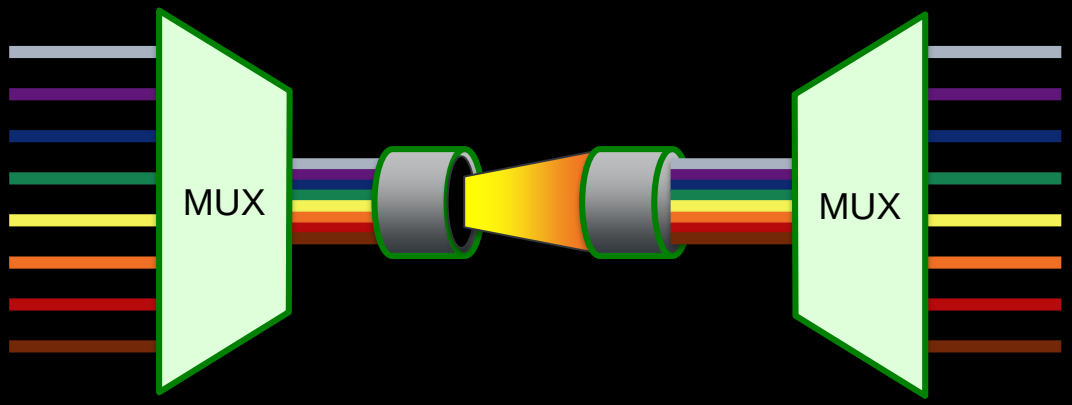
- Consider the trend in digital communications since the Internet was invented
- This trend is ~1.3 orders of magnitude per decade
- We believe spacecraft data needs will grow similarly – so we will use 1.0 orders of magnitude per decade



Decade 3: 1,000X Improvement over Today

Additional factor of 10 comes from second generation optical communication

- Increased laser efficiency
  - ~12% today to ~25% in this time frame
- Dense wavelength division multiplexing (DWDM)
  - Provide 10s-100sof downlink channels
  - Take advantage of new ASICs for coding and modulation
- Coherent communications
  - Possible factor of 3 to 5 improvement for outer planet missions
- Natural evolution of components to reduce size, weight, and power



Decade 4 & 5: 1,000,000X Improvement over Today

It is hard to predict exactly what technologies will pay off in this time frame for the remaining factor of 100

However, history shows that the DSN has found radio improvements even after 50 years of maturation

Some possibilities:

- Further increases in transmitter efficiency
- Better power sources for spacecraft, perhaps driven by human exploration far from Earth
- Further improvements in DWDM technology
- Antenna arraying on a massive scale
- Disruptive technologies
  - Quantum communications
  - X-ray communications

Relays and Networking

Some of these capabilities will not be practical on smaller spacecraft

Communications capability can be provided to these more capable relay spacecraft

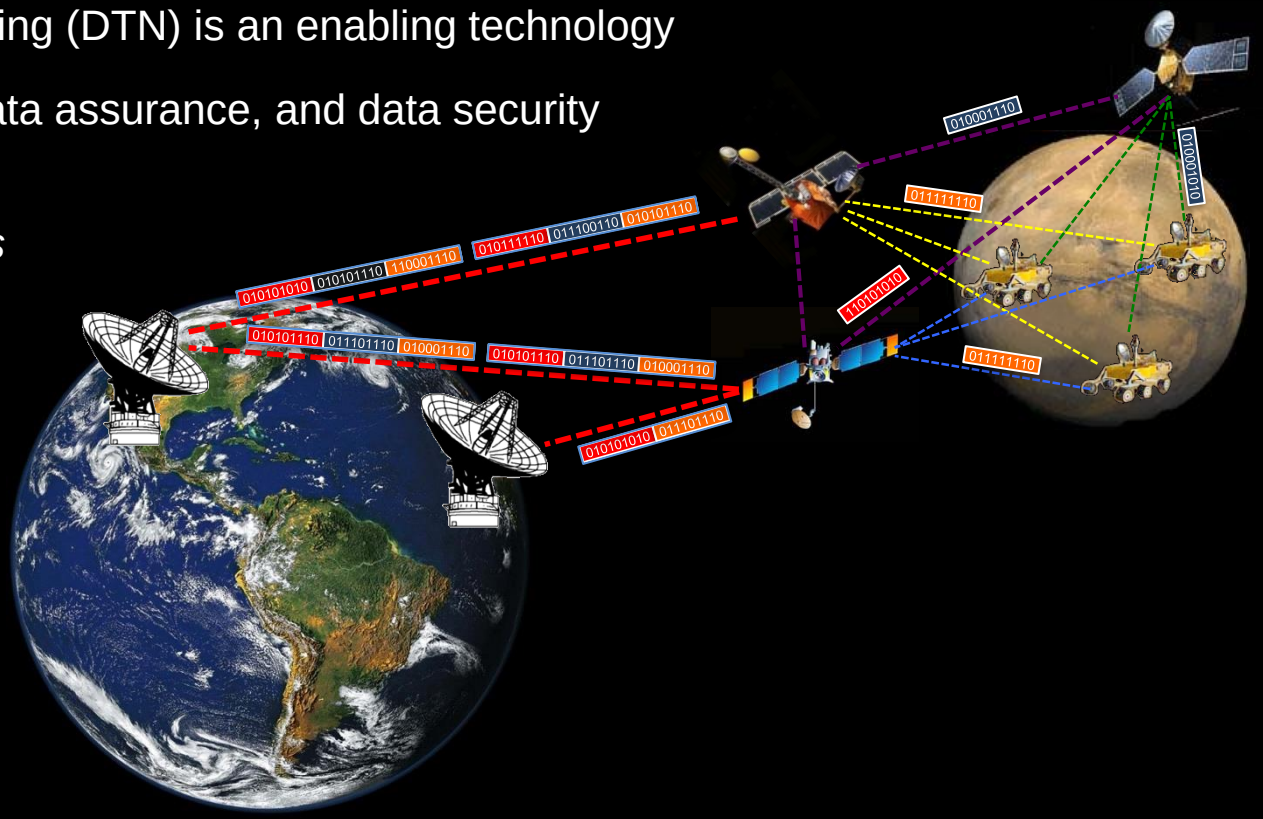
- Viking, Galileo Probe, Huygens, and Philae have taken advantage of this architecture

Disruption Tolerant Networking (DTN) is an enabling technology

- Provides automation, data assurance, and data security

NASA and our partners will emplace *planetary networks* to support areas of future intense exploration

- Today's *Mars Network* provides these services to landers and rovers



DSN Data Rates: Next 50 Years

Taking all of this into account, here are some likely data rate capabilities for the future DSN

	Distance (AU)	Today (Mbps)			2025 (Mbps)		2035 (Mbps)	2045 (Mbps)	2055 (Mbps)	2065 (Mbps)
DSN Configuration		34m X-band	3 x 34m X-band	34m Ka-band	4 x 34m Ka-band	Optical	Optical	Optical	?	?
Spacecraft Configuration		3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 180 W transmitter 1/2 LDPC code	0.3m optics 10 W transmitter PPM modulation	0.5m optics 50 W transmitter PPM modulation	0.5m optics 200 W transmitter 2nd gen modulation	?	?
Venus (Closest)	0.3	80.0	240	320	2,304	2,800	2.9E+04	2.9E+05	2.9E+06	2.9E+07
Venus (Farthest)	2.4	1.3	3.8	5	36	44	460	4,603	5.E+04	5.E+05
Mars (Closest)	0.6	20	60	80	576	700	7.E+03	7.E+04	7.E+05	7.E+06
Mars (Farthest)	2.6	1.1	3.2	4.26	30.7	37	392	4.E+03	4.E+04	4.E+05
Jupiter	5.4	0.247	0.741	0.99	7.1	8.6	91	909	9,093	9.E+04
Saturn	10.1	0.071	0.212	0.28	2.0	2.5	26	260	2,599	3.E+04
Uranus	19	0.020	0.060	0.08	0.57	0.70	7.3	73.4	734	7,345
Neptune	30.3	0.008	0.024	0.03	0.23	0.27	2.9	28.9	289	2,888

NASA's budget can not accommodate huge increases in DSN investment

We will achieve this through a combination of

- Internal technology and capability development
- Partnering with other parts of NASA, other US agencies, and other space agencies
- Leveraging developments from academia, industry, and other appropriate sources