Realizing the Future of Deep Space Communications and Navigation

Les Deutsch and Steve Townes
Jet Propulsion Laboratory, California Institute of Technology
Pete Vrotsos and Don Cornwell
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology

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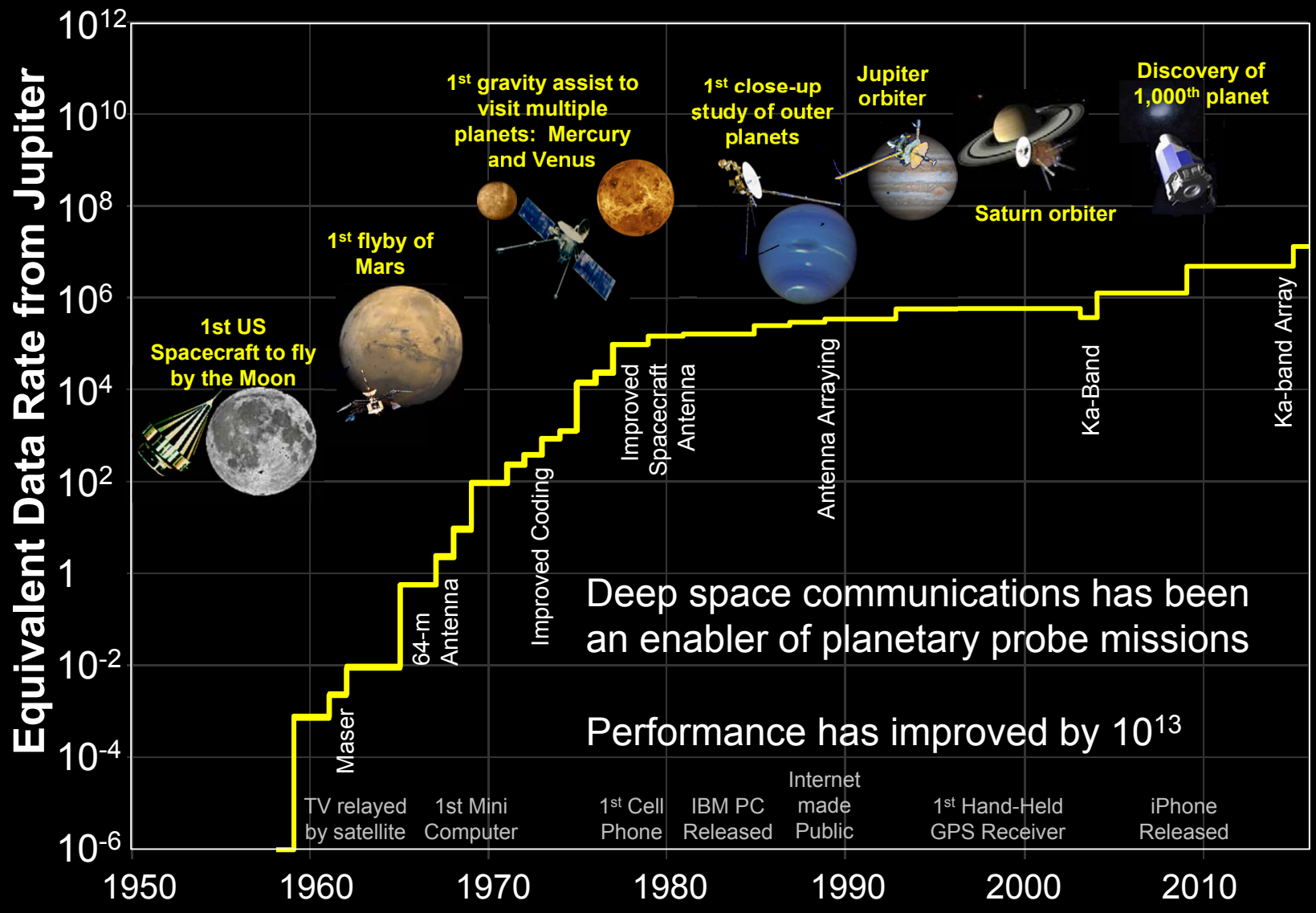
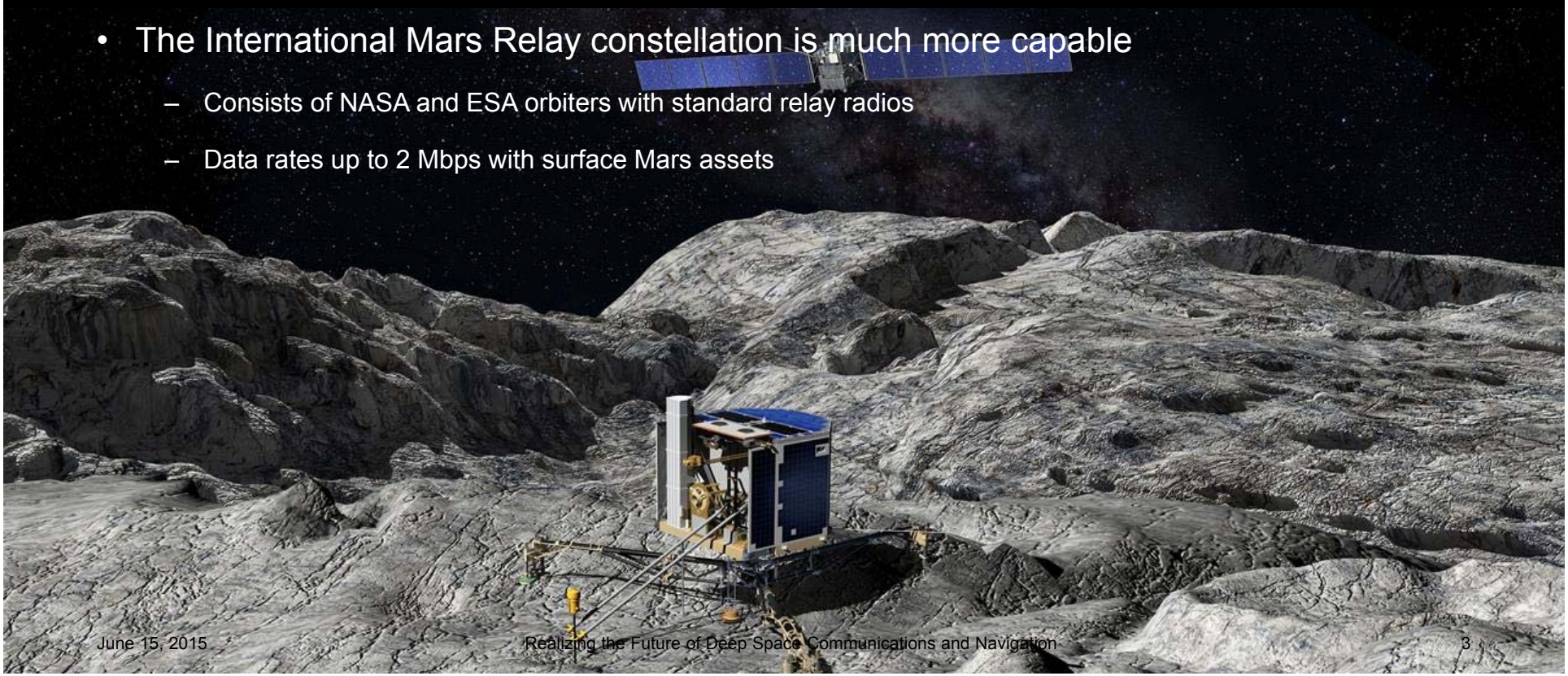
Deep Space Communication: Trunk lines



Deep Space Communications: Relay Links

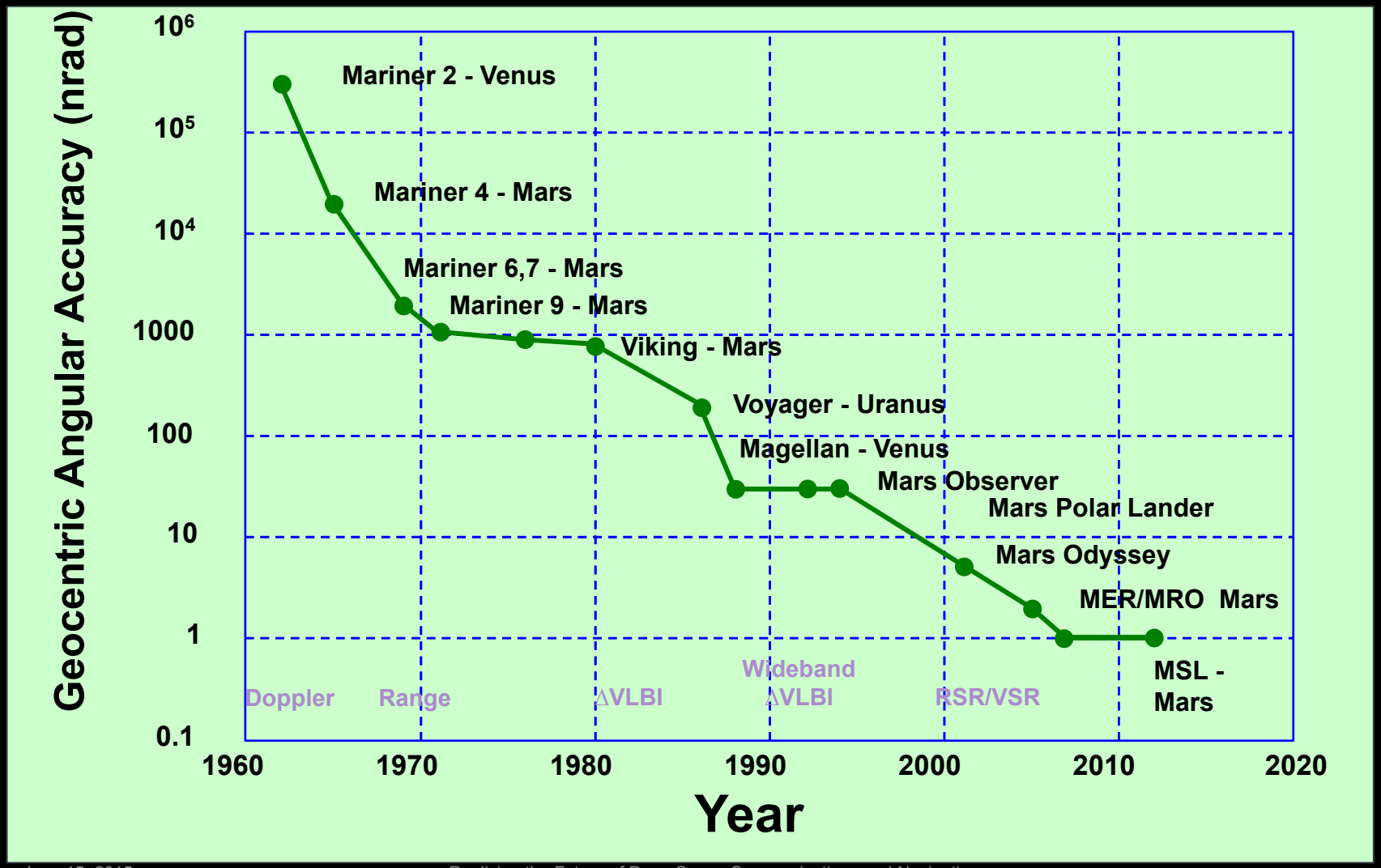
When the probe has limited communications capability, relays enable higher performance

- The 1995 Galileo Jupiter probe relayed data at ~1 kbps
  - The trunk line was actually much less capable due to the failure of the spacecraft's high gain antenna!
- The 2004 Huygens Titan Probe relayed data to Cassini at ~8 kbps
- The 2014 Philae 67P/Churyumov probe relays data to Rosetta at 16 kbps
- The International Mars Relay constellation is much more capable
  - Consists of NASA and ESA orbiters with standard relay radios
  - Data rates up to 2 Mbps with surface Mars assets



Deep Space Navigation

- Steering a probe to its destination is often a critical problem
- Measurements of the communication links provide much of the data

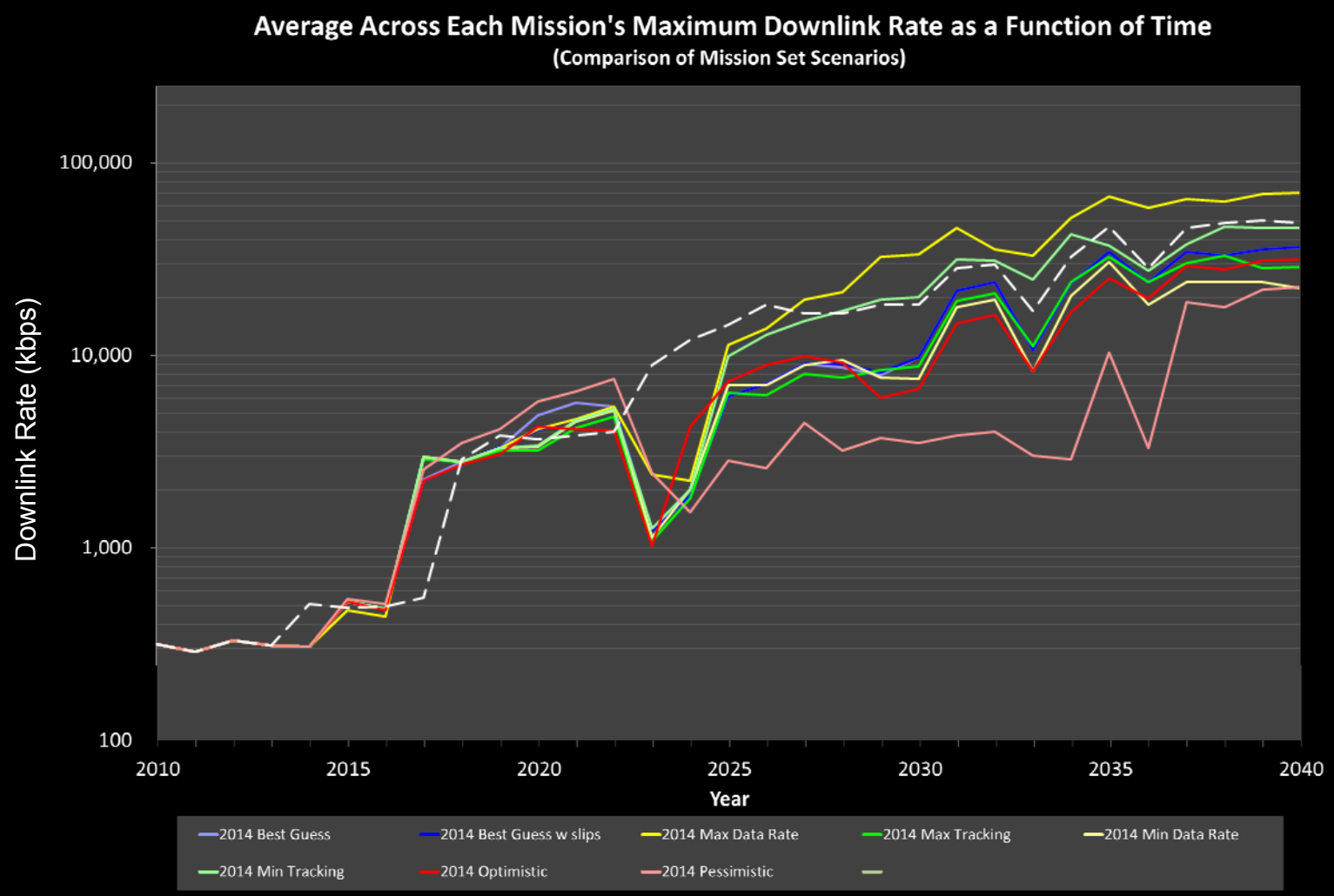


Standards for Comm and Nav

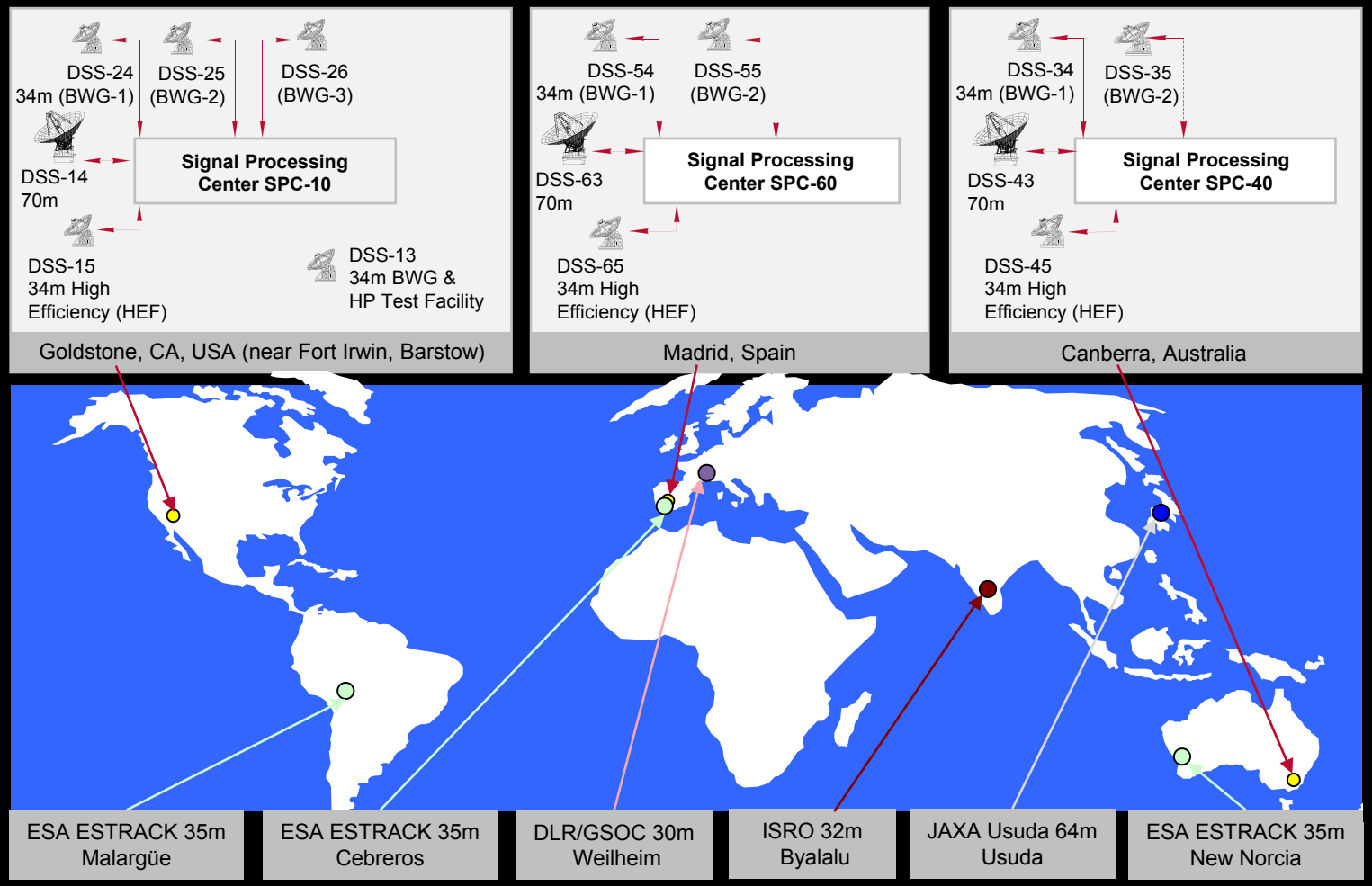
- The Consultative Committee for Space Data System Standards (CCSDS) is one of the true success stories for international cooperation in space exploration
- CCSDS currently has 141 published standards, along with suggested implementations, covering all aspects of communications and multimission operations
- 751 missions have used these standards so far
- Greatly simplified the process of international partnering
- Allows easy cross-support of missions
- 13 international space agencies participated at the last meeting

What Will We Need for the Future?

- Analysis of likely future missions to be tracked by the DSN indicates a need for 10x improvement in data rate per decade



Today's Earth Stations



Today's Earth Stations – and More:

- Standards have enabled tracking stations to cross-support spacecraft of other agencies
- Adds to the richness of international cooperation
- JAXA, ISRO, and probably others have plans to expand their capability
- In the future, we also expect additional deep space tracking stations from Korea, South Africa, and the United Arab Emirates

Plans for the DSN: Antennas

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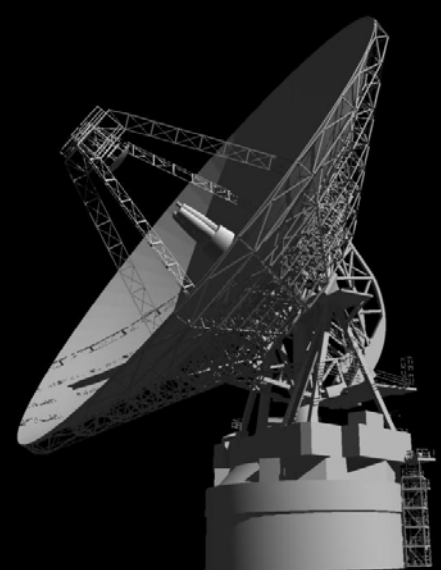


More DSN capability

More southern hemisphere coverage

More Ka-band

No more 70m single points of failure

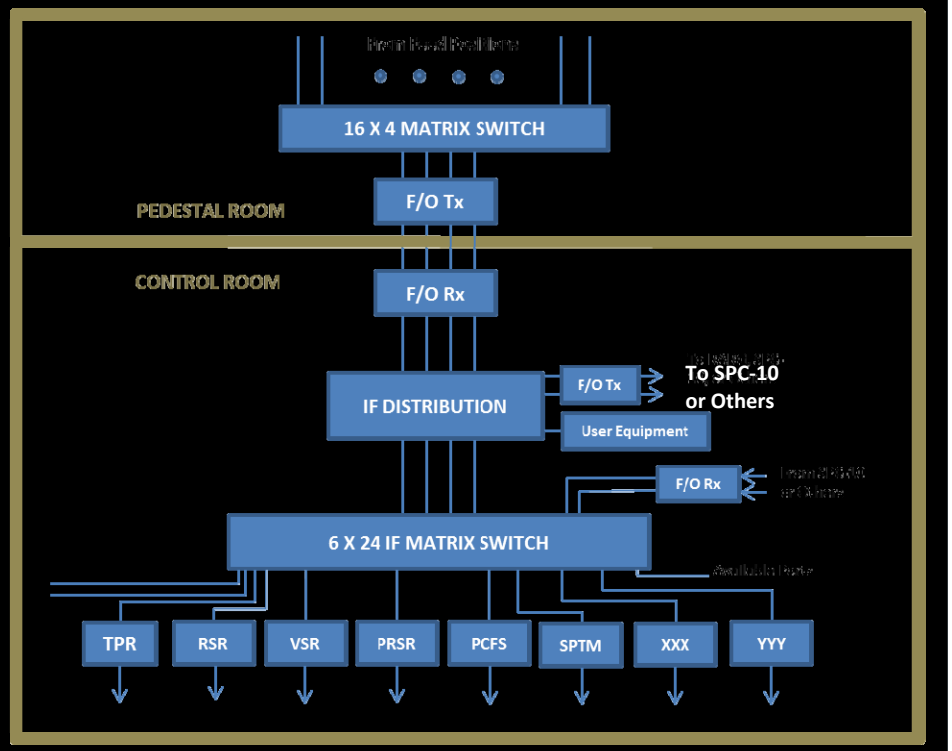
At all DSN locations

The Deep Space Network

Presents...

More DSN Plans

- "Common Platform" receiver
  - Software defined radio
  - Deep space and near-Earth telemetry, radio science, radar …
- Additional coding and modulation
  - LPDC coding suite
- Higher data rates
  - Data rates greater than 200 Mbps
- More frequent antenna arraying
- More tracking of multiple spacecraft in a single beam
  - Increase from today's two to four and maybe more



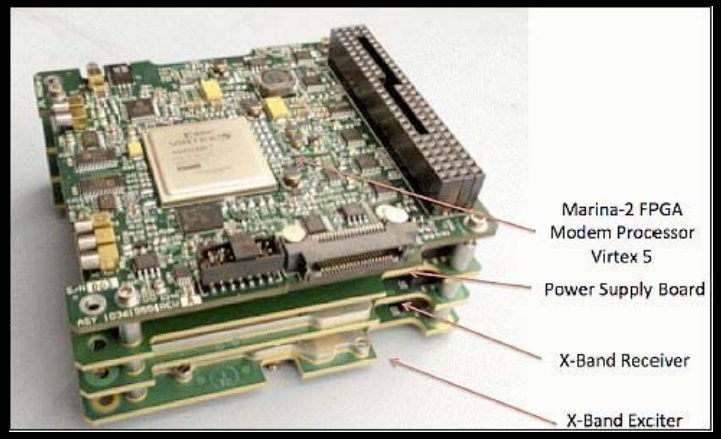
Deep Space Flight Radios Today

General Dynamics Small Deep Space Transponder X/X/Ka

Thales Alenia X/X/Ka Deep Space Transponder

QinetiQ MELACOM UHF Radio

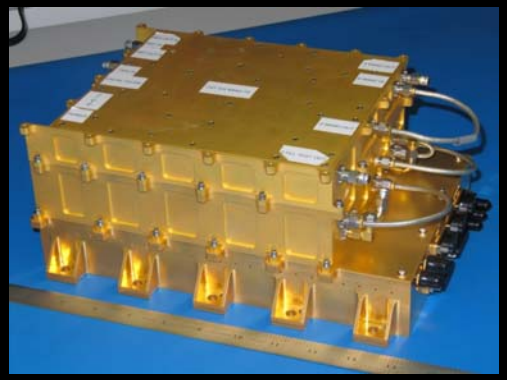
L3 Cincinnati Electronics-JPL Electra UHF Radio

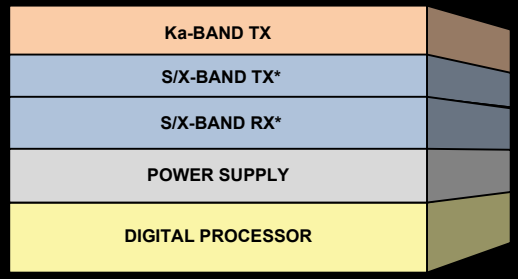


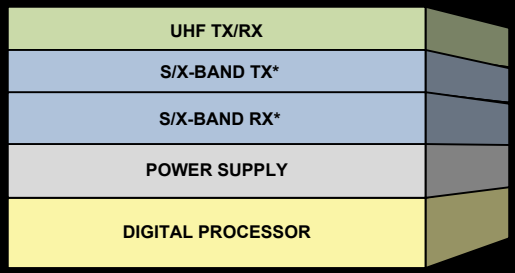
IRIS (Version 1) Deep Space Cubesat X-band Radio

Universal Space Transponder

- Powerful, reprogrammable Software Defined Radio (SDR)
  - Enables post-launch infusion of new capabilities, upgrades & fixes
  - NASA Space Telecommunications Radio System (STRS) Standard
  - Advanced communications protocols (e.g., Prox. 1, DTN)
  - Can perform functions normally handled by spacecraft computer
- Can be multi-band (e.g., UHF/X-band & X/Ka-band)
  - Simultaneous Direct-to-Earth and Relay
- Higher bi-directional data rates
  - 7.8 bps – 20 Mbps on forward link
  - 10 bps – 300 Mbps on return link
- Frequency agility to tune to any channel in a given band
- Arbitrary modulations and pulse shaping
- Advanced radiometrics
  - Pseudo Noise ranging
  - Wider separation ranging tones improve double nav accuracy
  - Open loop recording



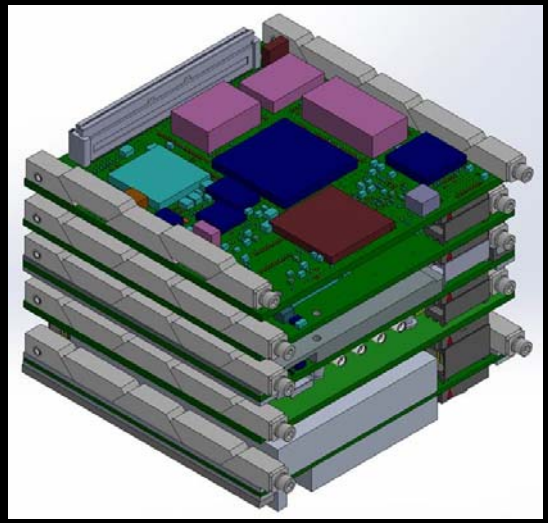




Other Future Radios

- Frontier Radio – JHU Applied Physics Laboratory (APL)
  - Reprogrammable Software-Defined Radio – STRS Compatible
  - X/X/Ka – Coherent
  - 1.3 Mb/s uplink
  - 300 Mb/s downlink (QPSK)
  - Pseudo Noise Ranging

- IRIS v3 for Nanosats – JPL
  - Ka-Band exciter/receiver/diplexer
  - Baseband Processor Module
    - Low power FPGA
    - Space qualified parts as needed
  - Flight reconfigurability through selection of multiple stored files
    - Additional files can be uploaded during flight
    - Enable running inherited Electra/UST software

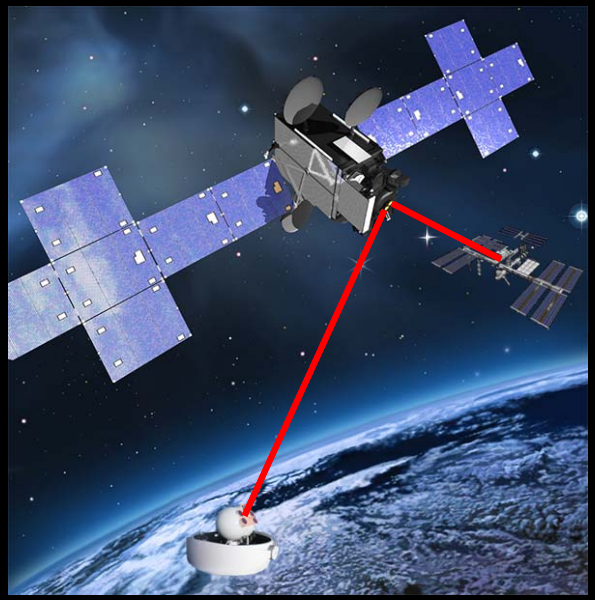


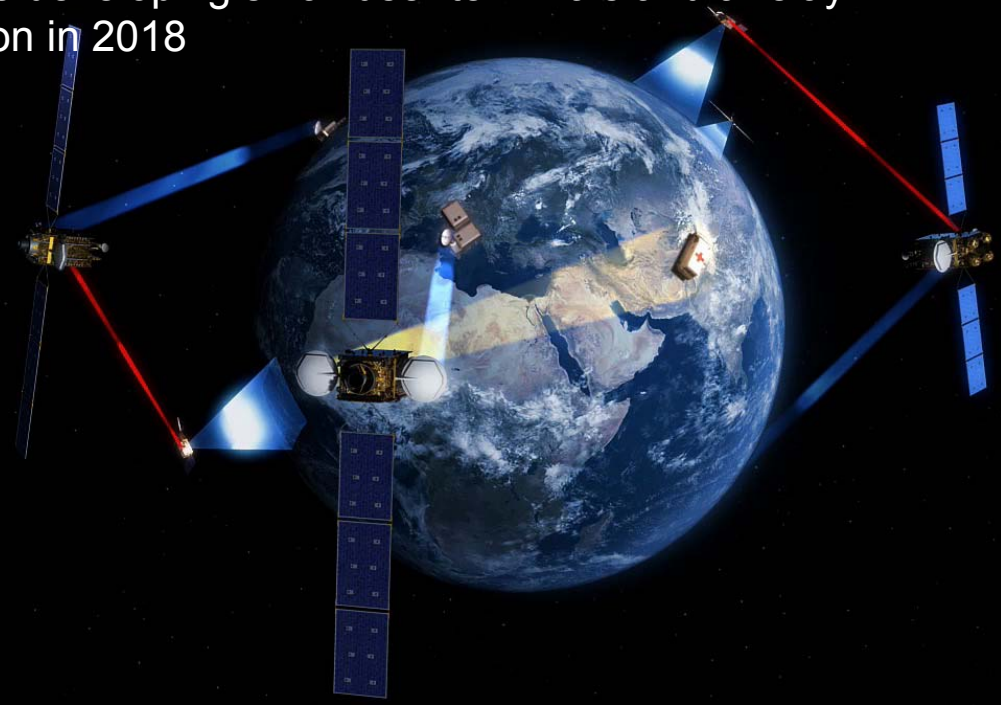
Optical Communications

- All else being equal, communication performance increases like the square of the carrier frequency
  - Due to the beam width of a signal from a fixed aperture
- We predict performance 10x Ka-band in the near term and 100x within another decade
  - For the same aperture mass, and power in space and a 12m Earth receive aperture
- There is a LOT of interest in optical communications worldwide – mostly for near-Earth applications where the big payoff is more bandwidth and less international restrictions
  - Radio spectrum is big business and very expensive to obtain
- In deep space, we will use the 10-100x advantage in various ways
  - More returned bits, smaller spacecraft, more accurate “light science” …

Status of Optical Communications – Near Earth

- ESA is developing a commercial optical communications capability for LEO space applications
  - The European Data Relay Satellite (EDRS) will provide services to LEO missions
  - Data rates up to 1.8 Gbps
  - First launch is later this year
- NASA and MIT Lincoln Laboratory are developing small user terminals and a relay satellite capability with a demonstration in 2018
  - Data rates up to 2.88 Gbps

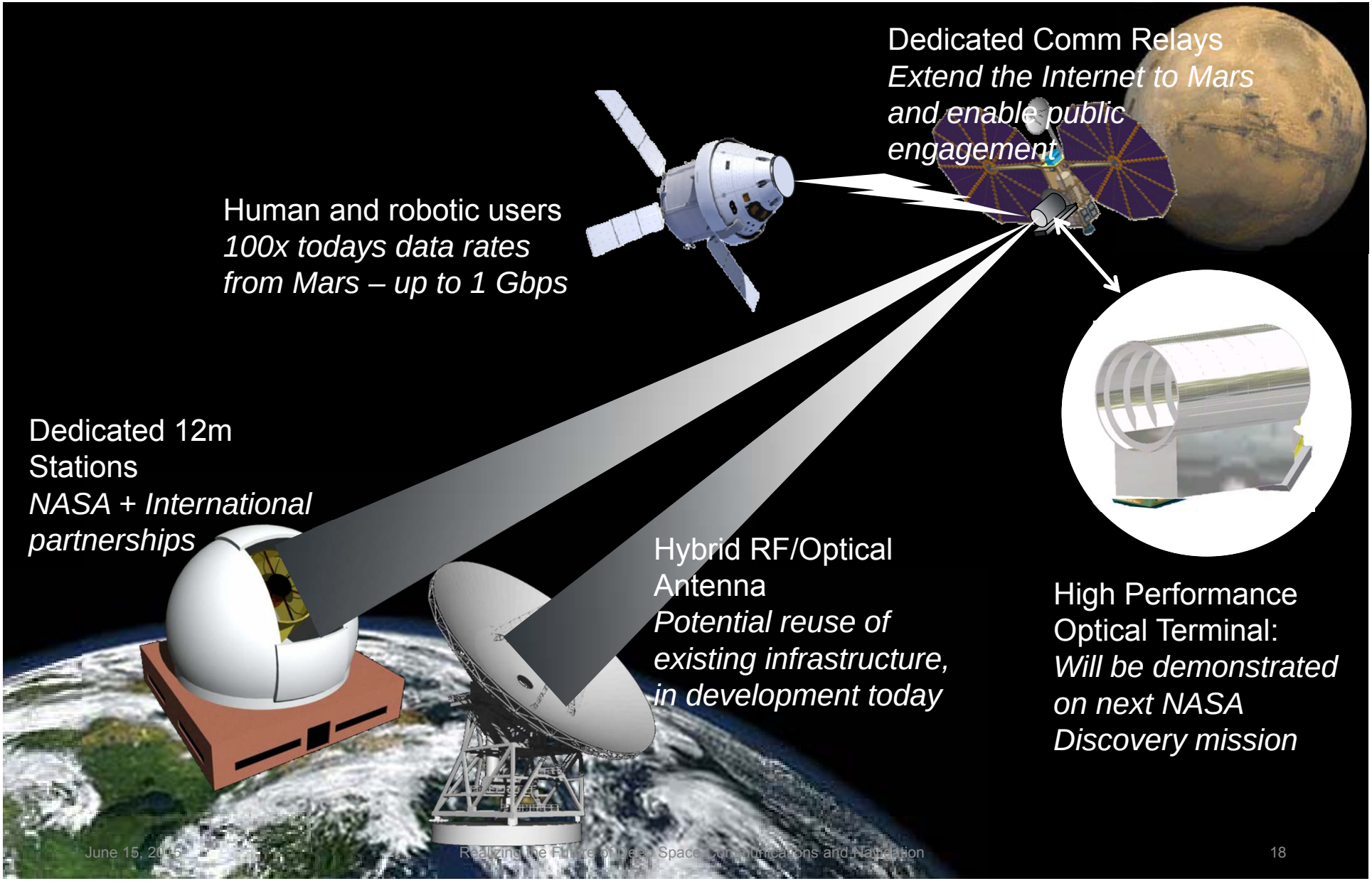




Deep Space Optical Communications

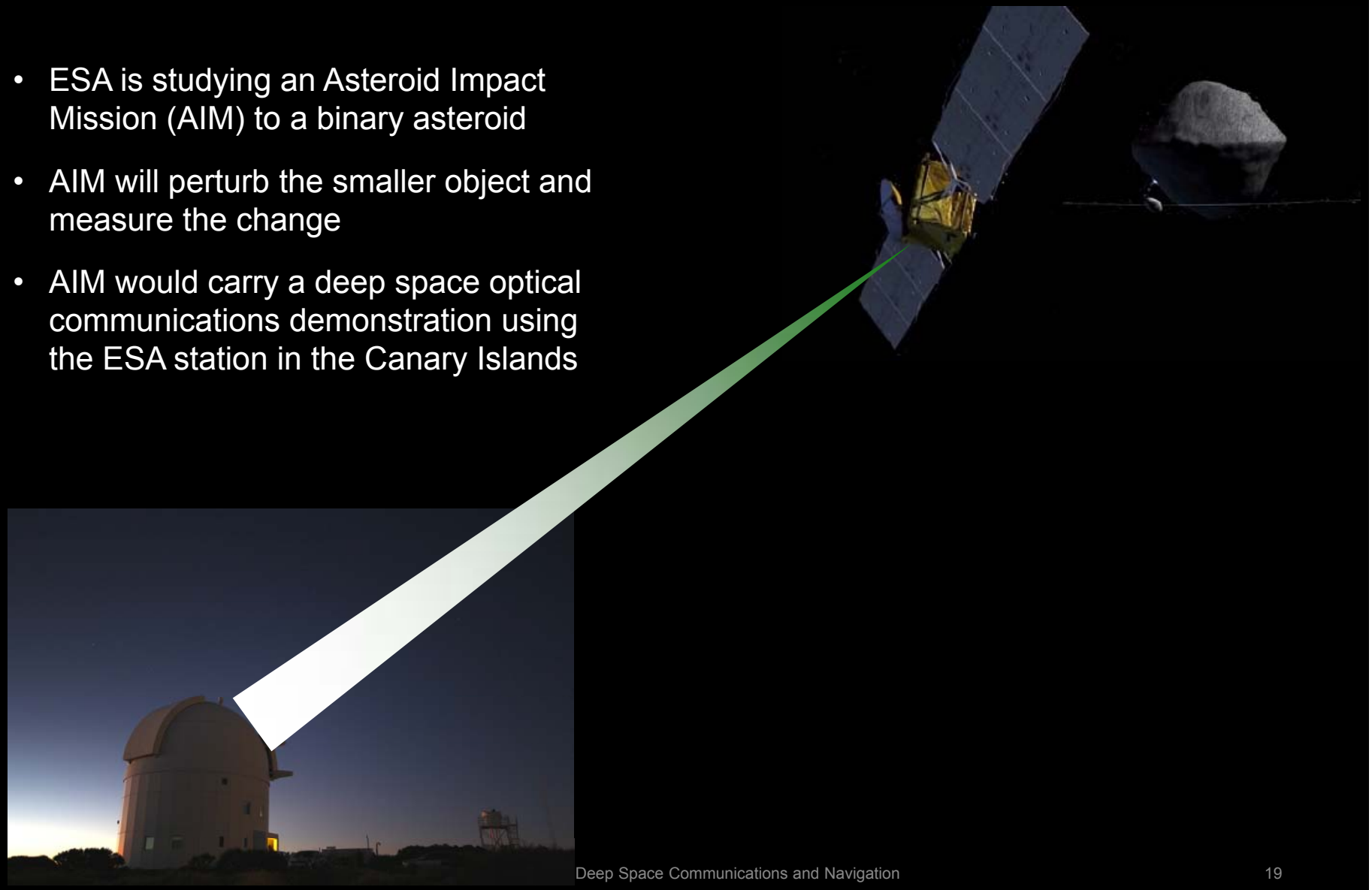
- Different from near-Earth systems
  - Individual photons matter
  - Pointing is difficult – including “point ahead”
- NASA flew the Lunar Laser Comm Demonstration (LLCD) on the Lunar Atmosphere and Dust Environment Explorer spacecraft
- Demonstrated optical communications between the Moon to Earth at rates up to 622 Mbps into a 40 cm ground receiver
  - Equivalent to ~11.5 kbps at Mars
  - …or 10.3 Mbps if we had a 12m ground station – more on that later
- Also demonstrated operational diversity to mitigate weather effects, using three ground terminals

Deep Space Optical Comm (DSOC) Terminal



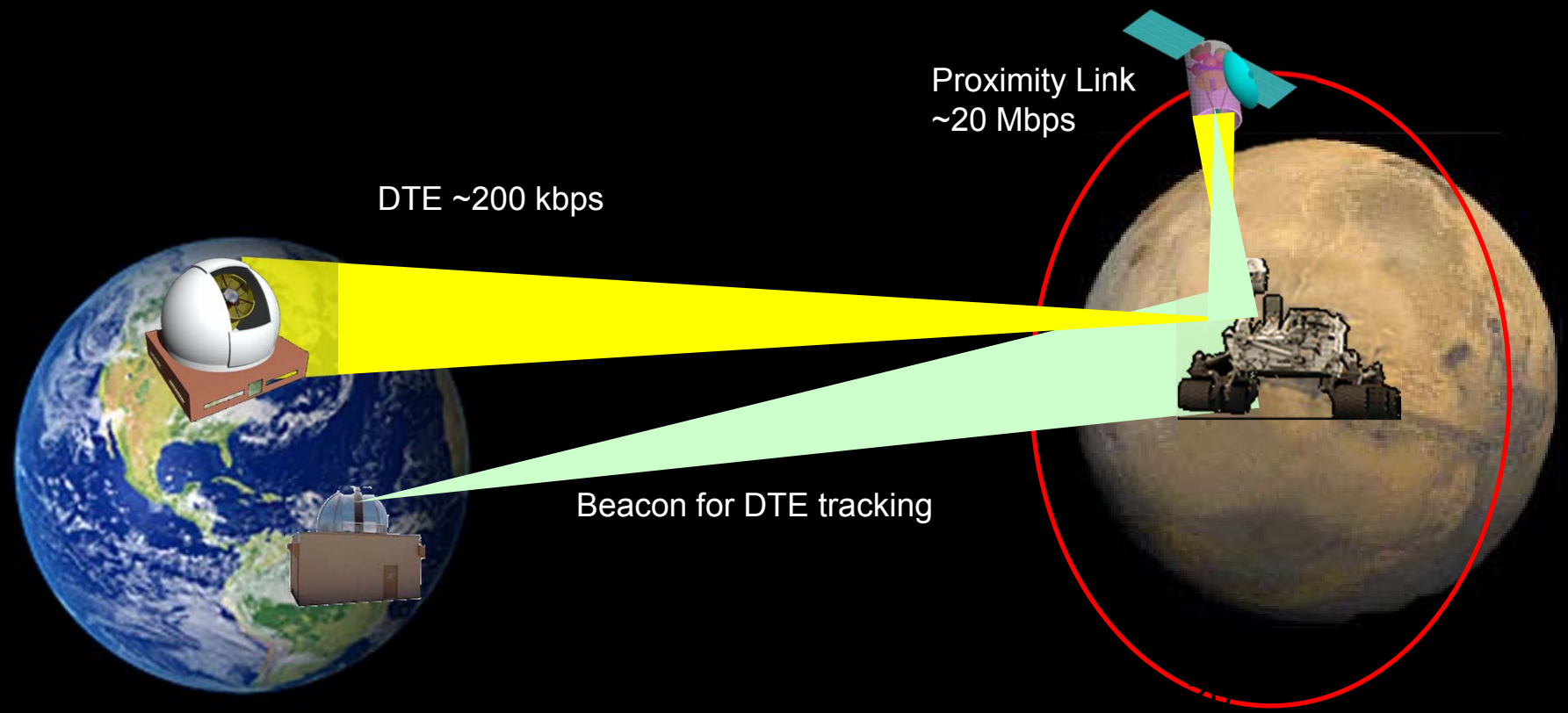
ESA Deep Space Optical Communications

- ESA is studying an Asteroid Impact Mission (AIM) to a binary asteroid
- AIM will perturb the smaller object and measure the change
- AIM would carry a deep space optical communications demonstration using the ESA station in the Canary Islands



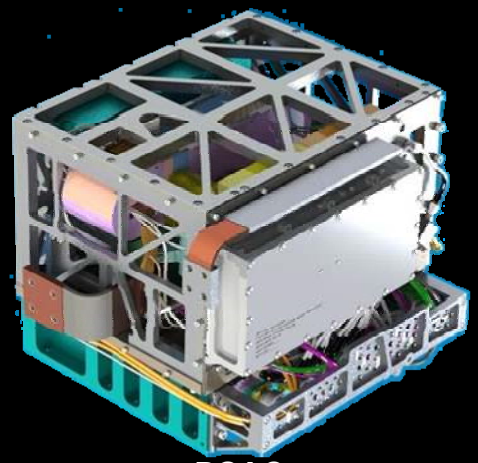
Relay Links using Optical Communications

- Studies using Mars 2020 indicate excellent performance for small (5 cm) terminal
- Additionally, a backup direct-to-Earth capability is possible

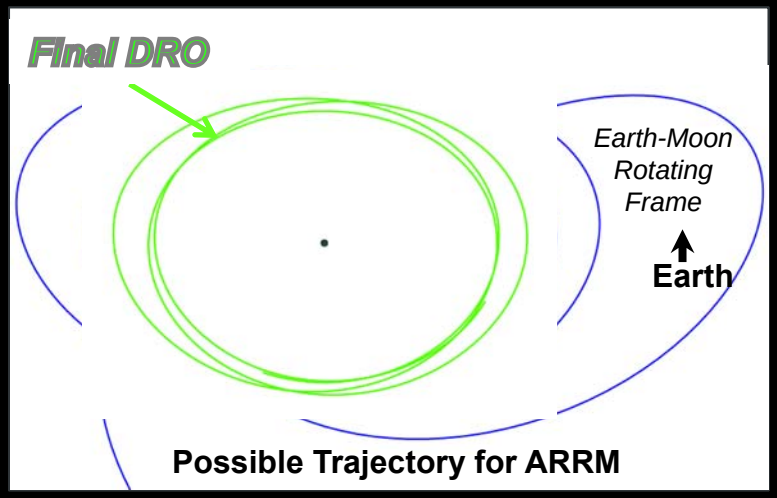


New Deep Space Navigation Techniques

- Deep Space Atomic Clock:
  Reduce ground tracking requirements
- Low-Thrust / Low-Energy Trajectories:
  Increase mass delivery
- Onboard Optical and Radio Navigation:
  Enable pinpoint landing and autonomous operations

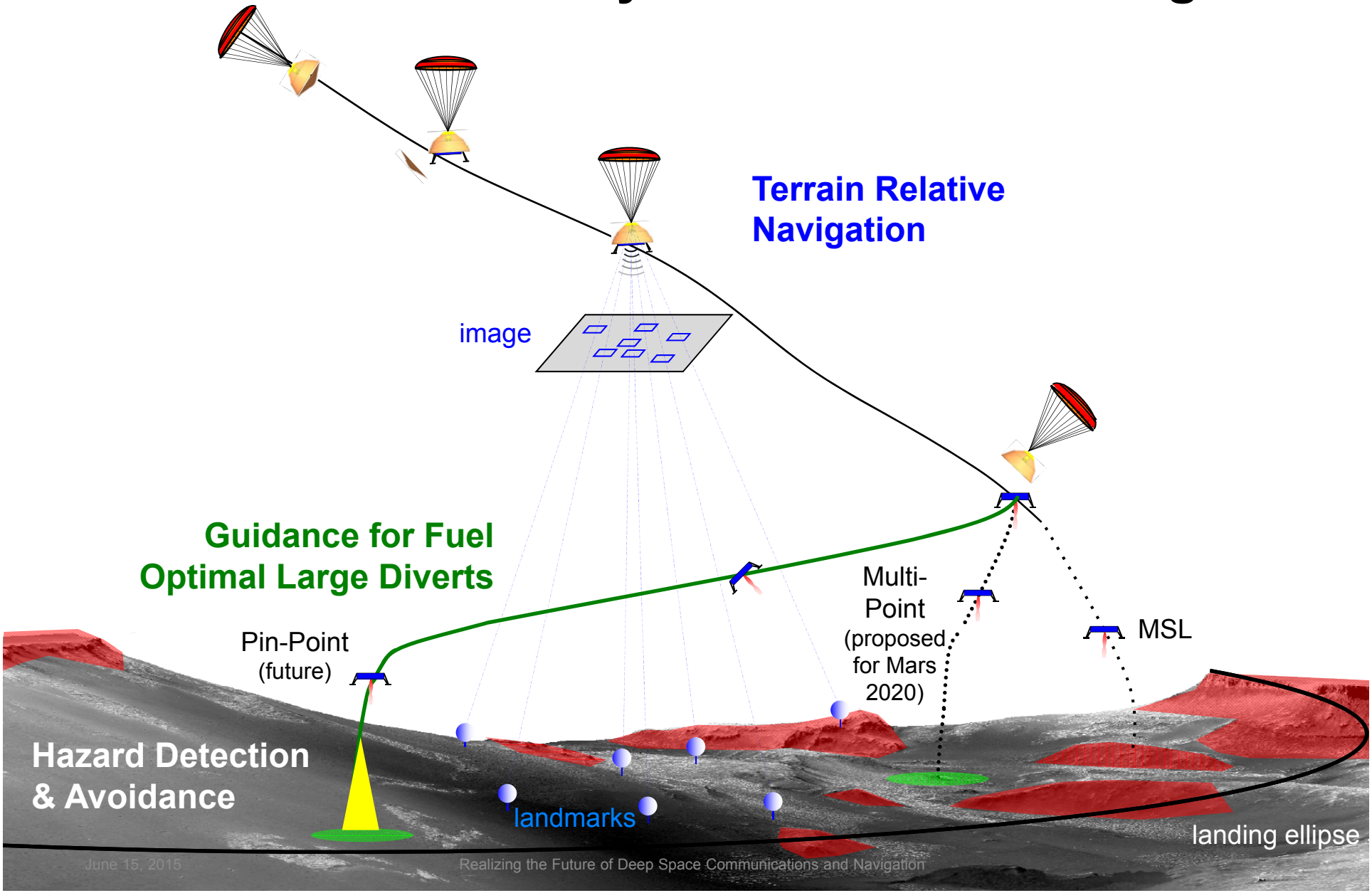


DSAC



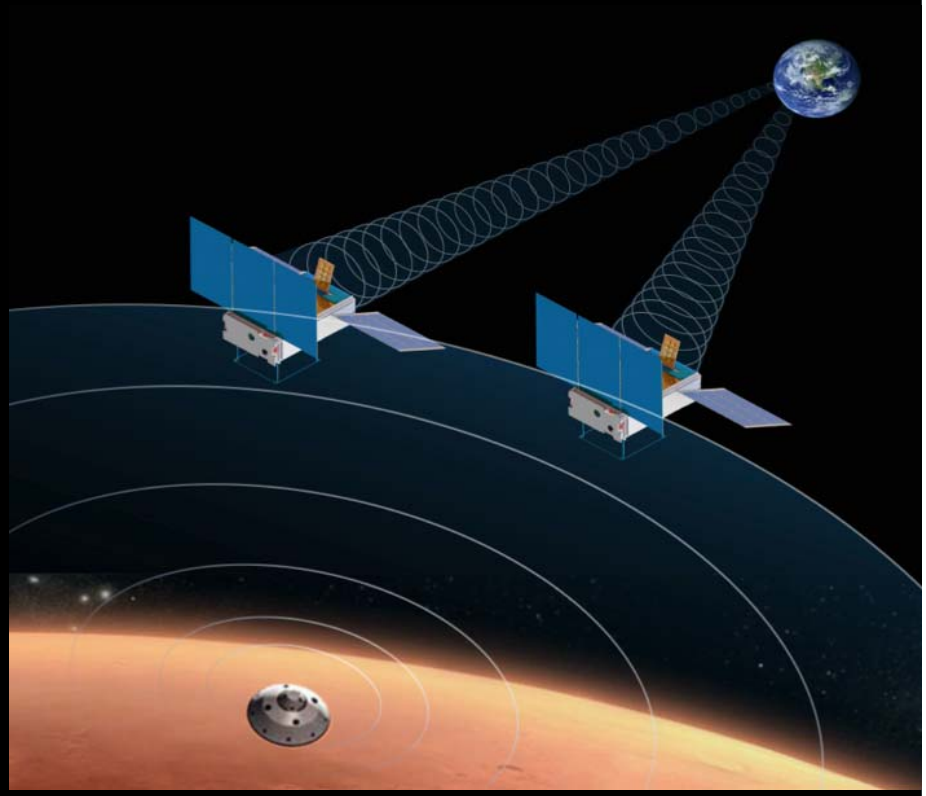
Possible Trajectory for ARRM

Next Generation Entry Descent and Landing



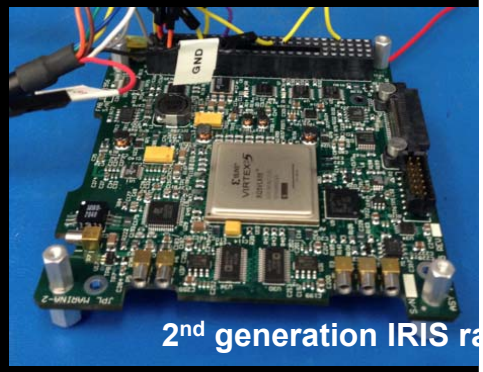
Role of NanoSats in Planetary Probe Missions

- Free-flying spacecraft, direct links to Earth
  - Several deep space CubeSats are planned for launch with the next Orion in 2018
  - Two MARCO CubeSats will fly to Mars alongside InSight in 2016 to help provide relay during EDL
- Communications and navigation are two bottlenecks for these kinds of missions
- Daughter spacecraft to enhance science missions
  - Several NASA Discovery proposal concepts include daughter CubeSats
  - Relay communications is critical to their success
- Daughter spacecraft to provide relay infrastructure at areas of intense exploration
  - Being considered for the future
- Probes

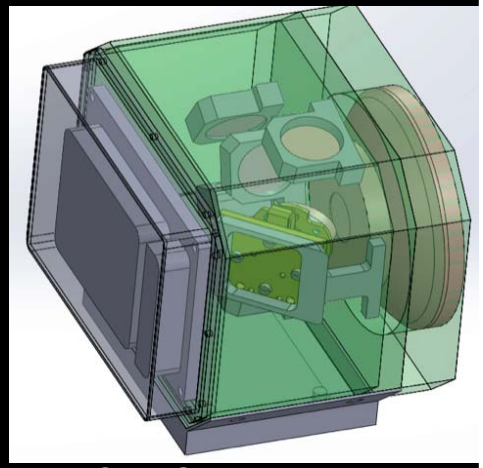


Emerging Deep Space NanoSat Technologies

- CCSDS-compatible X-band radio
- Optical terminals for CubeSats (NASA, ESA, DLR, …)
- Demo of DSN “opportunistic multiple spacecraft per aperture” (OMSPA) completed
  - Provide essentially unlimited number of simultaneously-tracked spacecraft
- 0.5m Ka-band deployable parabolic antenna
- Begun working with universities to create a federated network of ground antennas, based on existing standards

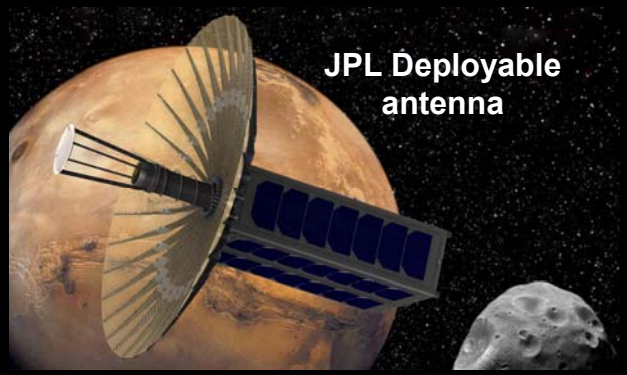


2nd generation IRIS ra



JPL CubeSat optical terminal

Morehead State University
21m Antenna



JPL Deployable
antenna

Possible Future Performance

- With the planned capabilities discussed today, we can expect this for trunk lines:

	Distance (AU)	Today (Mbps)			2025 (Mbps)			2035 (Mbps)
DSN Configuration		34m X-band	3 x 34m X-band	34m Ka-band	4 x 34m Ka-band	4 x 34m Ka-band	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 100 W transmitter 1/2 LDPC 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
Venus (Closest)	0.3	80.0	240	320	1,280	2,304	2,800	29,461
Venus (Farthest)	2.4	1.3	3.8	5	20	36	44	460
Mars (Closest)	0.6	20	60	80	320	576	700	7,365
Mars (Farthest)	2.6	1.1	3.2	4.26	17	31	37	392
Jupiter	5.4	0.247	0.741	0.99	3.95	7.11	8.6	91
Saturn	10.1	0.071	0.212	0.28	1.13	2.03	2.5	26
Uranus	19	0.020	0.060	0.08	0.32	0.57	0.70	7.3
Neptune	30.3	0.008	0.024	0.03	0.13	0.23	0.27	2.9

Note: these rates are indicated by physics and may be lessened due to systems limitations

- With planned in-situ links, there should be no problem achieving this performance all the way from the probe to Earth

Summary

- Many of the concepts we have reported in prior years have become real, funded tasks
  - Additional DSN antennas
  - Full DSN 70m backup capability
  - New DSN signal processing
  - Universal Space Transponder
  - Deep space optical communications terminal
- There is a real global tracking community forming
  - Enabled by international standards
  - NASA, ESA, JAXA, … and growing
- The future looks very bright for deep space communications and navigation