2017 Future Deep Space Mission Trends & Implications

Doug Abraham
Strategic Partnerships & Customer Formulation Office (911)
Interplanetary Network Directorate
Jet Propulsion Laboratory, California Institute of Technology

November 8, 2017

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Credits

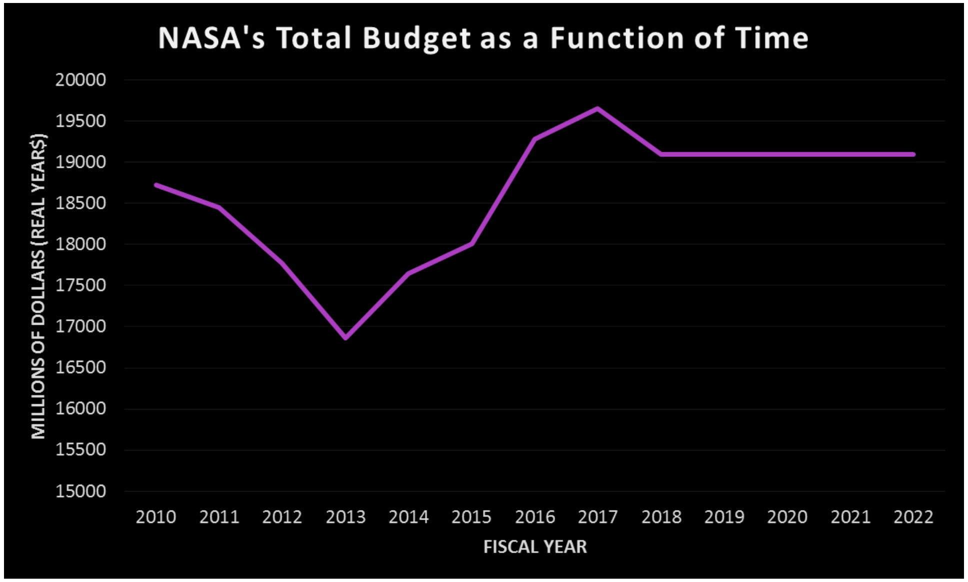
The following individuals significantly contributed to this product on a part-time basis:

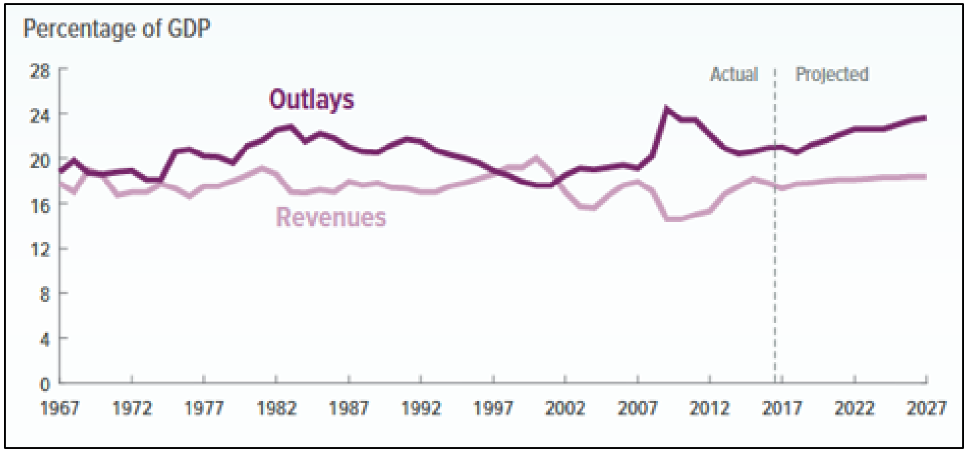
- **Dave Heckman** – Orbital Trajectory Inference Engine (OTIE) development, operation, maintenance, and analyses. And, associated aggregate mission set geometry and station visibility analyses.
- **Andy Kwok** – mission data research, mission modeling, model maintenance, and analysis.
- **Carlyn-Ann Lee** – mission data research, mission modeling, model maintenance, and analysis.
- **Bruce MacNeal** – Mission Set Analysis Tool (MSAT) and ALAT Schedule Analysis Tool (ASAT) development, operation, maintenance, and analyses. And, associated mission link budget and antenna EIRP & G/T analyses.
- **Jimmy Chen** – Architecture Loading Analysis Tool (ALAT) development, operation, maintenance, and loading analyses.
- **Kristy Tran** – mission data research, mission modeling, model maintenance, and analysis. Derivation of functional requirements applicable to Level 3 requirements modeling.
- **Janet Wu** – mission data research, mission modeling, model maintenance, and analysis. Optical mission set definition. Strategic Optical Link Tool (SOLT) operation, maintenance, and analyses.

Topics

- Environment
- Mission Set Analysis Process
- Mission Trends & Implications
  - Next 10 Years
  - Human Mars Exploration Era
- Conclusions
- Appendix: Detailed Report

Environment (1/2)





Credit: Plot from Congressional Budget Office, *An Update to the Budget & Economic Outlook: 2017-2027*, June 2017.

- Future NASA budget likely to remain flat.
- CBO projects U.S. Govt. outlays as a % of GDP remain greater than revenues – no new surpluses to fund significant agency budget increases.
- Human exploration likely to consume an increasing portion of NASA's overall budget in future.
- Robotic exploration may have to depend more on smallsats.

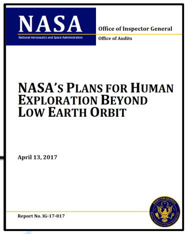
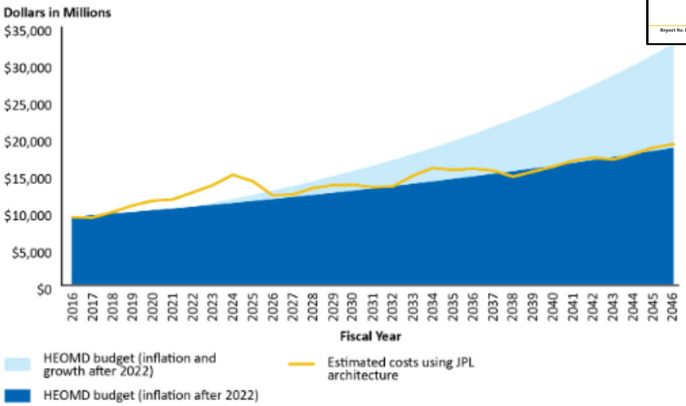


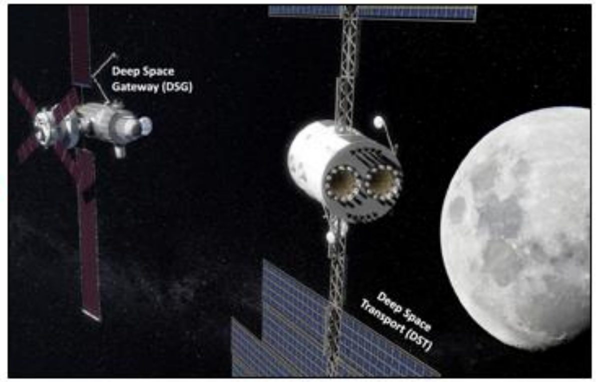
Figure 6: HEOMD Budget Assumptions Compared to JPL Architecture Cost Estimates



Source: NASA OIG analysis of JPL feasibility study data.

Environment (2/2)

Last Year: Asteroid Return Crewed Missions as a Precursor to Mars Exploration



This Year: Cislunar Development of a Deep Space Gateway that Paves the Way for a Deep Space Transport to Mars

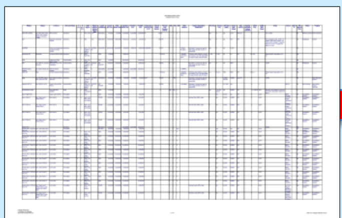
- Lunar focus likely over the next 10 years.
- Humans on Mars remains the goal after that.
- Commercial interest and investment in space activities beyond GEO is growing.
- Other countries are also increasingly engaging in missions beyond GEO.
    - Government Agencies
    - Companies
- These new players are not necessarily subject to the same federal budget vicissitudes as NASA.

Mission Set Analysis Process

Mission set analysis involves the coordinated application of a suite of specialized tools.

Space Communications Mission Model (SCMM)

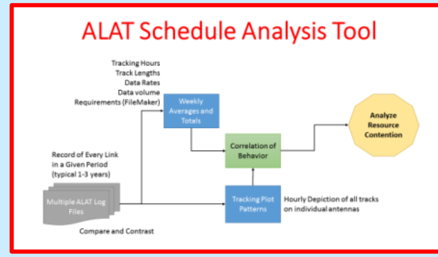
Mission Set Scenarios

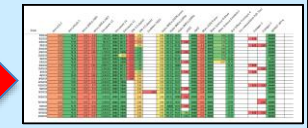


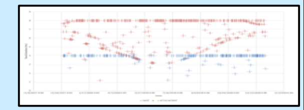
Agreed Upon Mission Set Between HQ, JPL, & GSFC. High-level Mission Characteristics

(ASAT)

Analyzes simulated schedule output from ALAT to understand underlying resource contention drivers



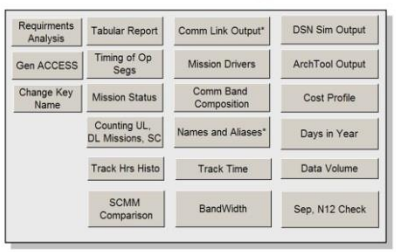


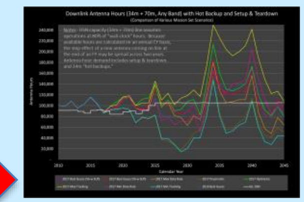


(MSAT)

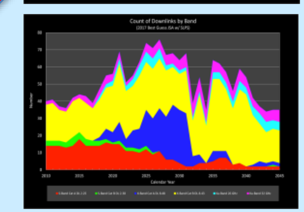
Detailed Mission & Spacecraft Characteristics; RF Link Analyses

Mission Set Analysis Tool

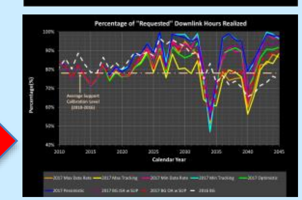


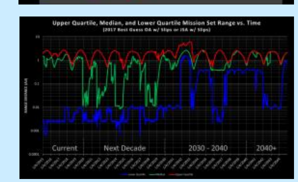


Aggregate Mission Set Trends & Requirements



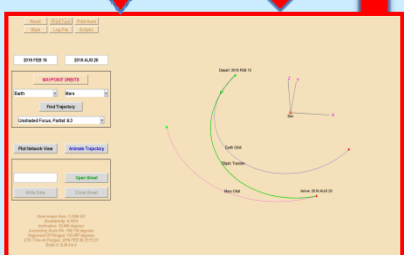
RF Link Requirements & Associated Spacecraft Telecom & Tracking Requirement Data





Orbital Trajectory Inference Engine (OTIE)

Spacecraft Range Distance, Geometry, and Visibility Relative to Ground Stations as a Function of Time



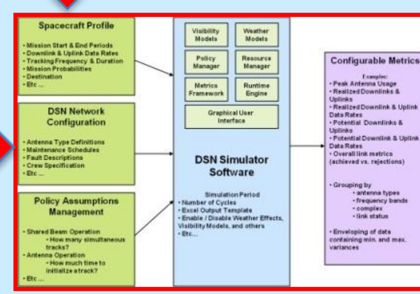
Strategic Optical Link Tool (SOLT)

Optical Link Parameters / High-Level Link Performance as a Function of Time

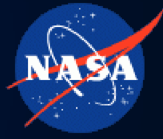
Architecture Loading Analysis Tool (ALAT)

Antenna/Telescope Architecture Loading Simulations

Architecture Loading & Data Traffic Implications

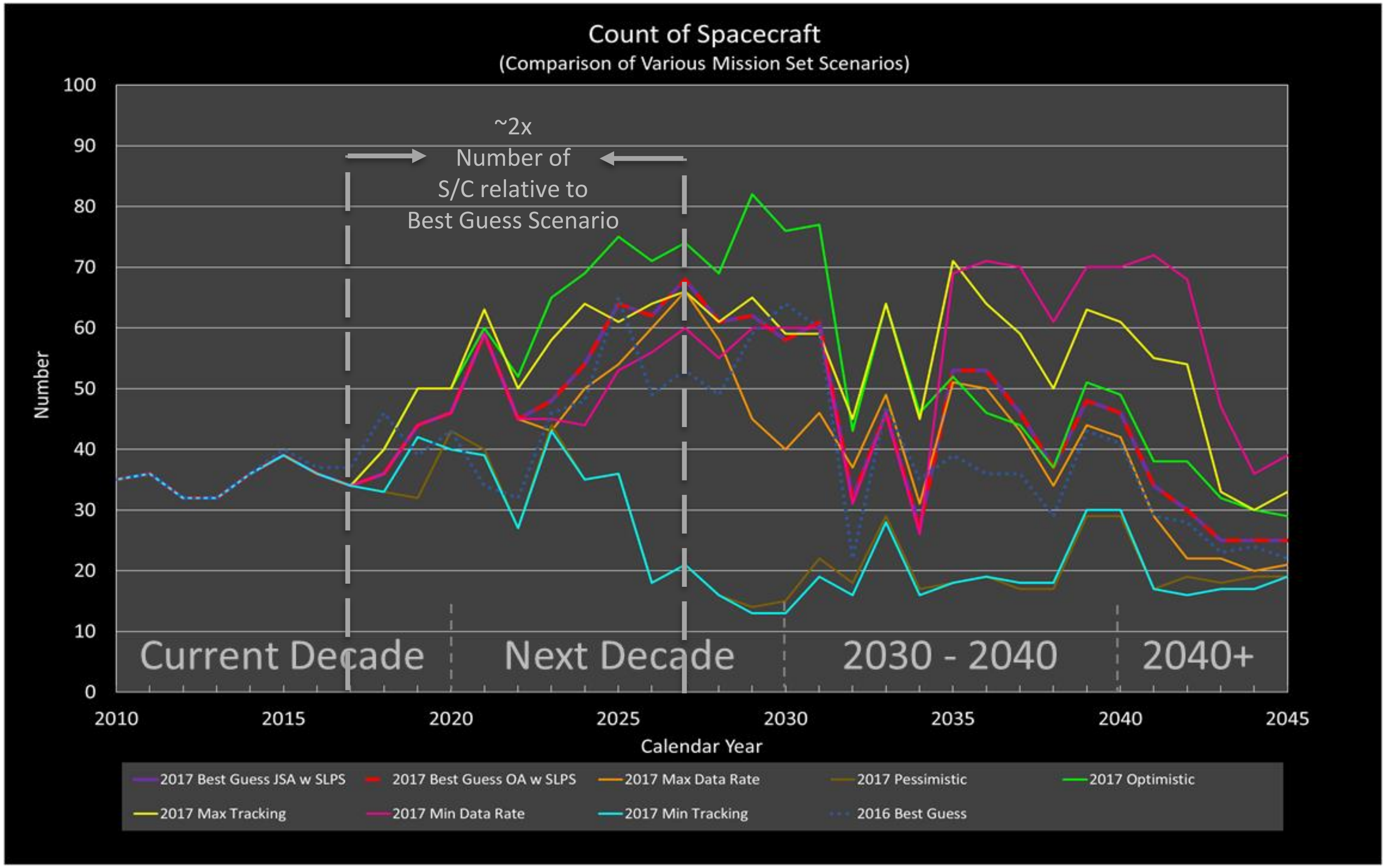


Aggregate & Individual Mission Geometry as a Function of Time



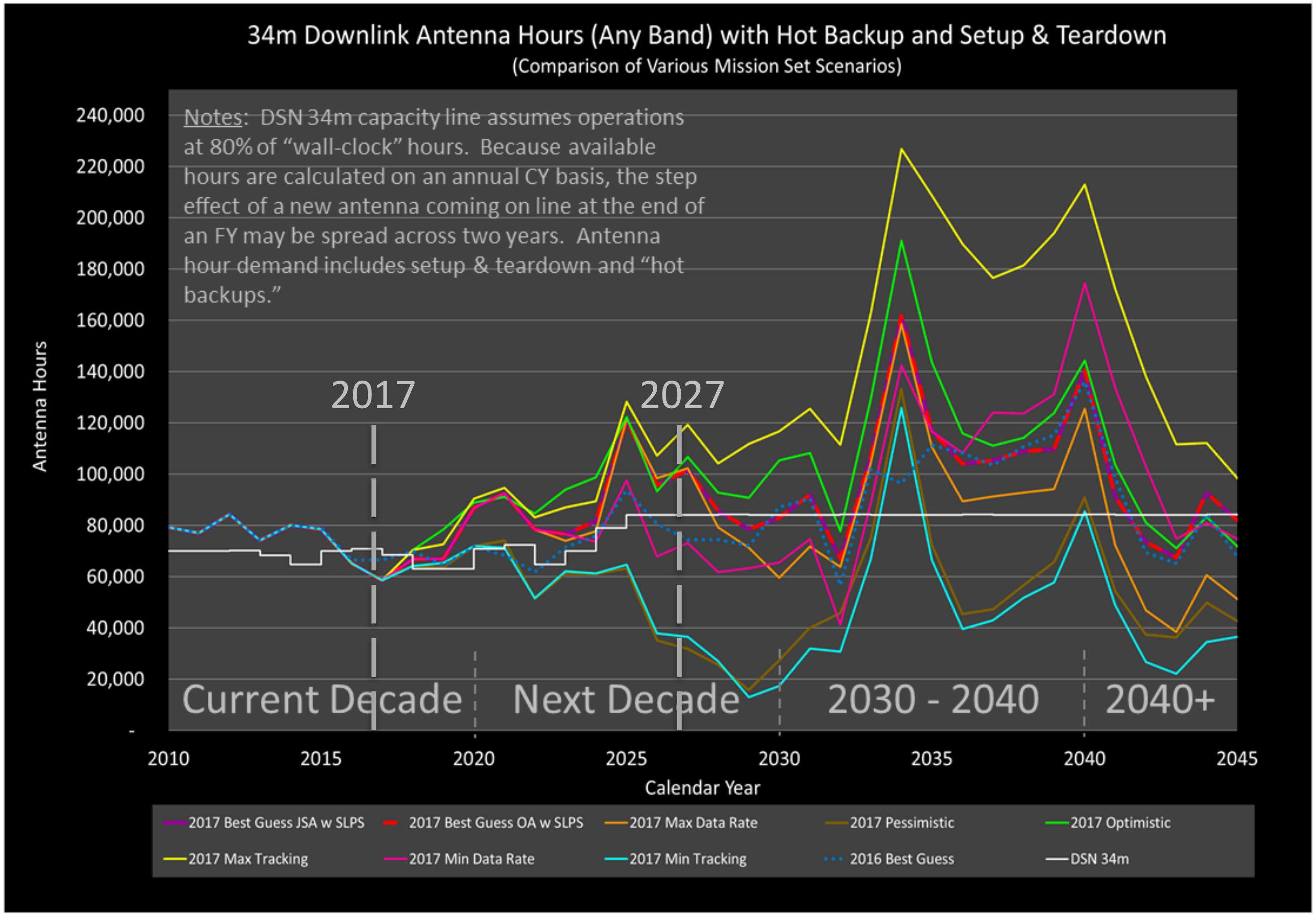
Mission Trends & Implications (1/10)

10-Year Projection: Significant Growth in the Customer Base



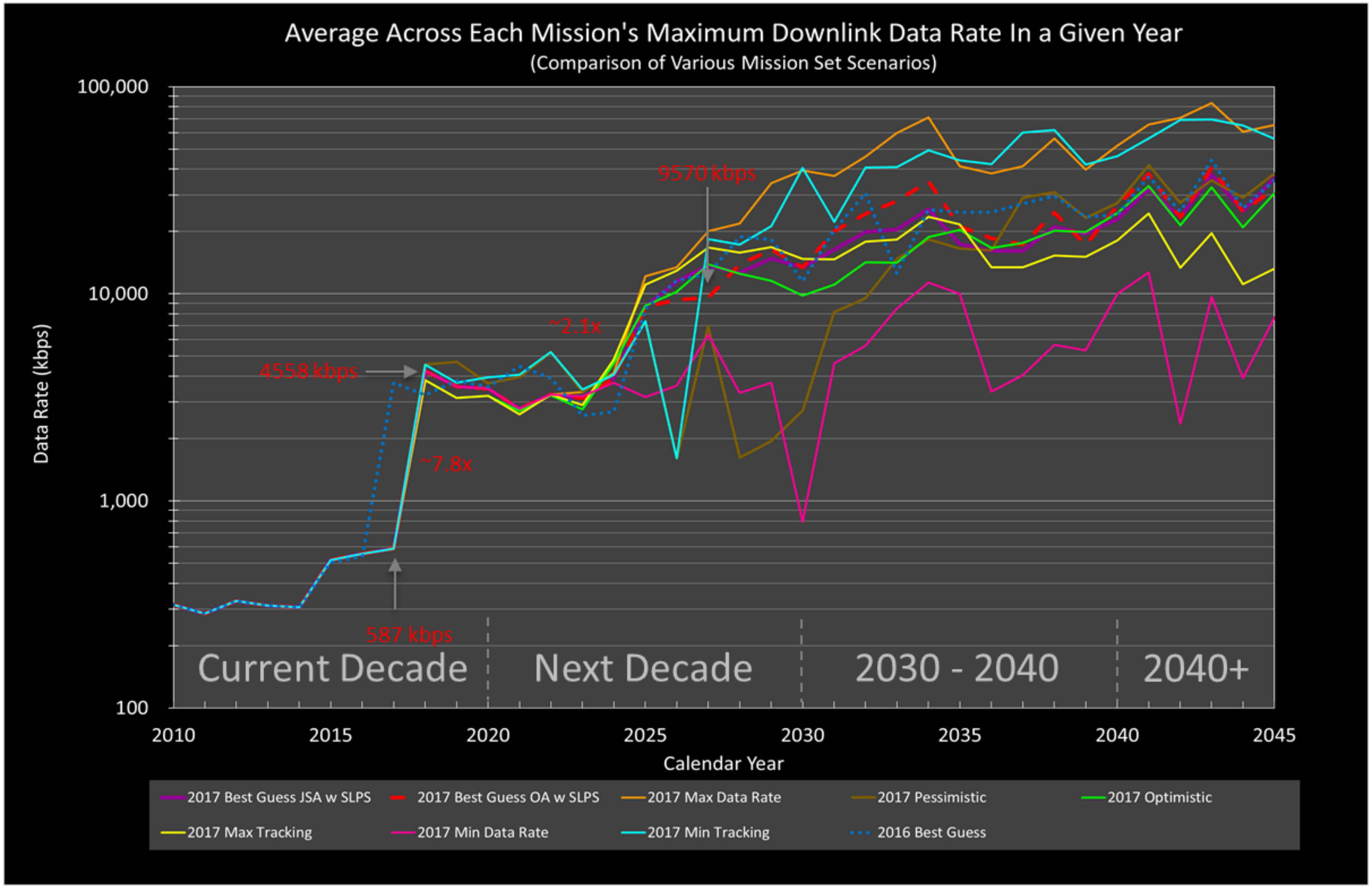
Mission Trends & Implications (2/10)

10-Year Projection: 34m Antenna-Hour Demand Exceeds Supply



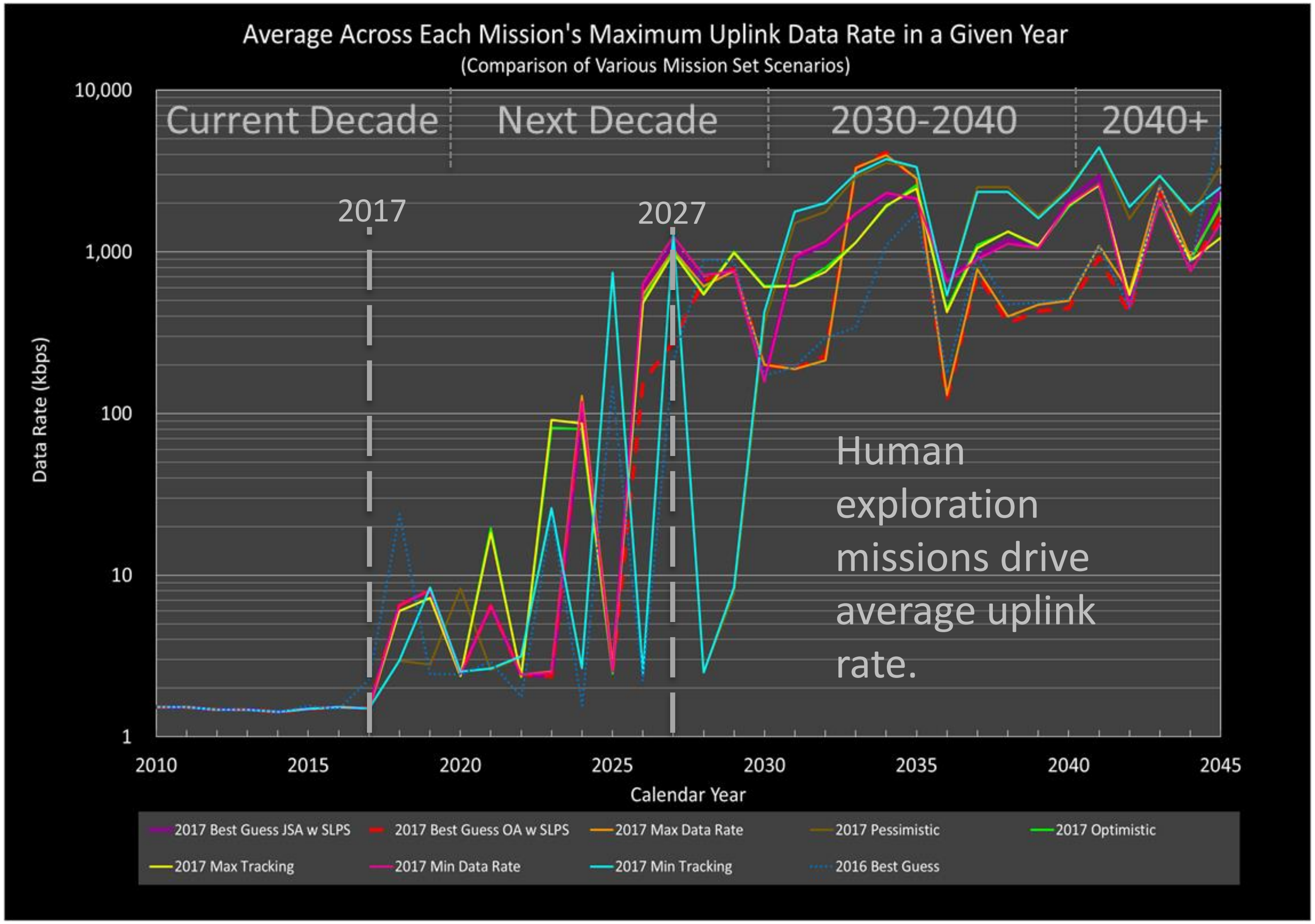
Mission Trends & Implications (3/10)

10-Year Projection: Ave. Downlink Rate Increases by ~16x



Mission Trends & Implications (4/10)

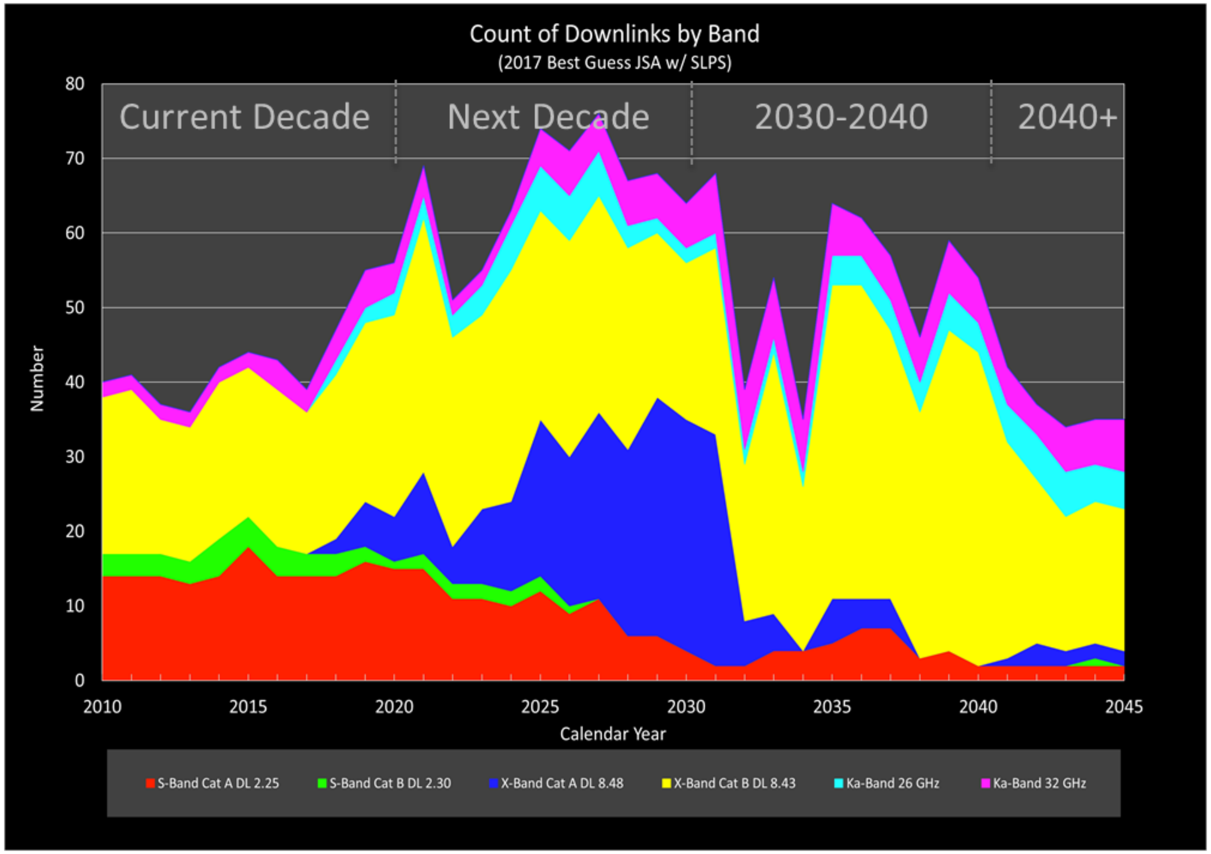
10-Year Projection: Ave. Uplink Rate Increases by ~1000x

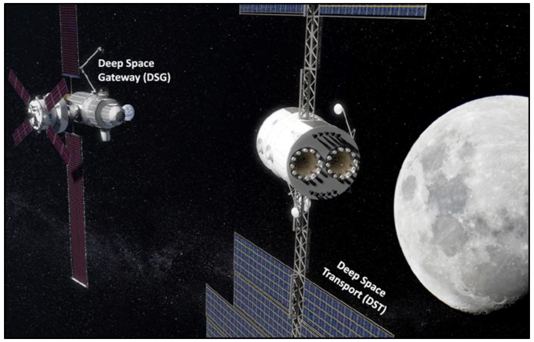


Pre-decisional – for Planning and Discussion Purposes Only

Mission Trends & Implications (5/10)

10-Year Projection: X-band Spectrum Contention Likely to Grow

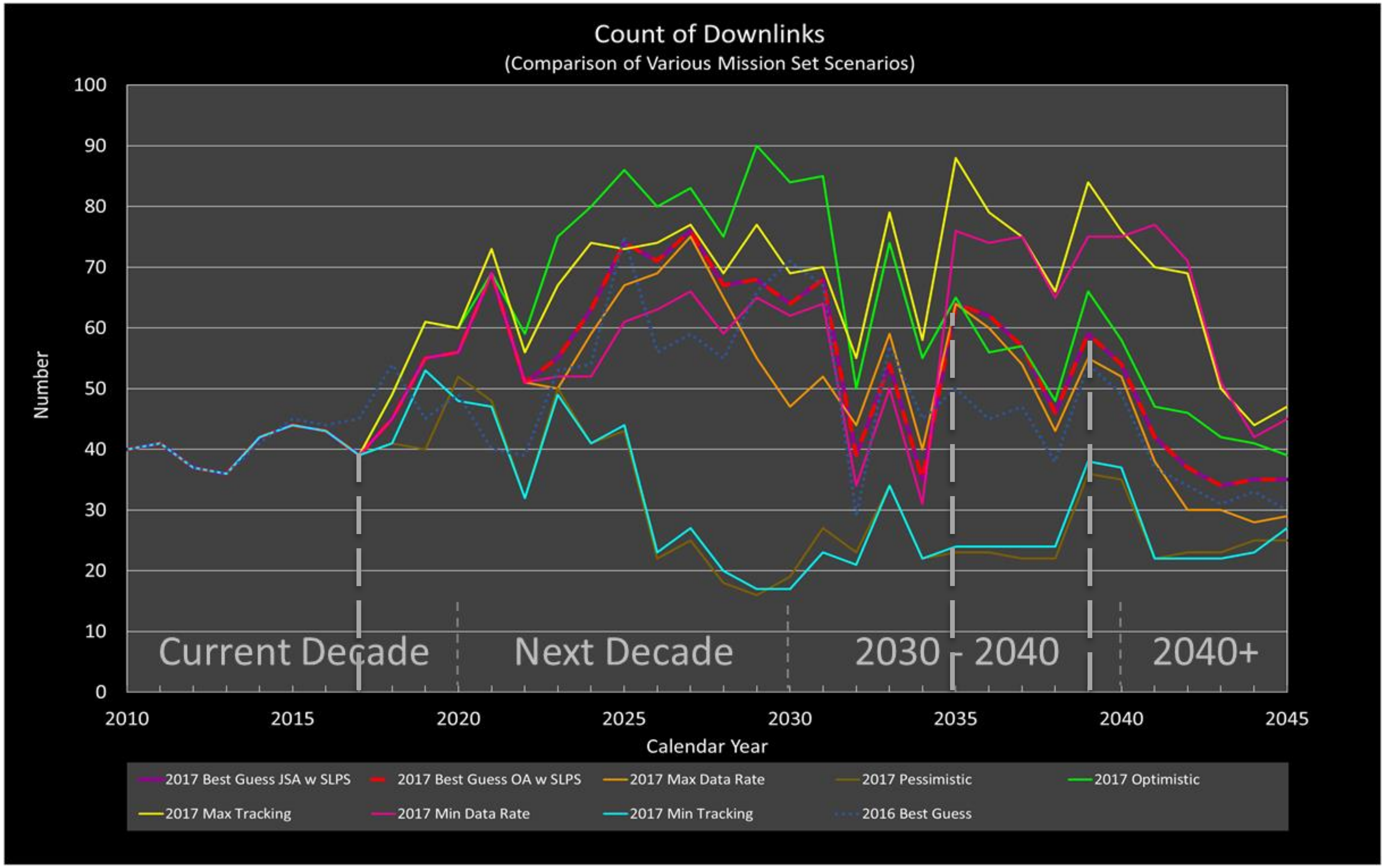




Lunar Deep Space Gateway plans since study was performed may suggest 22/26 GHz need beyond what was predicted.

Mission Trends & Implications (6/10)

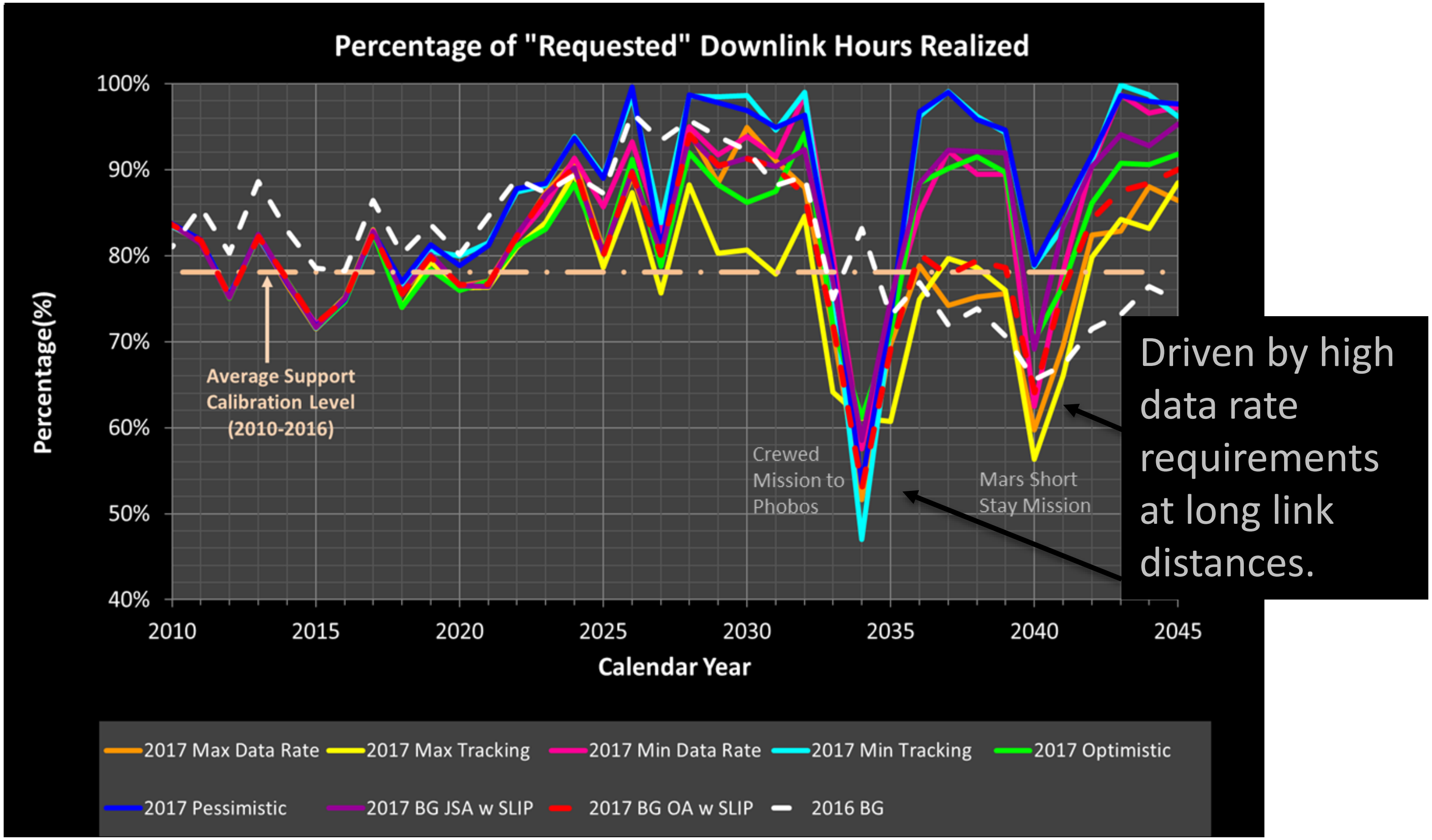
Human-Mars Era Projection: ~1.5x More Links than Today



Pre-decisional – for Planning and Discussion Purposes Only

Mission Trends & Implications (7/10)

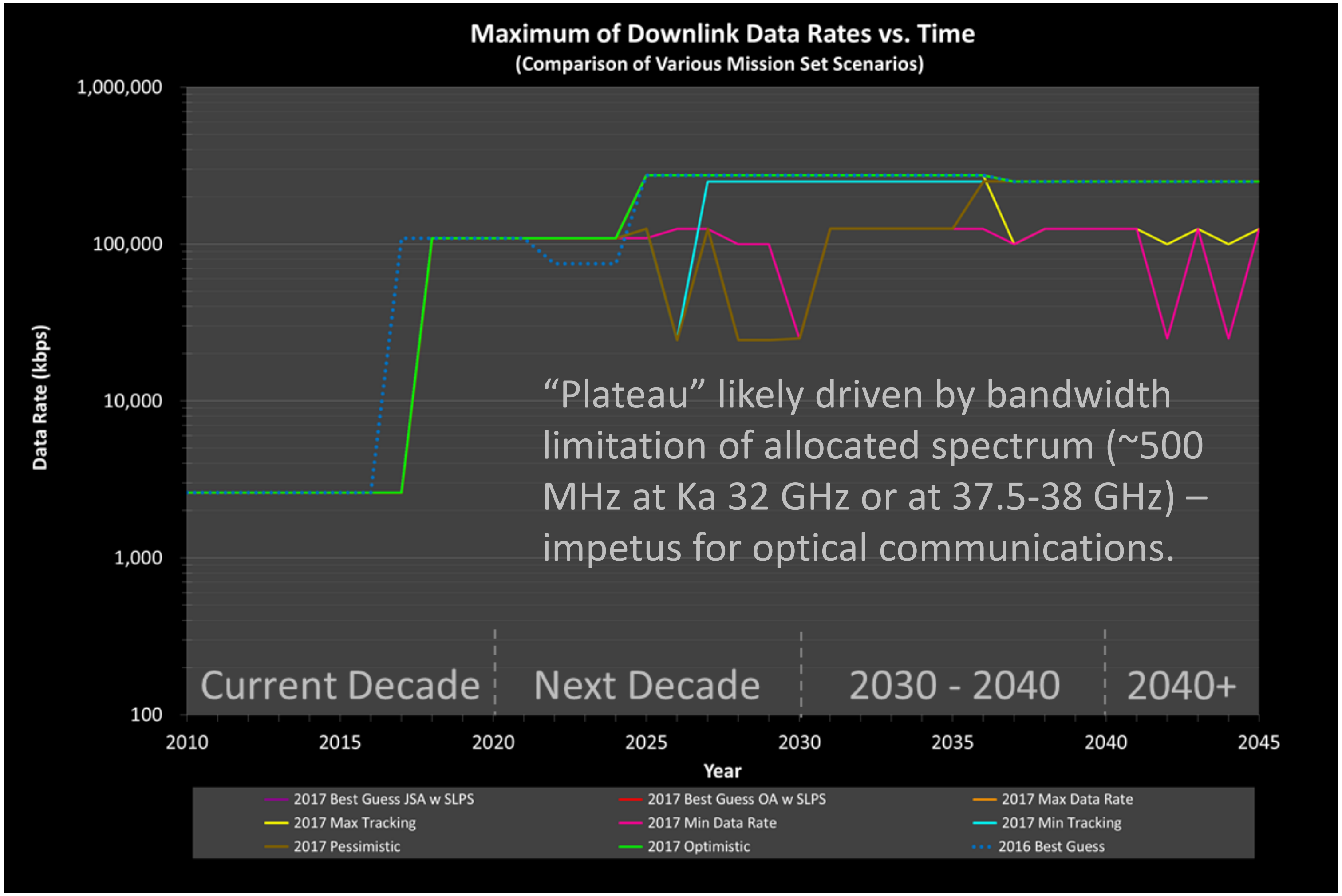
Human-Mars Era Projection: New Capability/Capacity Needed*



*Engineering and cost trade details and associated recommendations are available in the "Deep Space Capacity Study, Pass-2."

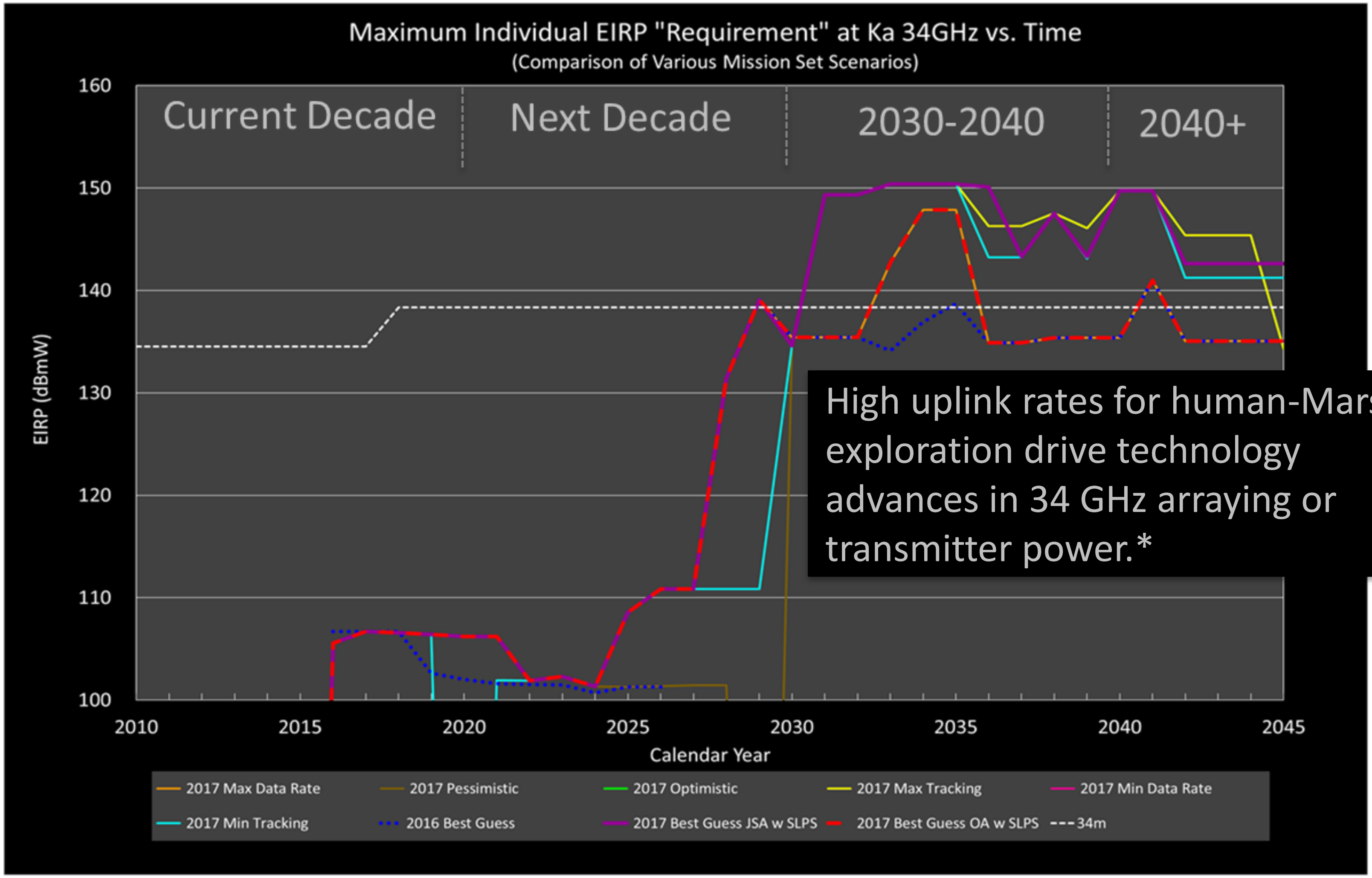
Mission Trends & Implications (8/10)

Human-Mars Era Projection: Max. Downlink Rates "Plateau"



Mission Trends & Implications (9/10)

Human-Mars Era Projection: Need for Greater 34 GHz EIRP*

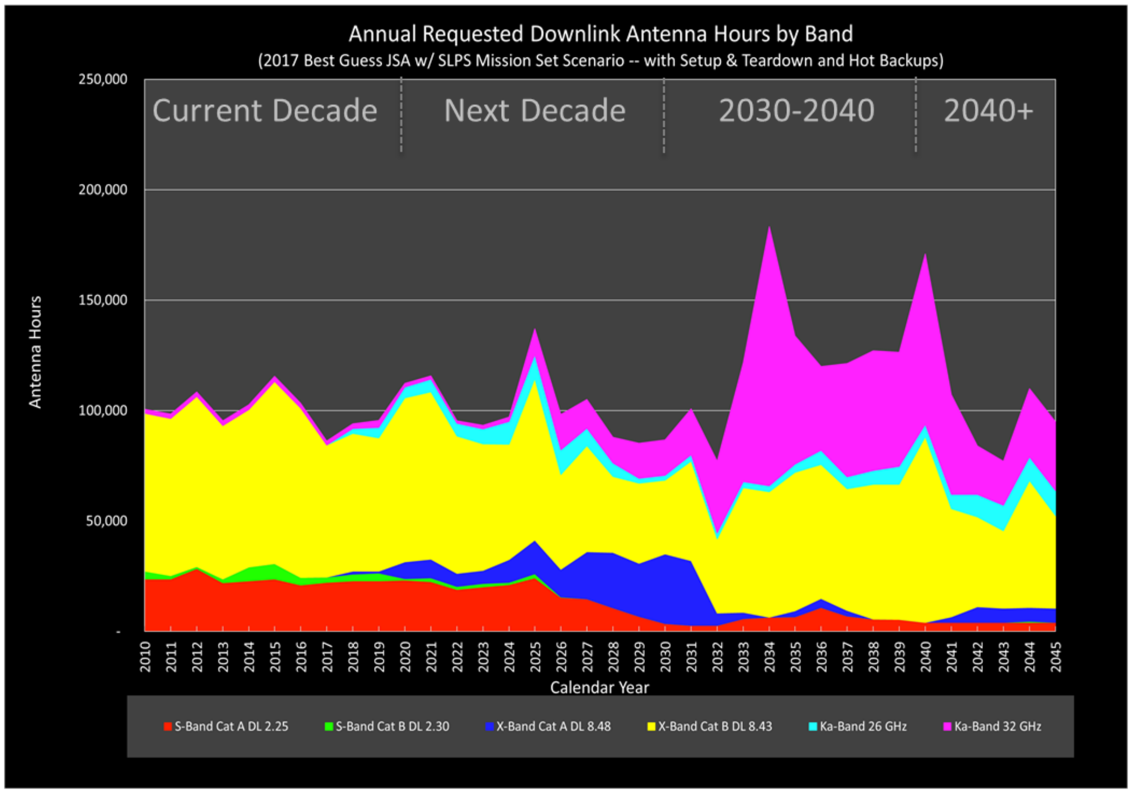


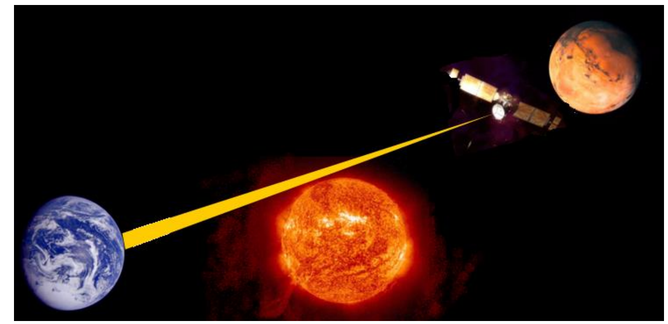
High uplink rates for human-Mars exploration drive technology advances in 34 GHz arraying or transmitter power.*

*Engineering and cost trade details and associated recommendations are available in the "Deep Space Capacity Study, Pass-2."

Mission Trends & Implications (10/10)

Human-Mars Era Projection: Ka-band Begins to Dominate Antenna-Hour Requirements





Even with higher-performing optical communications, human Mars missions will likely still need Ka-band links during the ~2.5 months of small Sun-Earth-Probe angles.*

Prohibitive power requirements for optical uplink to Mars may also drive Ka-band use for uplink.*

*Engineering and cost trade details and associated recommendations are available in the "Deep Space Capacity Study, Pass-2."

Conclusions

- Next 10 Years
  - Period of rapid change in a cost-constrained environment
    - Number of downlinks may double.
    - Data rates and volumes may increase by more than an order of magnitude.
    - Customer base will likely transition from robotic-only to a mix of human and robotic missions.
    - More foreign and commercial “players.”
  - Such change will require more efficient use of existing and planned antennas, additional antenna cross-support arrangements, and increased reliance on higher frequencies (possibly including 22 GHz uplink).
- Preparing for Human Mars Exploration Era
  - Fundamentally new capabilities would be needed to support the anticipated human exploration data rates at Mars distances. For instance:
    - RF antenna arraying at Ka-band (34 GHz up and 32 GHz down)
    - Optical downlink (particularly given allocated RF spectrum bandwidth limitations)
  - While the human Mars exploration era is out beyond the 10-year horizon, the capabilities it requires may take that long to develop and implement. Start now.

Appendix: Detailed Report

Keeping the universe connected.

www.nasa.gov

Credits

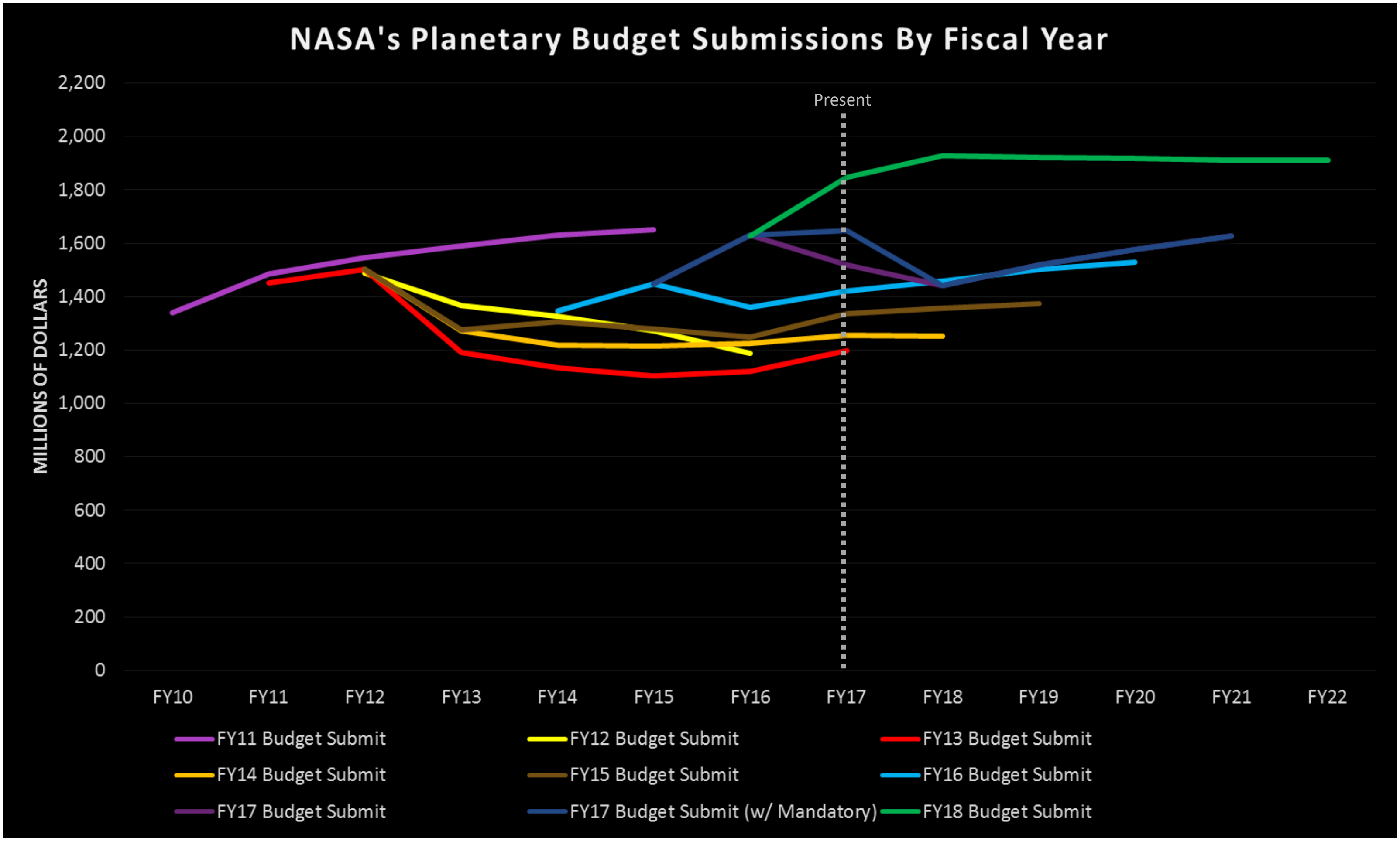
The following individuals significantly contributed to this product on a part-time basis:

- **Dave Heckman** – Orbital Trajectory Inference Engine (OTIE) development, operation, maintenance, and analyses. And, associated aggregate mission set geometry and station visibility analyses.
- **Andy Kwok** – mission data research, mission modeling, model maintenance, and analysis.
- **Carlyn-Ann Lee** – mission data research, mission modeling, model maintenance, and analysis.
- **Bruce MacNeal** – Mission Set Analysis Tool (MSAT) and ALAT Schedule Analysis Tool (ASAT) development, operation, maintenance, and analyses. And, associated mission link budget and antenna EIRP & G/T analyses.
- **Jimmy Chen** – Architecture Loading Analysis Tool (ALAT) development, operation, maintenance, and loading analyses.
- **Kristy Tran** – mission data research, mission modeling, model maintenance, and analysis. Derivation of functional requirements applicable to Level 3 requirements modeling.
- **Janet Wu** – mission data research, mission modeling, model maintenance, and analysis. Optical mission set definition. Strategic Optical Link Tool (SOLT) operation, maintenance, and analyses.

Topics

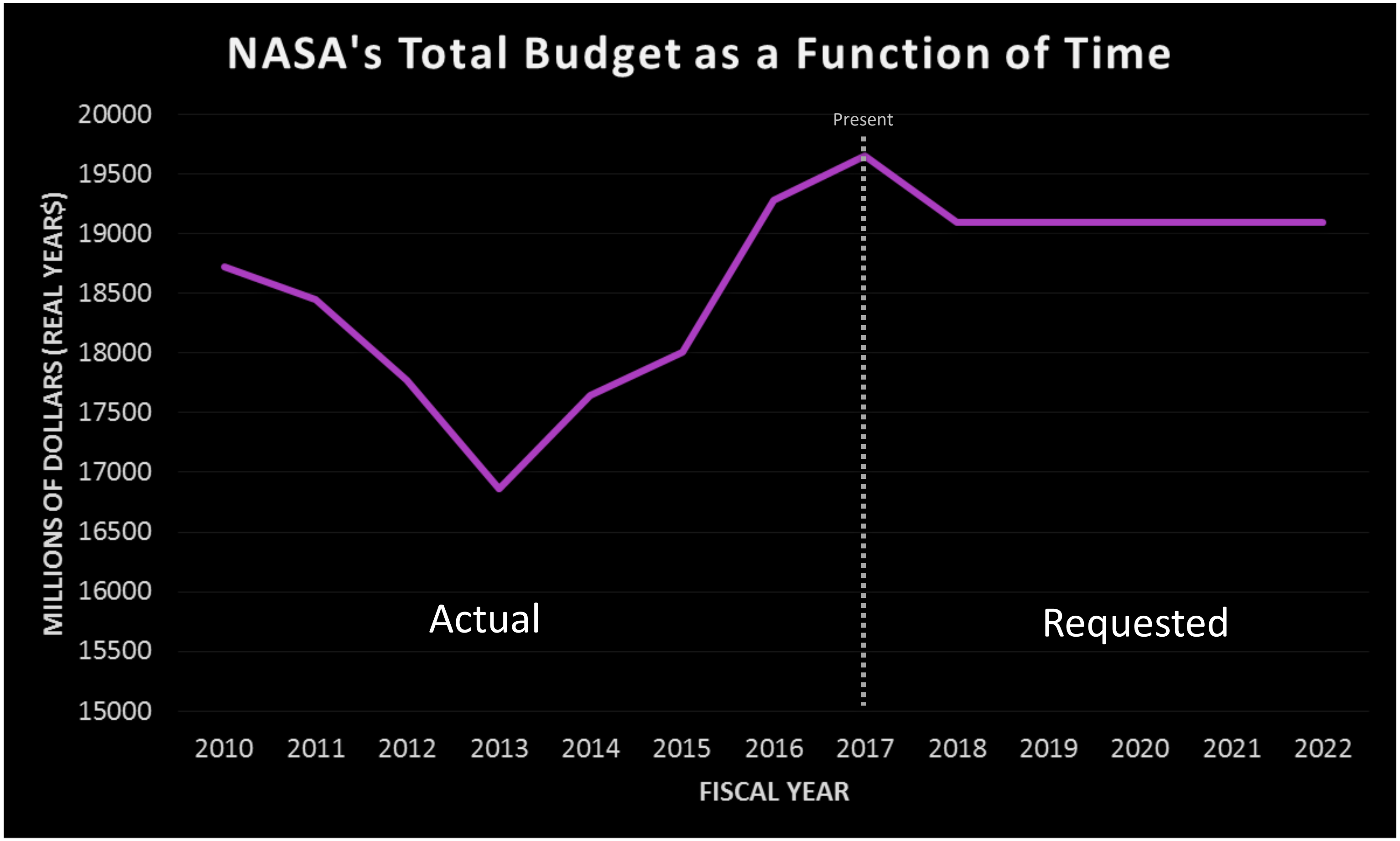
- **Factors Shaping the Anticipated Future Mission Set**: The Budget Situation, Uncertainty & Shifting Priorities for Human Exploration, and Increasing Globalization and Commercialization of Space Exploration Beyond GEO
- **Future Mission Set Analysis Methodology**: Definition of Mission Set Scenarios, Key Items Not Addressed In Scenarios, Mission Set Analysis Process, Other Assumptions, and Interpretation of Results
- **Selected Mission Set Analysis Results**
  - **Capacity:** Anticipated Customer Base, Antenna-Hour Demand, and Antenna Asset Visibilities
  - **Capability**
    - **Downlink**: Average Rates, Maximum Rates, Rate Drivers, Data Volumes, Mission Set Range, End-to-End Downlink Difficulty, Maximum Individual G/T, and Aggregate G/T
    - **Uplink:** Average Rates, Maximum Rates, Rate Drivers, Maximum Individual EIRP, and Aggregate EIRP.
  - **Spectrum:** Downlink Count, Downlink Antenna Hours, Uplink Count, and Uplink Antenna Hours
  - **Loading Simulation Results:** “Requested” Downlink Hours Realized, “Requested” Downlink Data Volume Realized, “Requested” Uplink Hours Realized, and “Requested” Uplink Data Volume Realized
- **Implications**: The Next 10 Years and The Human Mars Exploration Era

The Budget Situation (1/3)



Planetary science missions compose the largest percentage of the DSN's customer base. The budget outlook for planetary science has improved considerably since FY13.

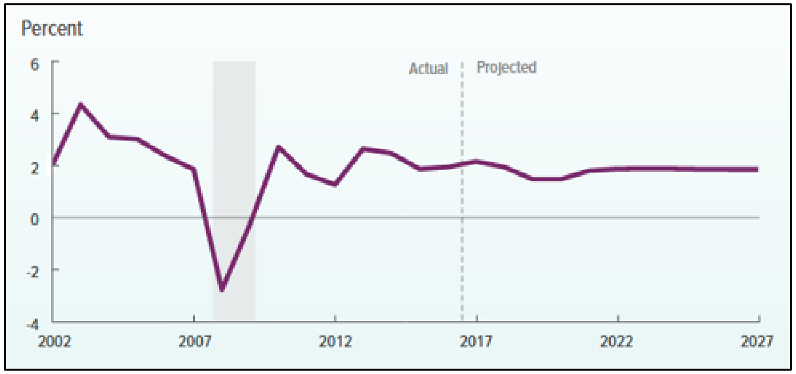
The Budget Situation (2/3)



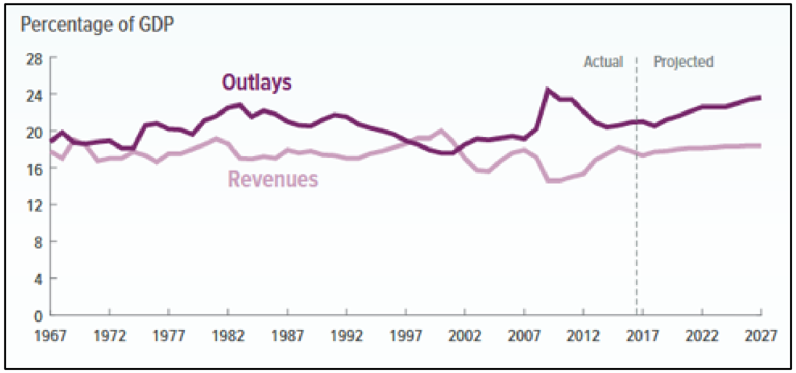
The overall NASA budget has also significantly improved since 2013. However, future growth, even to keep pace with inflation, has not been requested.

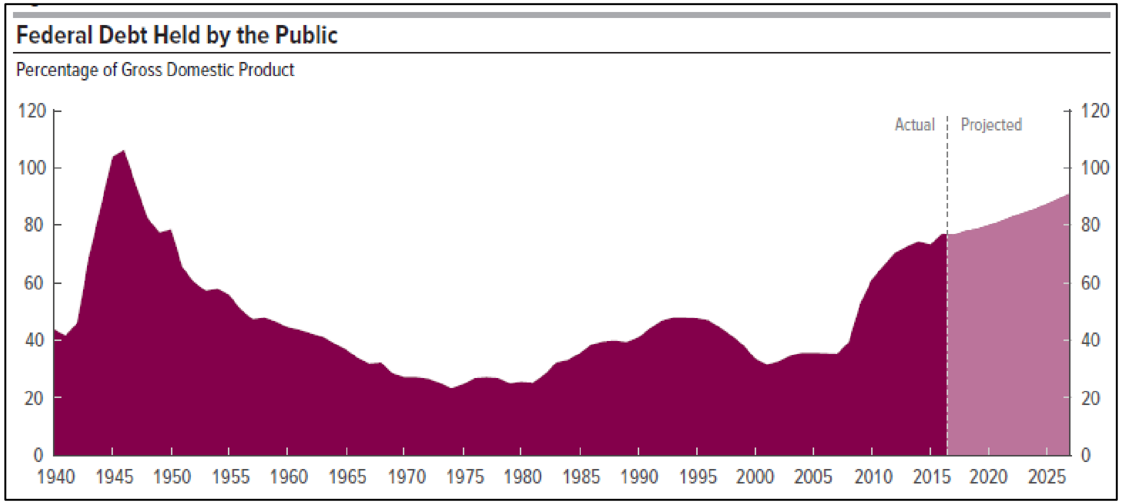
The Budget Situation (3/3)

Actual & Projected Growth in GDP



Revenues & Outlays as a Percentage of GDP





For the country as a whole, the projected growth in GDP and revenues remains flat, while projected outlays as a percentage of GDP grow. Hence, mounting debt will likely continue its downward pressure on discretionary spending.

Credit: Plots from Congressional Budget Office, *An Update to the Budget & Economic Outlook: 2017-2027*, June 2017.

Uncertainty & Shifting Priorities for Human Exploration (1/3)

Steve Helber / AP

Trump's Advisers Want to Return Humans to the Moon in Three Years

The plan could dramatically shift the mission of the space agency, prioritizing low-Earth orbit activity over distant exploration.

MARINA KOREN | FEB 9, 2017 | SCIENCE

Space.com > Spaceflight

Trump's 2018 NASA Budget Request Would Scrap Asteroid Redirect Mission

By Tariq Malik, Space.com Managing Editor | March 16, 2017 09:57am ET

Futurism NEWS INFOGRAPHICS VIDEOS

On March 21, President Trump issued a mandate for NASA: get people to Mars by 2033.

@KarlaLant Website

April 20, 2017

THE MARS MISSION

NASA Transition Authorization Act of 2017

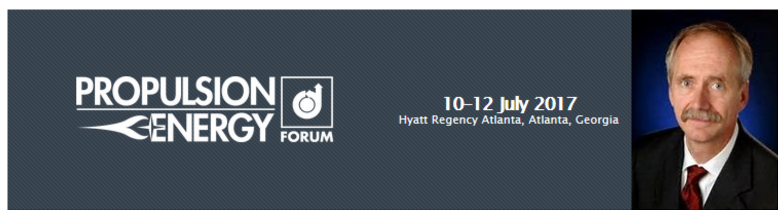
SEC. 202. GOALS AND OBJECTIVES.

(a) LONG TERM GOALS - The long-term goals of the human space flight and exploration efforts of NASA shall be -

(1) to expand permanent human presence beyond low-Earth orbit and to do so, where practical, in a manner involving international, academic, and industry partners;

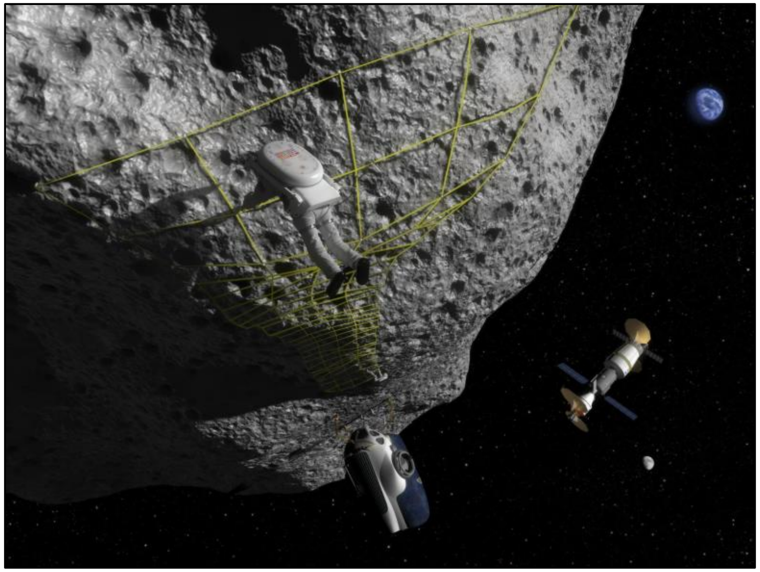
(2) crewed missions and progress toward achieving the goal in paragraph (1) to enable the potential for subsequent human exploration and the extension of human presence throughout the solar system; and

(3) to enable a capability to extend human presence, including potential human habitation on another celestial body and a thriving space economy in the 21st Century.

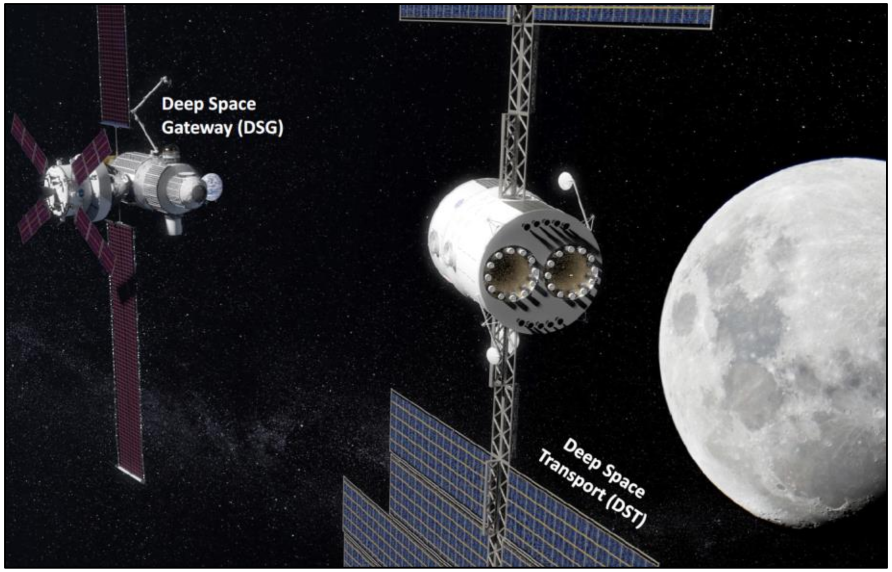


"I can't put a date on humans on Mars, and the reason really is the other piece is, at the budget levels we described, this roughly 2 percent increase, we don't have the surface systems available for Mars. And that entry, descent, and landing is a huge challenge for us for Mars."

Uncertainty & Shifting Priorities for Human Exploration (2/3)



Last Year: Asteroid Return Crewed Missions as a Precursor to Mars Exploration

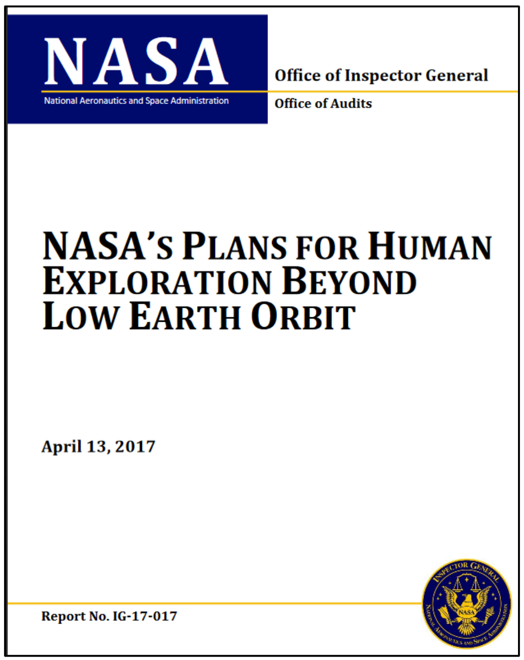


This Year: Cislunar Development of a Deep Space Gateway that Paves the Way for a Deep Space Transport to Mars

Along with the change in Administrations, the focus on human asteroid exploration as a precursor to human Mars exploration has been superseded by the development of a cis-lunar space station as a test ground and jumping-off point for deep space transport to Mars.

Uncertainty & Shifting Priorities for Human Exploration (3/3)

Plot from:

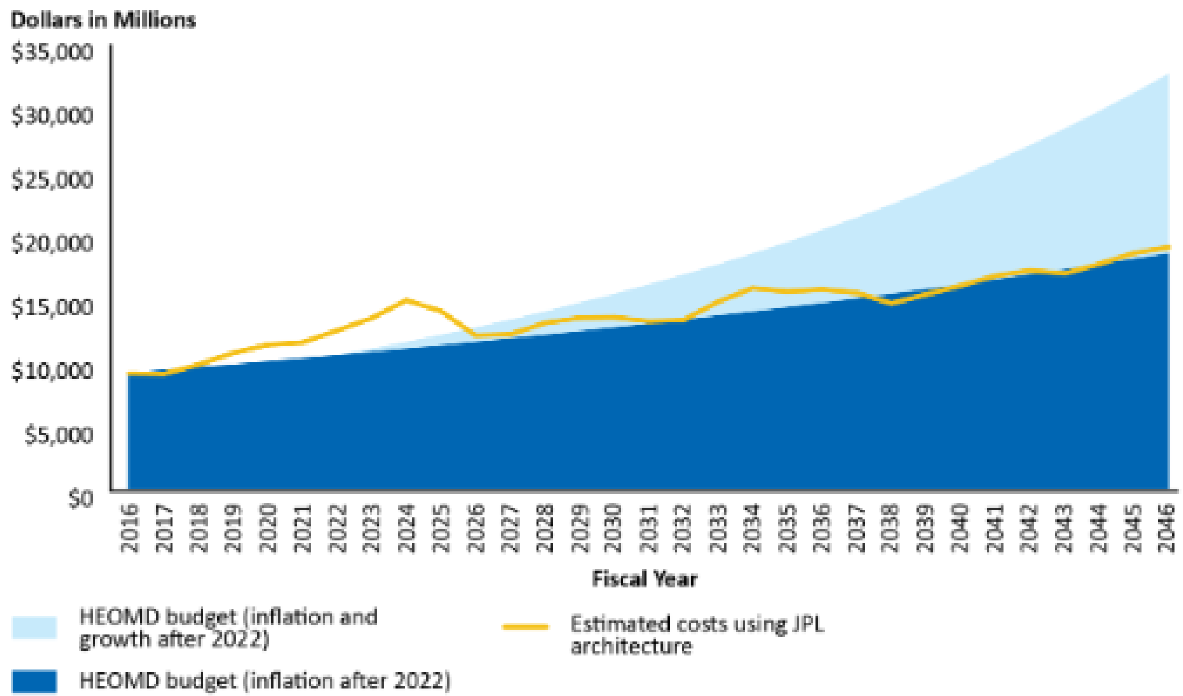

NASA
National Aeronautics and Space Administration
Office of Inspector General
Office of Audits

NASA'S PLANS FOR HUMAN EXPLORATION BEYOND LOW EARTH ORBIT

April 13, 2017

Report No. IG-17-017

Figure 6: HEOMD Budget Assumptions Compared to JPL Architecture Cost Estimates



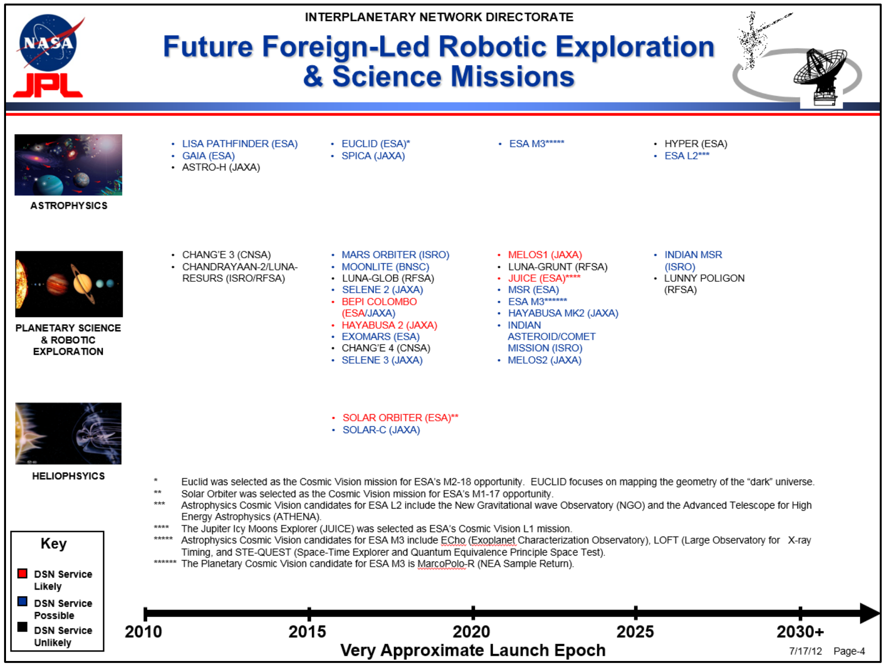
Source: NASA OIG analysis of JPL feasibility study data.

Unless NASA's budget grows at a rate faster than inflation, human exploration will likely require an increasing portion of NASA's overall budget.

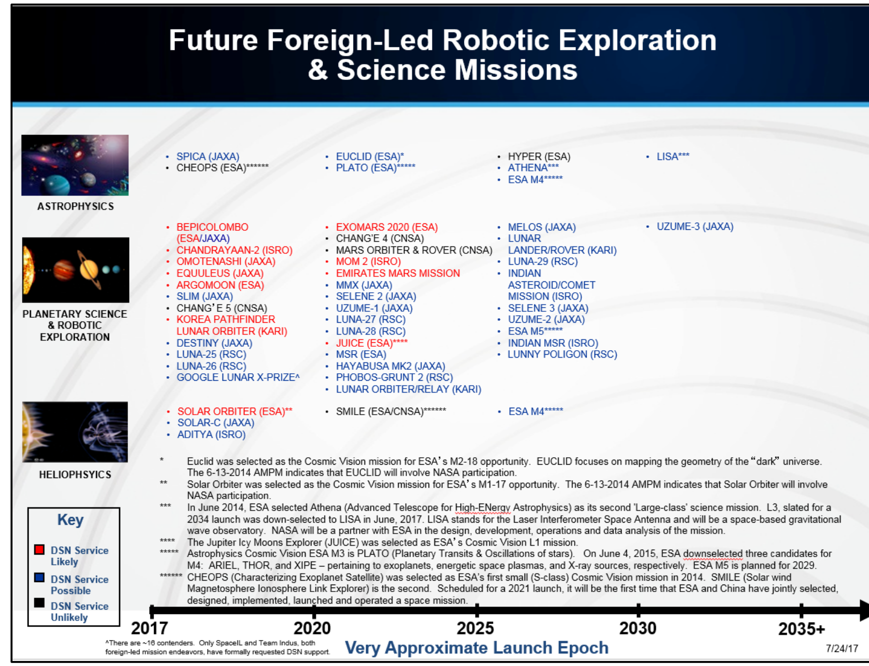
Other NASA mission directorates may need to rely more heavily on smallsats to reduce launch costs and maintain mission cadence.

Increasing Globalization & Commercialization of Space Exploration Beyond GEO (1/3)

2012



2017



In just five years:

- The number of foreign-led missions beyond GEO has almost doubled.
- The number of such missions that are likely DSN supports has doubled.
- Two additional space agencies are planning missions.
- At least two foreign, private sector missions beyond GEO are being planned.

Increasing Globalization & Commercialization of Space Exploration Beyond GEO (2/3)

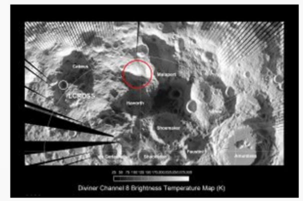
Astrobotic and ATLAS Announce Lunar Laser Communications Payload at the Paris Air Show

Astrobotic and ATLAS Partner to Establish World's First Laser Communication Link from the Lunar Surface

Paris, France – Astrobotic, which is making the Moon accessible to the world, and ATLAS Space Operations Inc., the US leader in cloud-based satellite management and control services proudly announce today at the Paris Air Show that they have signed a payload reservation and partnership to deliver and operate the first-ever laser communications terminal on Astrobotic's upcoming mission to the Moon. This

JULY 21, 2017

INTERNATIONAL LUNAR OBSERVATORY TO BE ESTABLISHED AT MOON'S SOUTH POLE IN 2019



International Lunar Observatory Association (ILOA) and Moon Express recently announced a collaboration for the delivery of the first International Lunar Observatory to the South Pole of the Moon in 2019 (ILO-1). Moon Express has been contracted by ILOA to develop advanced landing technologies supporting the mission.

The ILO-1 astrophysical observatory and research station will be the world's first instrument to image the Milky Way Galaxy and to conduct

ATLAS S and X Band Network

ATLAS Space Operations S and X Band Network 2016

Deep Space Industries partners with Luxembourg to test asteroid mining technologies

TechCrunch

Deep Space Industries, the asteroid mining company, has signed a Memorandum of Understanding with the Luxembourg Government to co-fund the development and launch of DSI's first spacecraft. Known as Prospector-X, the small spacecraft will test key technologies in Low Earth Orbit that will be necessary for future asteroid prospecting. **Read More...**

In Quest to Reach Alpha Centauri, Breakthrough Starshot Launches World's Smallest Spacecraft

FEBRUARY 27, 2017

SPACEX TO SEND PRIVATELY CREWED DRAGON SPACECRAFT BEYOND THE MOON NEXT YEAR

We are excited to announce that SpaceX has been approached to fly two private citizens on a trip around the Moon late next year. They have already paid a significant deposit to do a Moon mission.

July 13, 2017
Space Mining Law Passes in Luxembourg

TECH

Team Indus To Send Seven Experiments To The Moon Including Three From India

The rover will be launched through PSLV rocket by ISRO.

ASTROBOTIC AND UNITED LAUNCH ALLIANCE ANNOUNCE MISSION TO THE MOON

JULY 26, 2017

Rust Belt Company, Astrobotic selects ULA to launch its Peregrine Lander in 2019 for lunar mission 50 years after Apollo 11

Space.com › Spaceflight

Private Space Stations Could Orbit the Moon by 2020, Robert Bigelow Says

By Tariq Malik, Space.com Managing Editor | March 9, 2017 06:30am ET

SpaceIL Technology

Innovation in Space Exploration

Leveraging Israeli expertise in micro-satellite technologies, SpaceIL is building a small, smart and a relatively cheap spacecraft. The team is applying know-how garnered from a defense related necessity (satellites) to a new purpose of space exploration. The SpaceIL spacecraft is about the size of a dishwasher.

Increasing Globalization & Commercialization of Space Exploration Beyond GEO (3/3)

- Space exploration beyond GEO is no longer just the domain of a couple of space agencies.
    - Several space agencies are now moving beyond GEO.
    - Several private sector ventures have aspirations beyond GEO.
- For the private sector, space exploration is less about science and more about making use of some aspect of the space environment.
- The lunar vicinity tends to be a key target for exploration beyond GEO.
- In many cases, smallsats enable such deep space exploration via the greater affordability conferred by their lower development and launch costs.
    - Their links, however, tend to be designed to the largest available antennas on the ground.
- As the number of players, and potential players, continue to increase, a "market" for development, launch, and operations infrastructure may begin to coalesce.
    - This "market" may only be partially correlated to U.S. and NASA budget constraints.

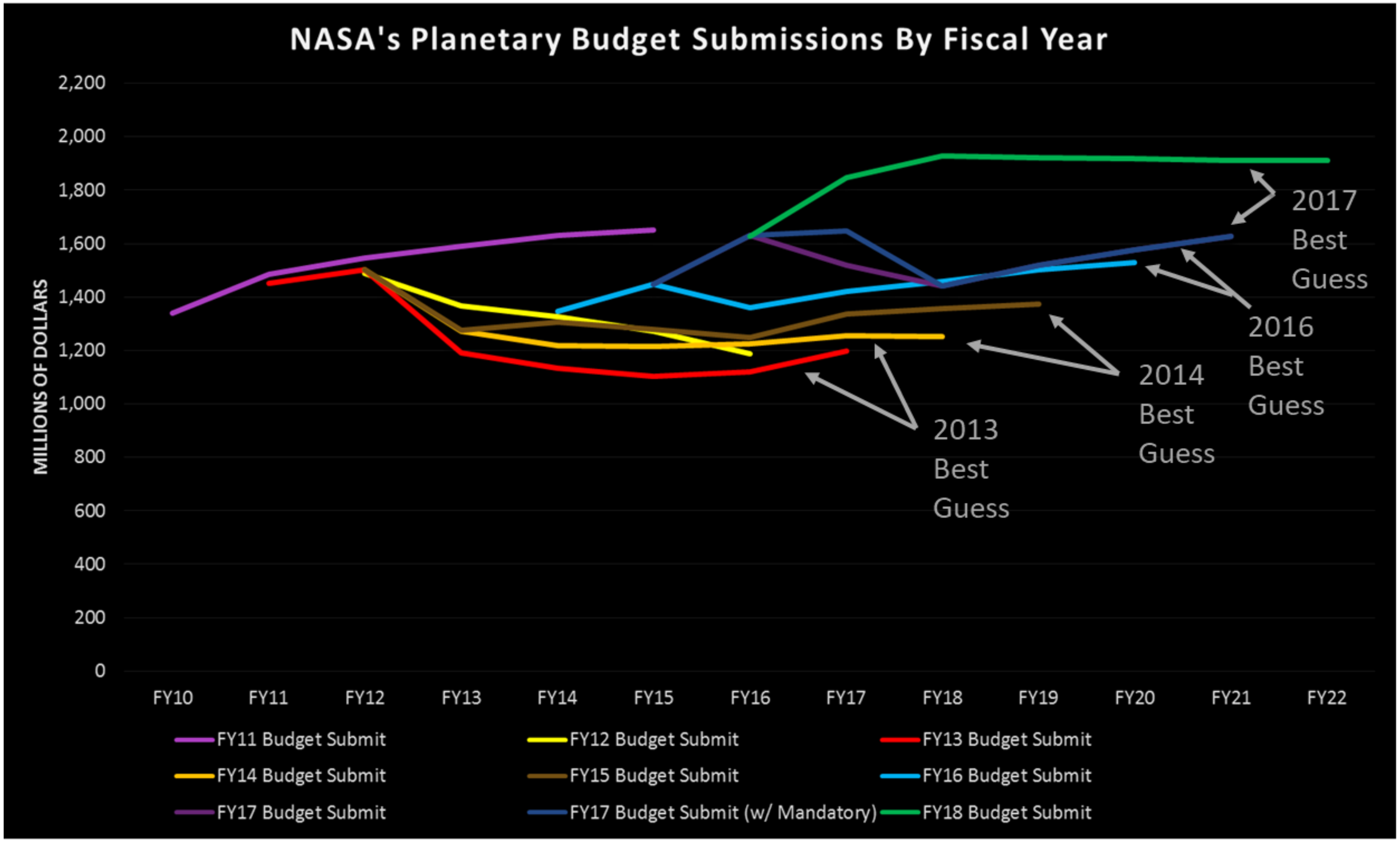
Factors Shaping the Anticipated Future Mission Set: Takeaways

- The upward trend in the planetary science budget has fueled some optimism regarding the possible number and nature of future deep space missions.
- However, the requested out-year NASA budget and CBO projections regarding the nation's overall fiscal status through 2027 suggest sustained budgetary pressure that may constrain the number and nature of future deep space missions.
    - Human exploration may require an increasingly large share of the overall NASA budget.
    - Robotic deep space exploration may have to rely more heavily on small spacecraft that are cheaper to develop and launch in order to maintain the desired cadence.
- NASA's shift toward development of a Deep Space Gateway & Transport System in a lunar orbit as a pathway to Mars, rather than an asteroid-driven pathway, may better accommodate the financial realities alluded to above.
    - This shift is still in progress, making the anticipated future mission set harder to "nail down."
- Increasing foreign-space agency and, eventually, private sector forays into deep space exploration may create demand for deep space communications support (among other things) that is less correlated to NASA's budgetary constraints.

Topics

- **Factors Shaping the Anticipated Future Mission Set**: The Budget Situation, Uncertainty & Shifting Priorities for Human Exploration, and Increasing Globalization and Commercialization of Space Exploration Beyond GEO
- **Future Mission Set Analysis Methodology**: Definition of Mission Set Scenarios, Key Items Not Addressed In Scenarios, Mission Set Analysis Process, Other Assumptions, and Interpretation of Results
- **Selected Mission Set Analysis Results**
  - **Capacity:** Anticipated Customer Base, Antenna-Hour Demand, and Antenna Asset Visibilities
  - **Capability**
    - **Downlink**: Average Rates, Maximum Rates, Rate Drivers, Data Volumes, Mission Set Range, End-to-End Downlink Difficulty, Maximum Individual G/T, and Aggregate G/T
    - **Uplink:** Average Rates, Maximum Rates, Rate Drivers, Maximum Individual EIRP, and Aggregate EIRP.
  - **Spectrum:** Downlink Count, Downlink Antenna Hours, Uplink Count, and Uplink Antenna Hours
  - **Loading Simulation Results:** “Requested” Downlink Hours Realized, “Requested” Downlink Data Volume Realized, “Requested” Uplink Hours Realized, and “Requested” Uplink Data Volume Realized
- **Implications**: The Next 10 Years and The Human Mars Exploration Era

Definition of Mission Set Scenarios (1/3)



The nature of the "Best Guess" mission set scenario for a given year is at least partially correlated to the 5-year budget runout and the sorts of pre-formulation activities that it supports. This was particularly true when NASA's CFO would publicly release an Agency Mission Planning Model (AMPM) in conjunction with the budget. This has not occurred, however, since the start of FY'15.

Definition of Mission Set Scenarios (2/3)

? AMPM ?

SCMM

NASA Budget Submittal, Roadmaps & Strategic Plans; NAS/NRC Studies

Flight Project Updates; SUPRWG Inputs

2017 Best Guess Mission Set Scenario

SCaN Direction for Deep Space Capacity Studies

2017 Best Guess OA Mission Set Scenario

2017 Best Guess JSA Mission Set Scenario

Candidate Missions that maximize data rates for competitively-bid/unassigned placeholder missions → **2017 Max Data Rate Scenario**

Candidate Missions that minimize data rates for competitively-bid/unassigned placeholder missions → **2017 Min Data Rate Scenario**

Candidate Missions that maximize average annual tracking time for competitively-bid/unassigned placeholder missions → **2017 Max Tracking Scenario**

Candidate Missions that minimize average annual tracking time for competitively-bid/unassigned placeholder missions → **2017 Min Tracking Scenario**

Includes all the deep space missions that NASA desires on the desired timescale. Also, includes additional foreign-led and commercial-led missions. And, assumes most SMEX missions are DSN-supported. → **2017 Optimistic Scenario**

Includes only NASA's most prominently planned missions. Stretches out human exploration. Curtails applicable cubesat, competitively-bid, and foreign-led missions. No commercial-led missions. → **2017 Pessimistic Scenario**

Definition of Mission Set Scenarios (3/3)

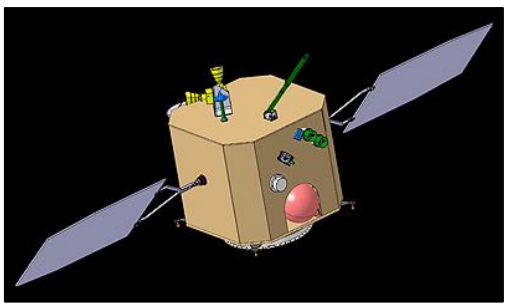
Significant Mission Set Changes Post-2018 Presidential Budget Request (e.g., ARM cancellation, EM-1 deferral to 2019, associated cubesat deferrals, advance in Psyche launch date, tracking time changes, etc.)

Mission Set Scenarios Used in the 2017 Mission Trends & Implications Analysis

(For an enumeration of the specific missions included in each mission set, please see the appendix.)

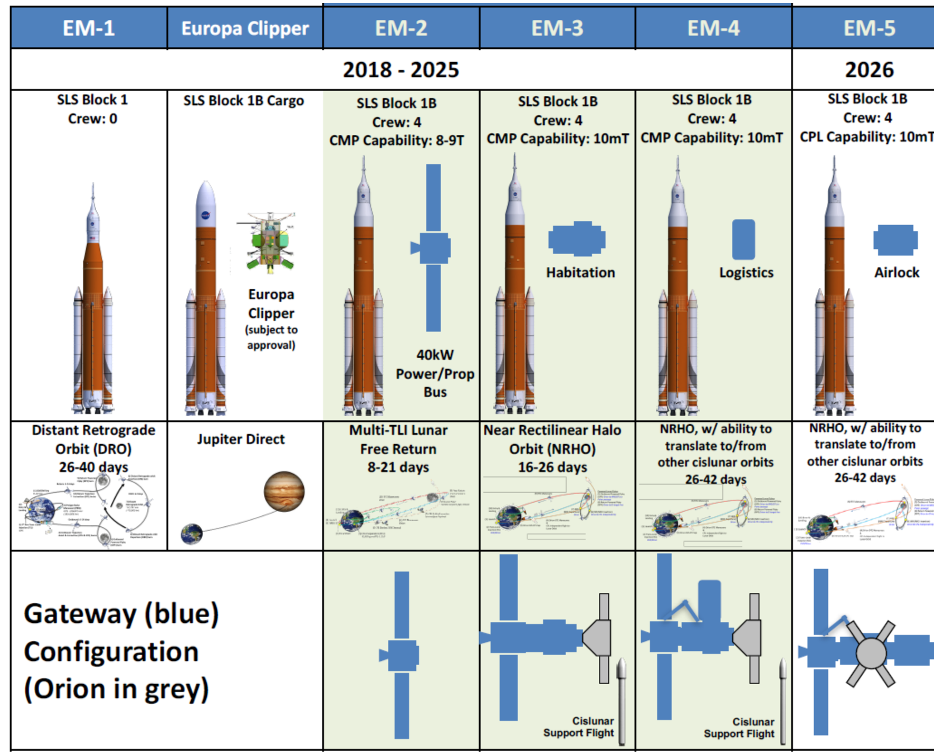
Key Items Not Addressed In Scenarios (1/2)

Removal of Space-X Red Dragons



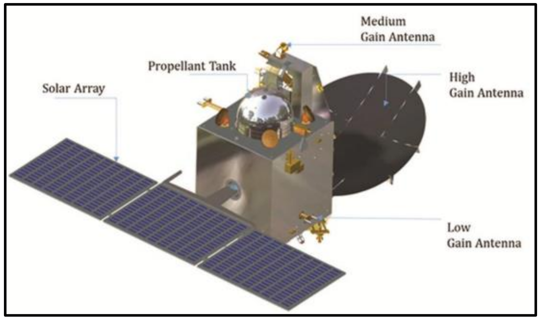
Korea Pathfinder Lunar Orbiter (KPLO) Launch Delay from July 2020 to December 2020

Delay/acceleration of EM-2 Launch to 2022 and Deployment of PPE for the Deep Space Gateway

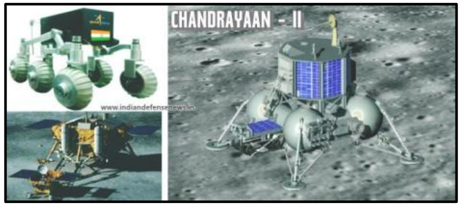


- The exact durations enumerated above for each EM-n mission in the new Deep Space Gateway & Transport Plan.
- Continued communications with the Deep Space Gateway in between EM-n missions.
- Use of the Near Rectilinear Halo Orbits (entries still based on DROs, etc.).

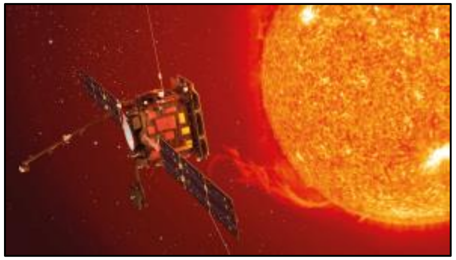
Key Items Not Addressed In Scenarios (2/2)



Delay of MOM-2 Launch to 2022

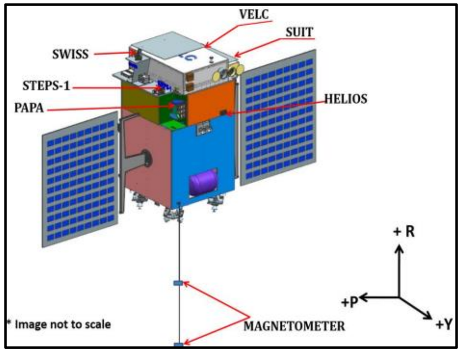


Possible Delay of Chandrayaan-2 Launch Past March 2018

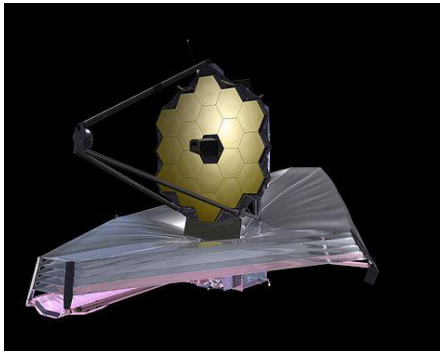


Delay of Solar Orbiter Launch to February 2019

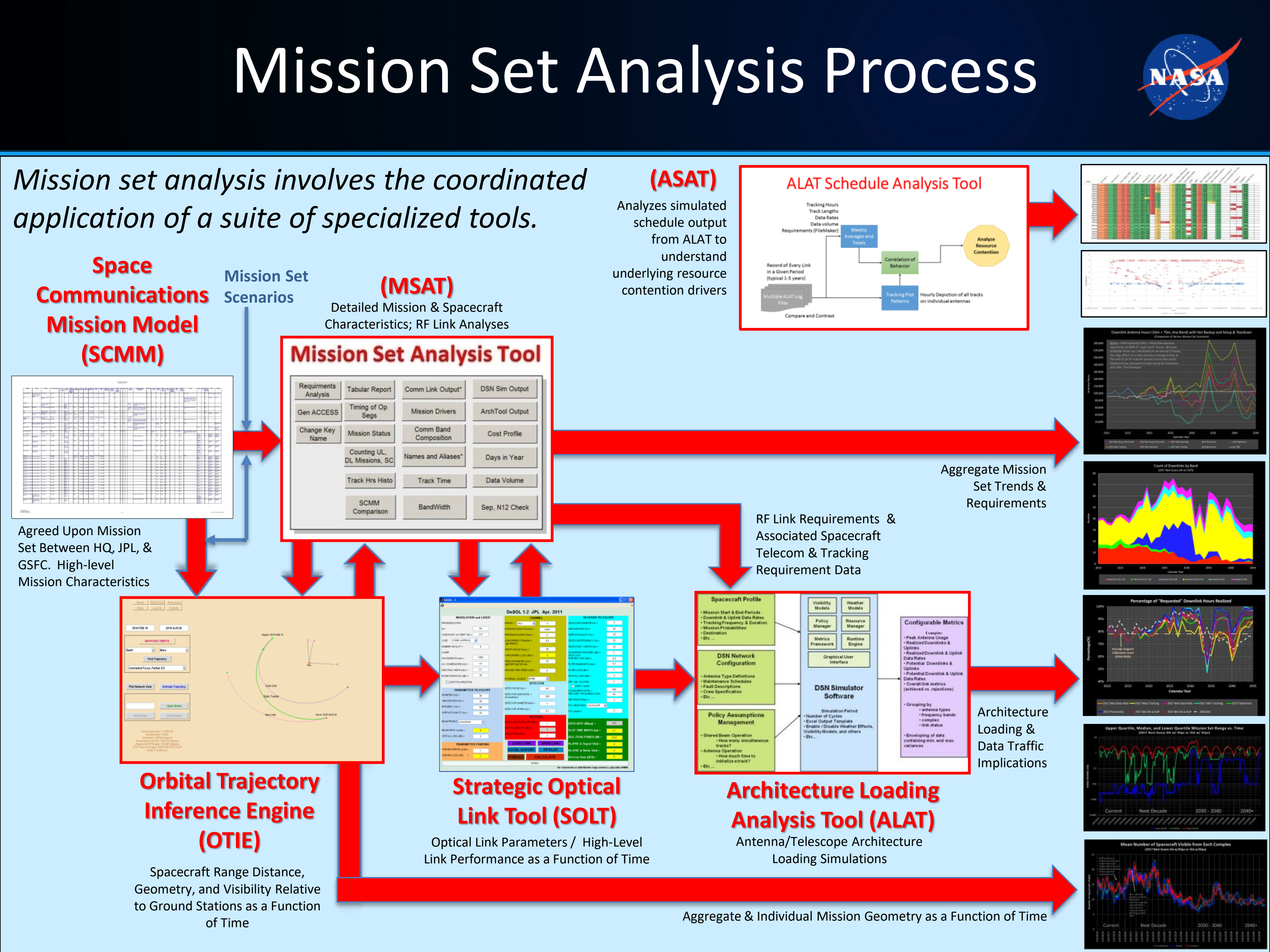
Korean Lunar Exploration Post-KPLO



Acceleration of ADITYA Launch from 2020 to 2019



Delay of JWST Launch to March-June 2019



Mission Set Analysis Process
NASA
Mission set analysis involves the coordinated application of a suite of specialized tools.
Space Communications Mission Model (SCMM)
Mission Set Scenarios
Agreed Upon Mission Set Between HQ, JPL, & GSFC. High-level Mission Characteristics
(MSAT)
Detailed Mission & Spacecraft Characteristics; RF Link Analyses
Mission Set Analysis Tool
Requirements Analysis
Tabular Report
Comm Link Output*
DSN Sim Output
Gen ACCESS
Timing of Op Segs
Mission Drivers
ArchTool Output
Change Key Name
Mission Status
Comm Band Composition
Cost Profile
Counting UL, DL Missions, SC
Names and Aliases*
Days in Year
Track Hrs Histo
Track Time
Data Volume
SCMM Comparison
BandWidth
Sep, N12 Check
(ASAT)
Analyzes simulated schedule output from ALAT to understand underlying resource contention drivers
ALAT Schedule Analysis Tool
Tracking Hours
Track Lengths
Data Rates
Data volume
Requirements (FileMaker)
Weekly Averages and Totals
Correlation of Behavior
Analyze Resource Contention
Record of Every Link in a Given Period (typical 1-3 years)
Multiple ALAT Log Files
Tracking Plot Patterns
Hourly Depiction of all tracks on individual antennas
Compare and Contrast
Aggregate Mission Set Trends & Requirements
RF Link Requirements & Associated Spacecraft Telecom & Tracking Requirement Data
Orbital Trajectory Inference Engine (OTIE)
Spacecraft Range Distance, Geometry, and Visibility Relative to Ground Stations as a Function of Time
DeSOL 1.2 JPL Apr. 2011
Strategic Optical Link Tool (SOLT)
Optical Link Parameters / High-Level Link Performance as a Function of Time
Spacecraft Profile
DSN Network Configuration
Policy Assumptions Management
DSN Simulator Software
Configurable Metrics
Architecture Loading Analysis Tool (ALAT)
Antenna/Telescope Architecture Loading Simulations
Architecture Loading & Data Traffic Implications
Aggregate & Individual Mission Geometry as a Function of Time

Other Key Assumptions (1/3)

- Antenna-time analyses and loading simulations have been run with the same DSN baseline starting-point assumptions as the "Deep Space Capacity Study." Note that some of these assumptions may have since changed due to budgetary factors.
  - 4-MSPA capability for Mars missions.
  - DSN 34m HEF closures with DSS-45 closed on November 1, 2016, DSS-15 closed on November 1, 2017, and DSS-65 closed on May 31, 2021.
  - DSS-36 comes up on October 1, 2016 with 250W S-band uplink, S-band downlink, 20 kW X-band uplink, X-band downlink, and Ka 32 GHz downlink.
  - DSS-26 gets 250W S-band uplink and S-band downlink added on October 21, 2017. 80 kW capability already resides on DSS-26.
  - DSS-25's current 350W 34 GHz uplink is upgraded to 1 kW on December 21, 2020.
  - DSS-56 goes up March 4, 2020 with 250W S-band uplink, S-band downlink, 20 kW X-band uplink, X-band downlink, Ka 32 GHz downlink and Ka 26 GHz downlink.
  - DSS-35 receives 1 kW 34 GHz uplink capability on December 21, 2018.
  - DSS-54 goes down January 1, 2022 and comes back up on January 1, 2024.

Other Key Assumptions (2/3)

- DSS-53 comes up October 1, 2020 with 80 kW X-band uplink, X-band downlink, and Ka 32 GHz downlink.
- DSS-43 goes down from March 15, 2020 to September 11, 2020 for transmitter replacement, elevation bearing installation, and power upgrades.
- DSS-55 receives 1 kW 34 GHz uplink capability on December 21, 2019.
- DSS-14 goes down from April 5, 2021 to October 2, 2021 for transmitter replacement, elevation bearing installation, and power upgrades.
- DSS-26 receives 26 GHz downlink capability – approximated as April 1, 2021.
- DSS-36 receives 26 GHz downlink capability – approximated as April 1, 2022.
- DSS-33 comes up on October 1, 2024 with 80 kW X-band uplink, X-band downlink, and Ka 32 GHz downlink.
- DSS-23 comes up on October 1, 2022 with 20 kW X-band uplink, X-band downlink, and Ka 32 GHz downlink.
- DSS-63 goes down from April 4, 2022 to October 1, 2022 for transmitter replacement and power upgrades.

Other Key Assumptions (3/3)

- No new frequency bands are assumed in the baseline (e.g., 22 GHz up, 40 GHz up, 37-38 GHz down, optical).
- Human exploration missions are assumed to require a "hot backup" antenna that can be quickly swapped in if the other antenna fails. In some cases, a mission's high-data-rate requirement at Mars distance necessitates arraying up multiple 34m antennas in order to close the link. In such cases, only one "hot backup" antenna is assumed for the whole array.
- Loading plots assume 24/7 antenna availability. Antenna-hour plots assume that each antenna is used for mission tracking 80% of the time.
  - The remaining 20% of the time goes to a combination of planned maintenance, engineering & operations, unplanned corrective maintenance, and times when mission geometry precludes visibility from the Complex.

Interpretation of Results

We are not trying to predict the future. We're trying to understand the implications of NASA's current plans for the future and suggest ways to best position the network to support those plans.

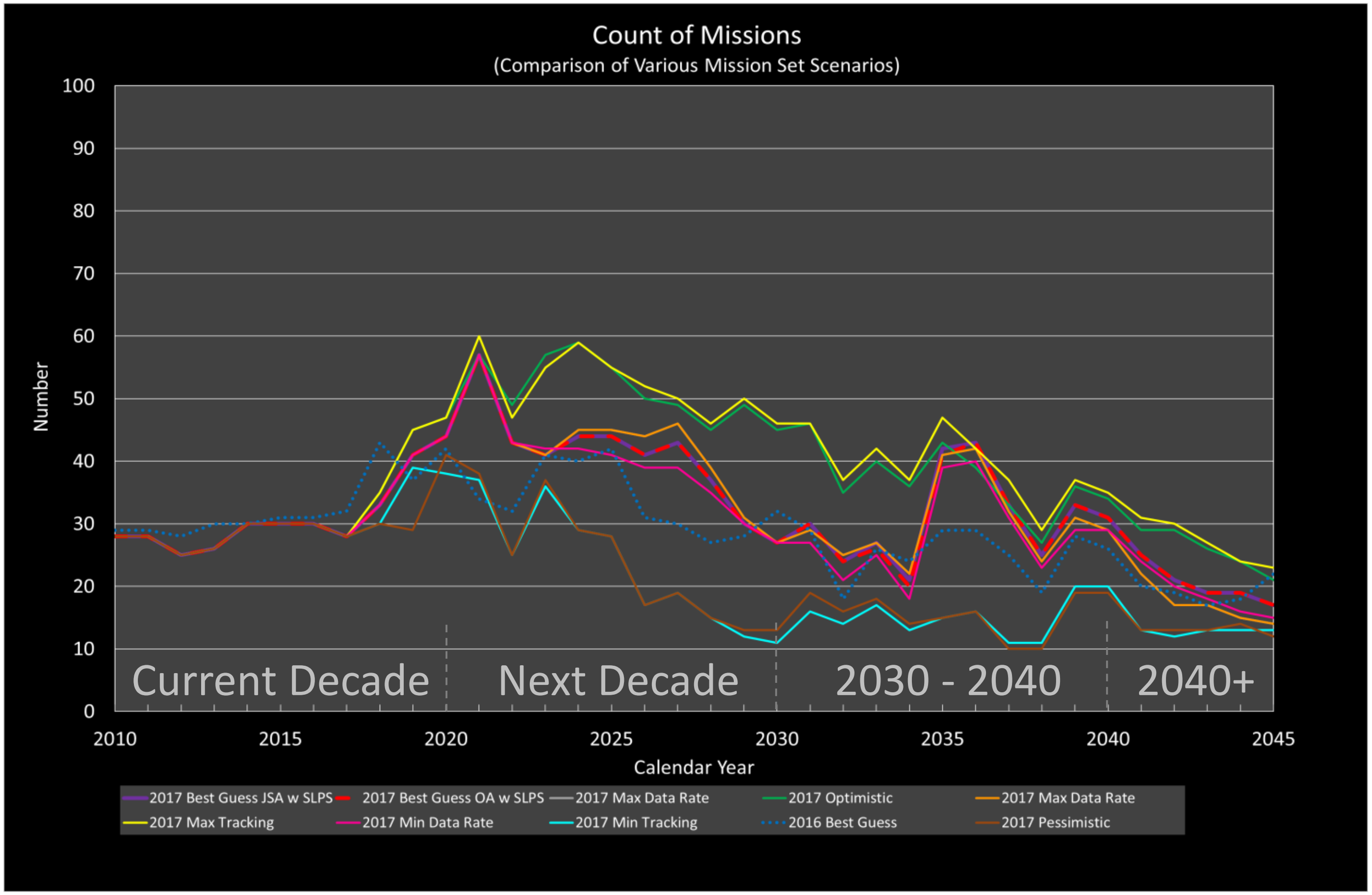
- Multiple mission set scenarios are used to try and "envelope" the possibility space.

- Inferred requirements and architectural solutions that derive from, or work across, the majority of the scenarios will be the most resilient to the inevitable mission set changes that occur over time.

Topics

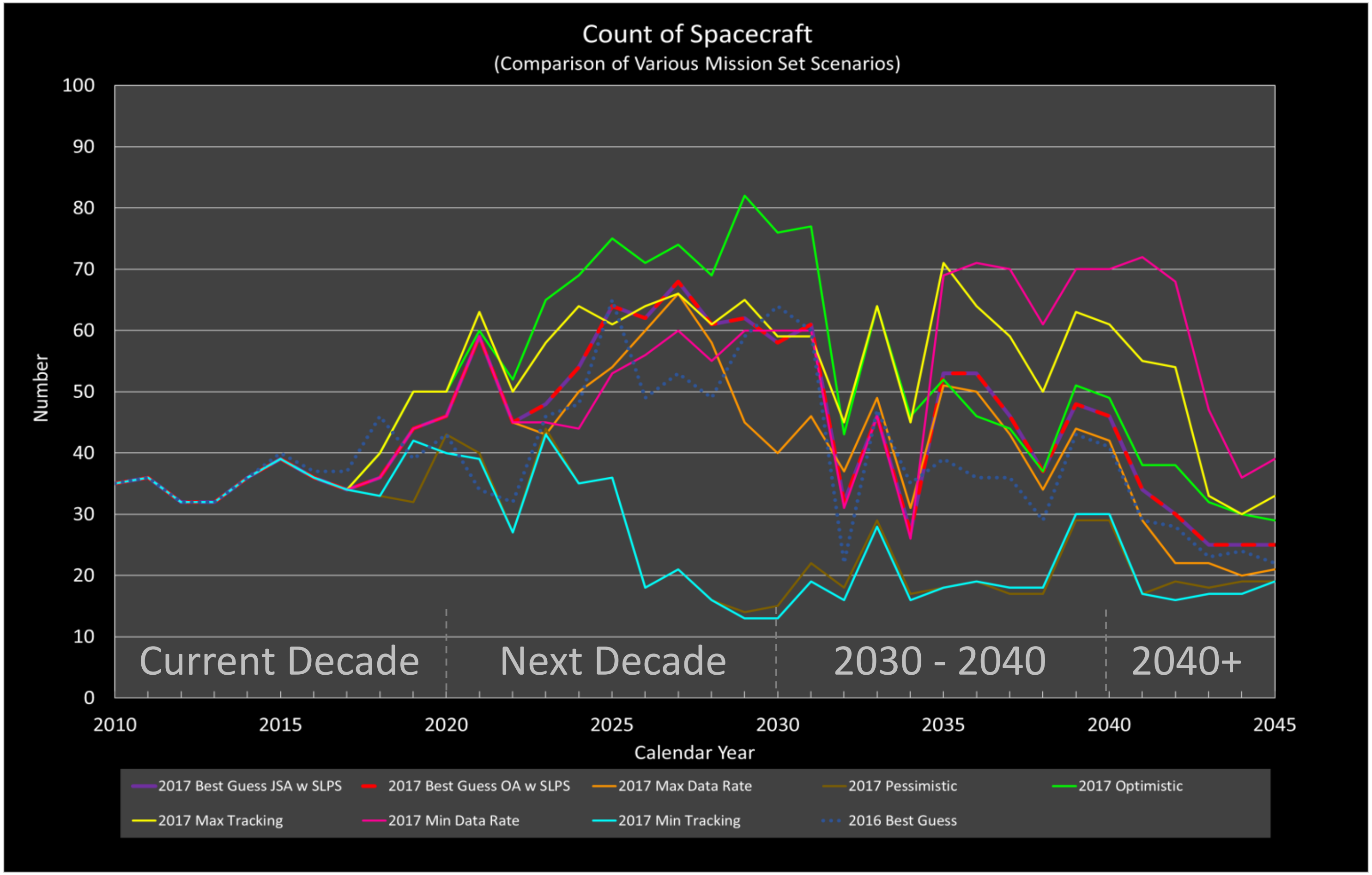
- **Factors Shaping the Anticipated Future Mission Set**: The Budget Situation, Uncertainty & Shifting Priorities for Human Exploration, and Increasing Globalization and Commercialization of Space Exploration Beyond GEO
- **Future Mission Set Analysis Methodology**: Definition of Mission Set Scenarios, Key Items Not Yet In Scenarios, Mission Set Analysis Process, Other Assumptions, and Interpretation of Results
- **Selected Mission Set Analysis Results**
  - **Capacity:** Anticipated Customer Base, Antenna-Hour Demand, and Antenna Asset Visibilities
  - **Capability**
    - **Downlink**: Average Rates, Maximum Rates, Rate Drivers, Data Volumes, Mission Set Range, End-to-End Downlink Difficulty, Maximum Individual G/T, and Aggregate G/T
    - **Uplink:** Average Rates, Rate Drivers, Maximum Individual EIRP, and Aggregate EIRP.
  - **Spectrum:** Downlink Count, Downlink Antenna Hours, Uplink Count, and Uplink Antenna Hours
  - **Loading Simulation Results:** "Requested" Downlink Hours Realized, "Requested" Downlink Data Volume Realized, "Requested" Uplink Hours Realized, and "Requested" Uplink Data Volume Realized
- **Implications**: The Next 10 Years and The Human Mars Exploration Era

Anticipated Customer Base (1/6)



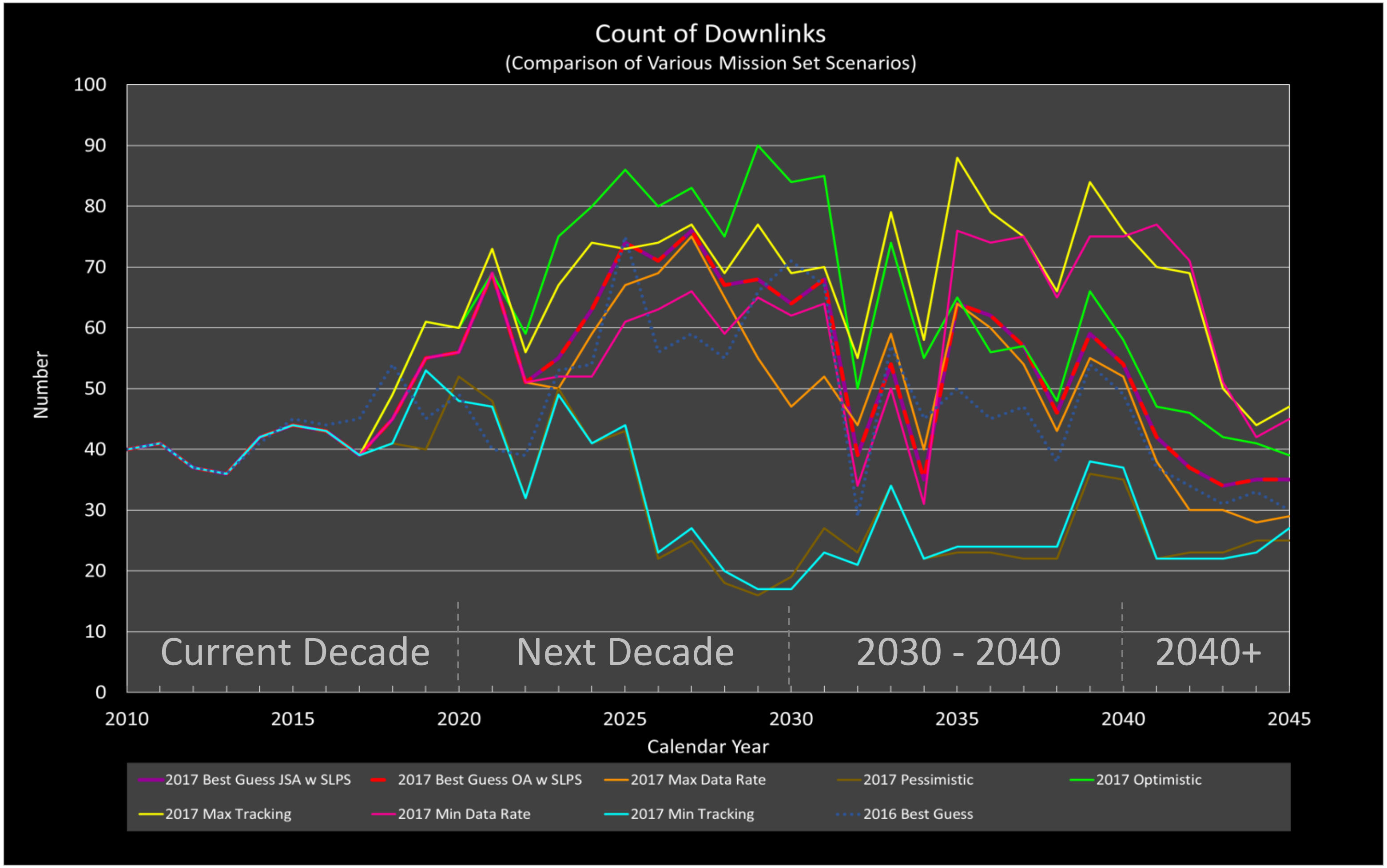
In most scenarios, over the next 10 years, a more robust planetary science budget and more numerous cubesat secondary payload launch opportunities cause a substantial increase in the postulated number of missions. Beyond that, human exploration missions are assumed to consume a larger portion of NASA's budget, leading to a decline in total mission count.

Anticipated Customer Base (2/6)



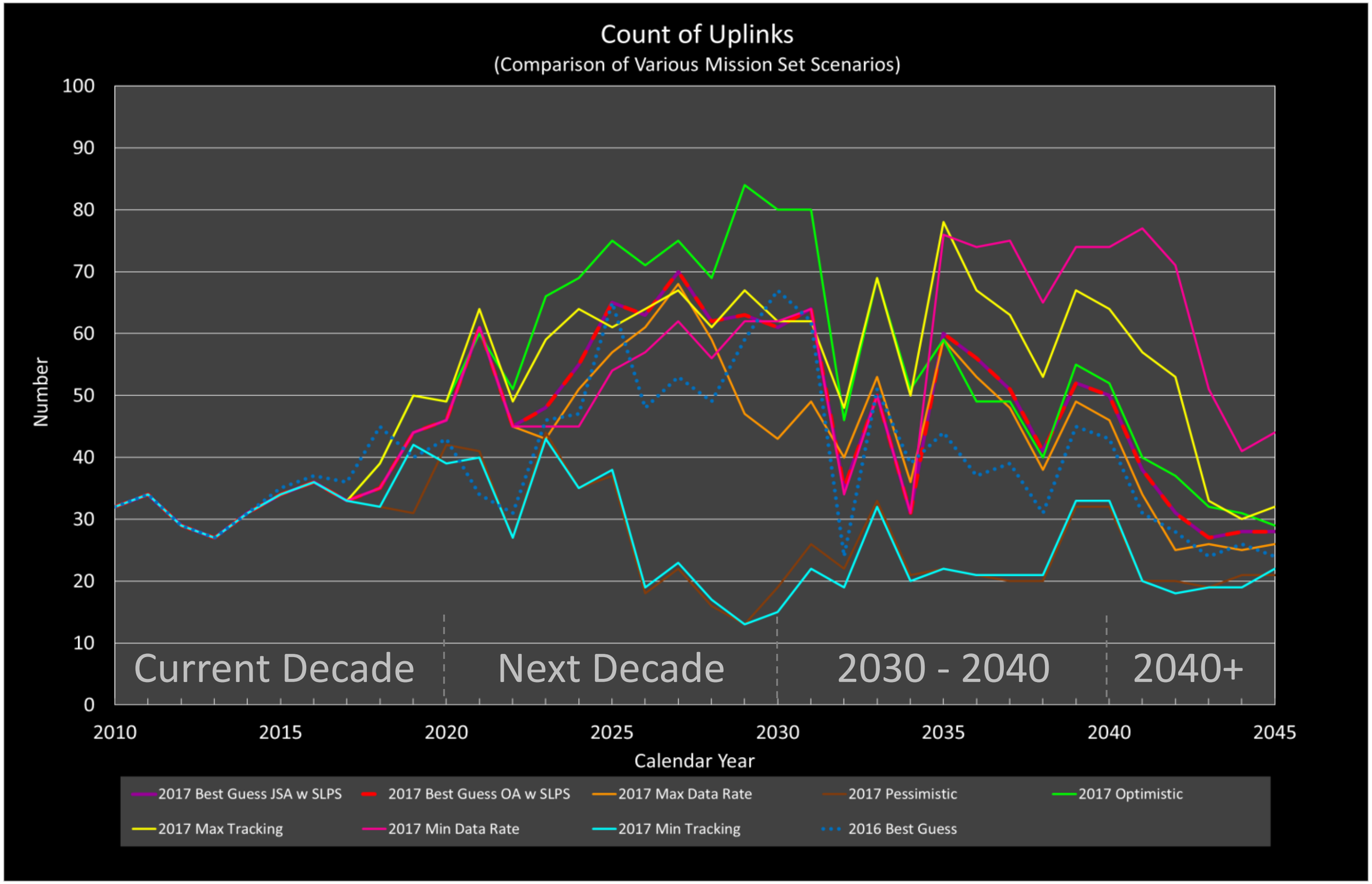
With more missions in the near term and some involving multiple spacecraft, the spacecraft count is expected to roughly double by 2027. In the 2030s, spacecraft numbers are projected to remain higher than today since the human exploration missions generally involve multiple elements.

Anticipated Customer Base (3/6)



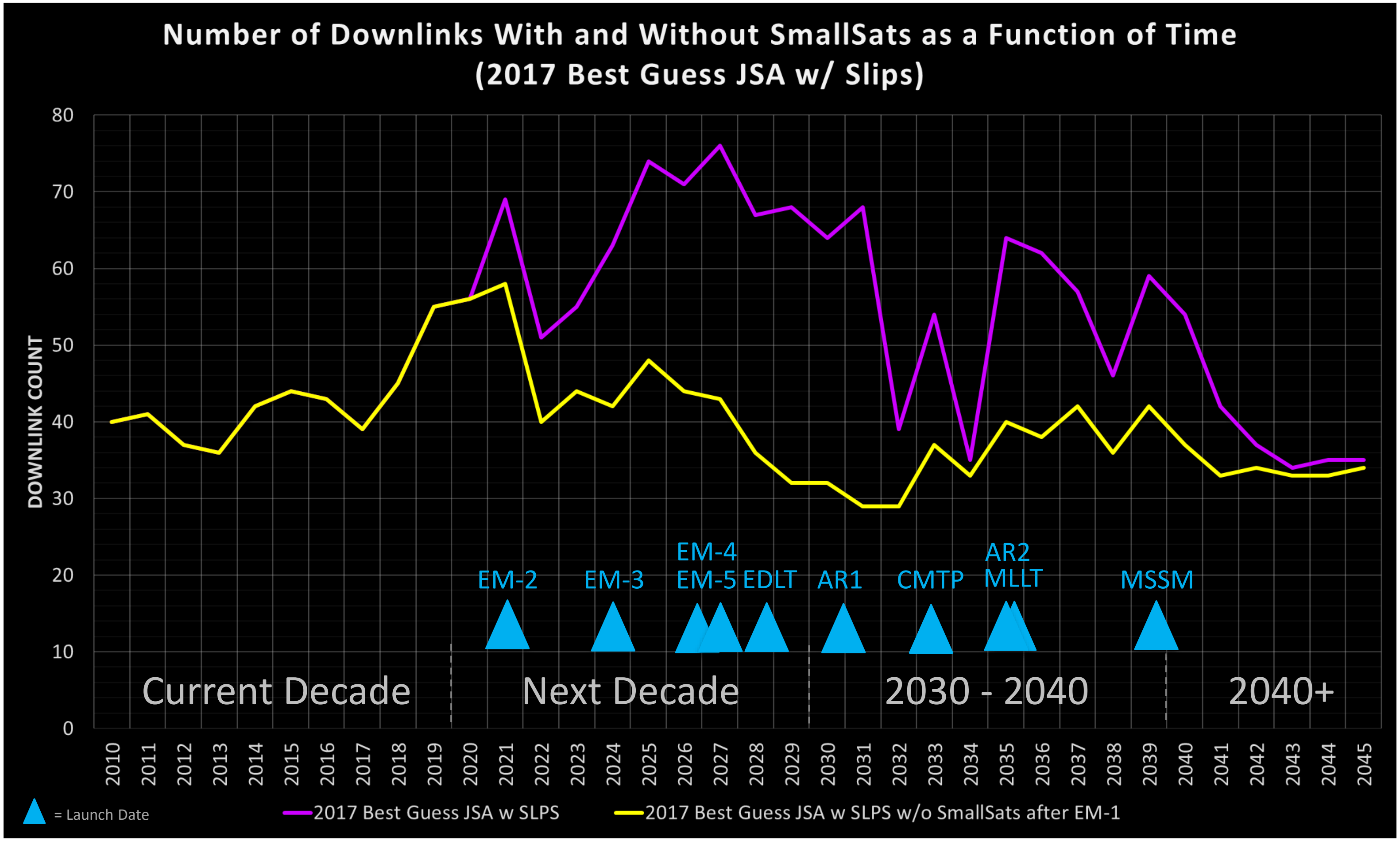
Since some spacecraft use multiple downlinks, the downlink count can be substantially greater than the number of projected spacecraft, depending upon the timeframe of interest.

Anticipated Customer Base (6/6)



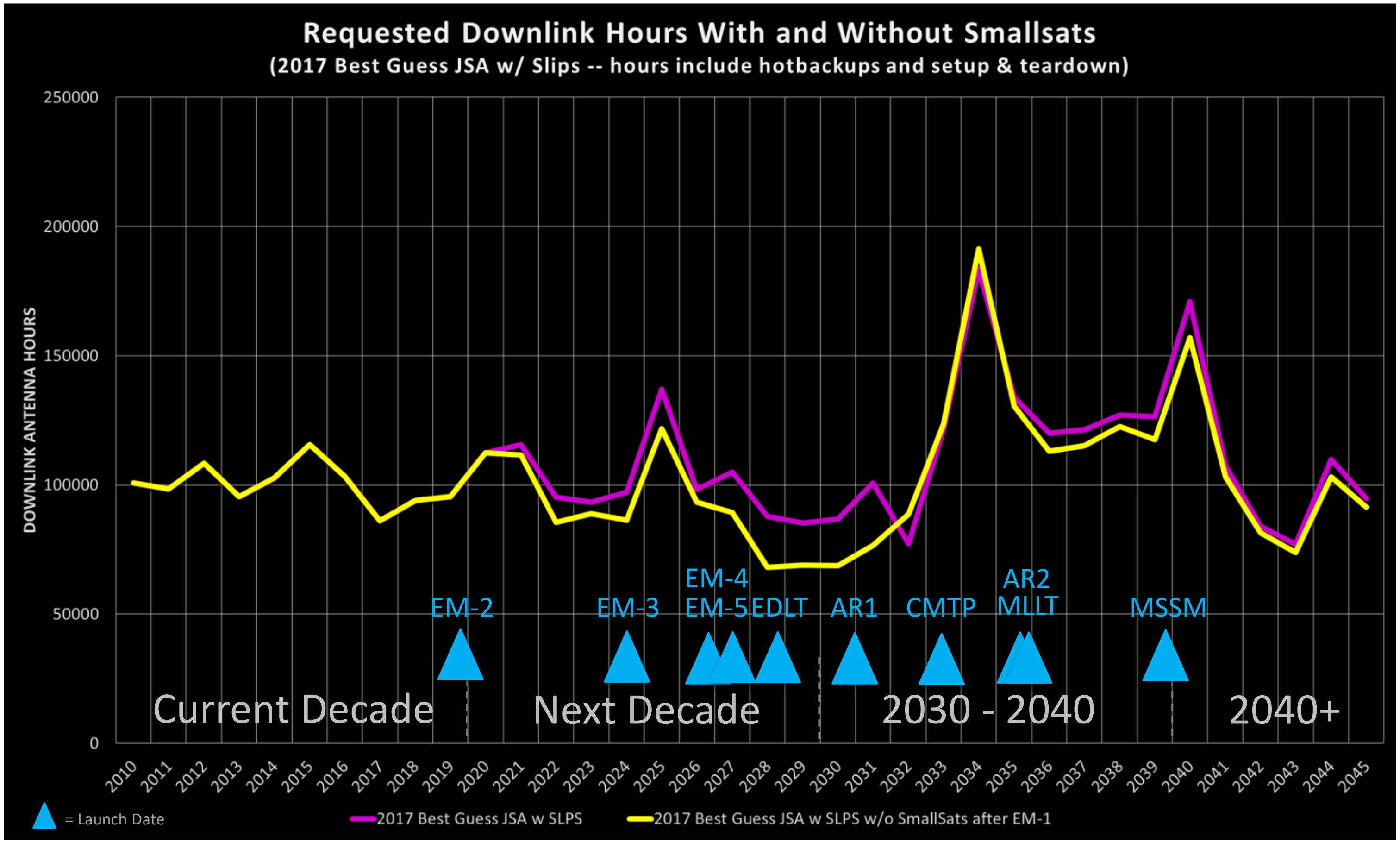
Human exploration spacecraft tend to make use of multiple uplinks. Hence, the projected uplink support numbers also tend to be higher than the spacecraft count.

Anticipated Customer Base (4/6)



Smallsats comprise a significant portion of the anticipated downlink demand. Their peak downlink numbers tend to correspond to the secondary launch opportunities associated with human exploration launches. As the timing and nature of these launches shift, the smallsat peaks can be expected to shift as well.

Anticipated Customer Base (5/6)



While smallsats contribute significantly to downlink numbers, their contribution to requested downlink hours will likely be relatively small. In some cases, the hours requested without smallsats can exceed those with when, for instance, a single large spacecraft requires more tracking than several quiescent smallsats in passive formation.

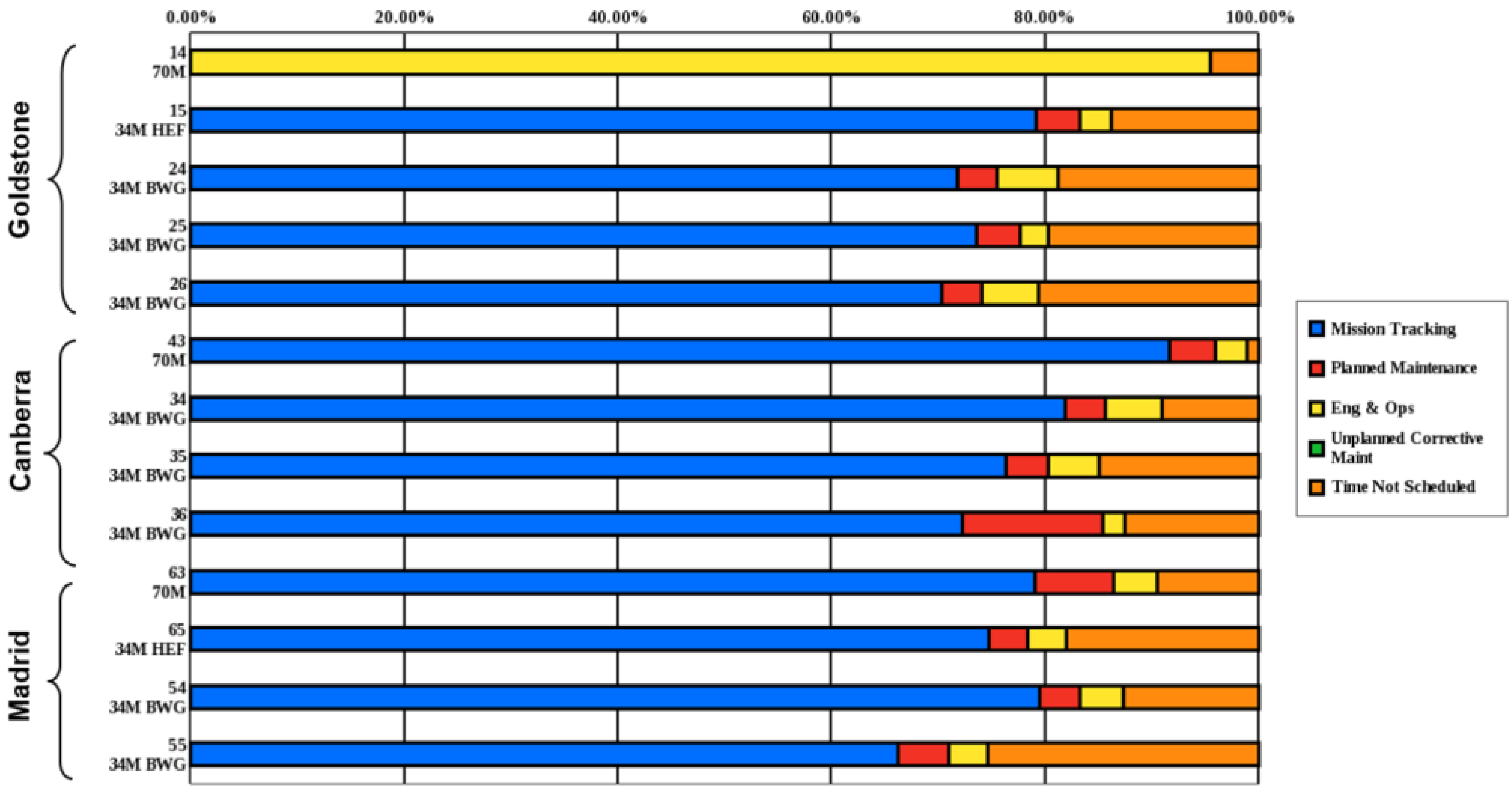
Anticipated Customer Base (5/5)

Takeaways:

- While the projected future mission set has grown somewhat since last year, anticipated long-term budget constraints still cause it to trend down somewhat over time.
  - Human exploration missions are expected to require an increasingly large portion of the NASA budget.
- Even though the projected mission set trends down somewhat over time, the projected number of spacecraft, downlinks, and uplinks all grow substantially over the next 10 years and still remain at levels greater than today's through the subsequent decade.
  - Human exploration missions involve multiple spacecraft, each with multiple uplinks and downlinks associated with them.
  - The number of uplink and downlink supports are projected to almost double by 2027.
- Smallsats constitute a significant portion of the increase in anticipated downlink numbers, but only slightly increase antenna-hour demand.
  - Smallsat downlink numbers tend to peak during human exploration missions due to the secondary payload launch opportunities such missions will likely extend to cubesats.

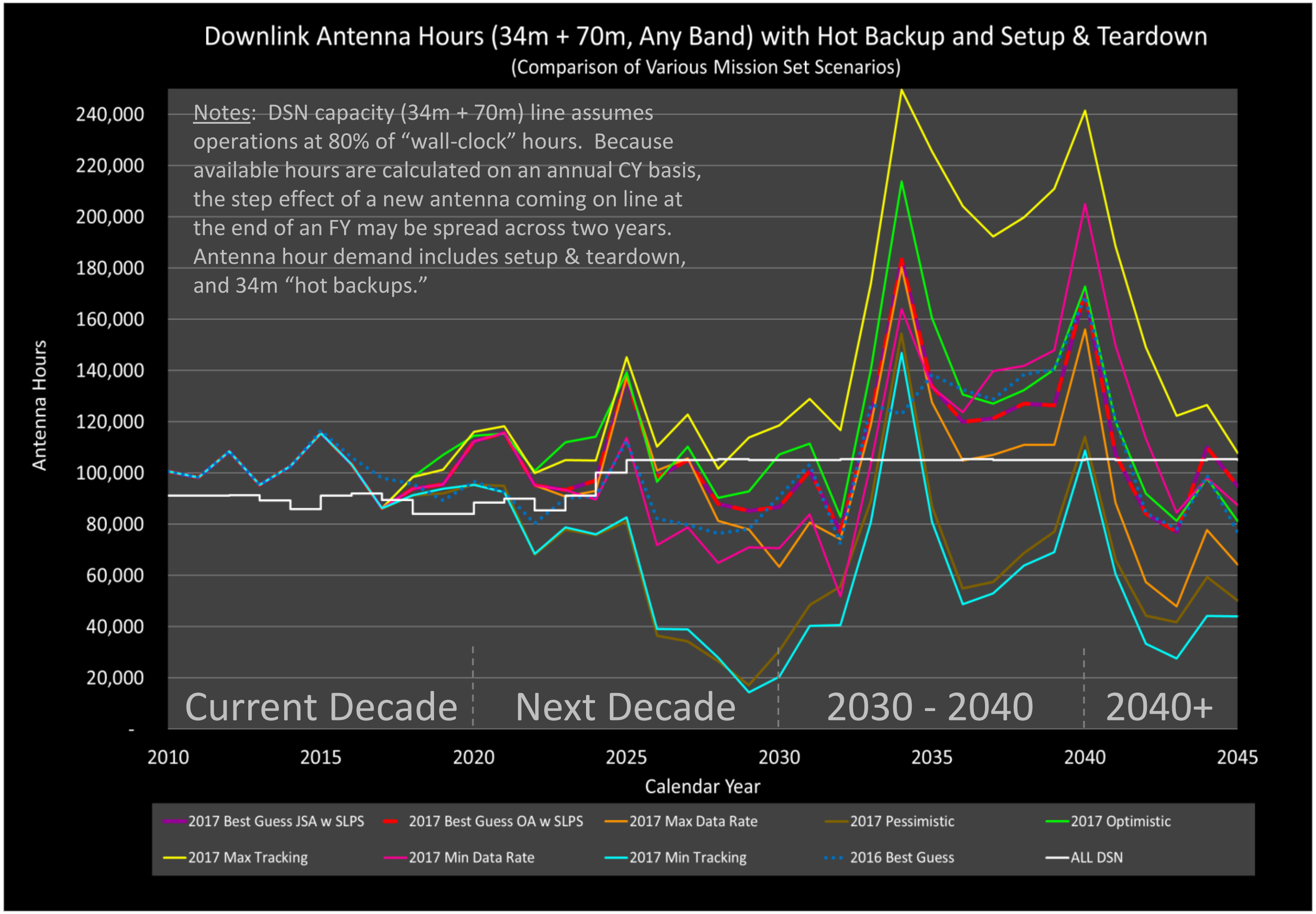
Antenna-Hour Demand (1/5)

Antenna Utilization: July 2017



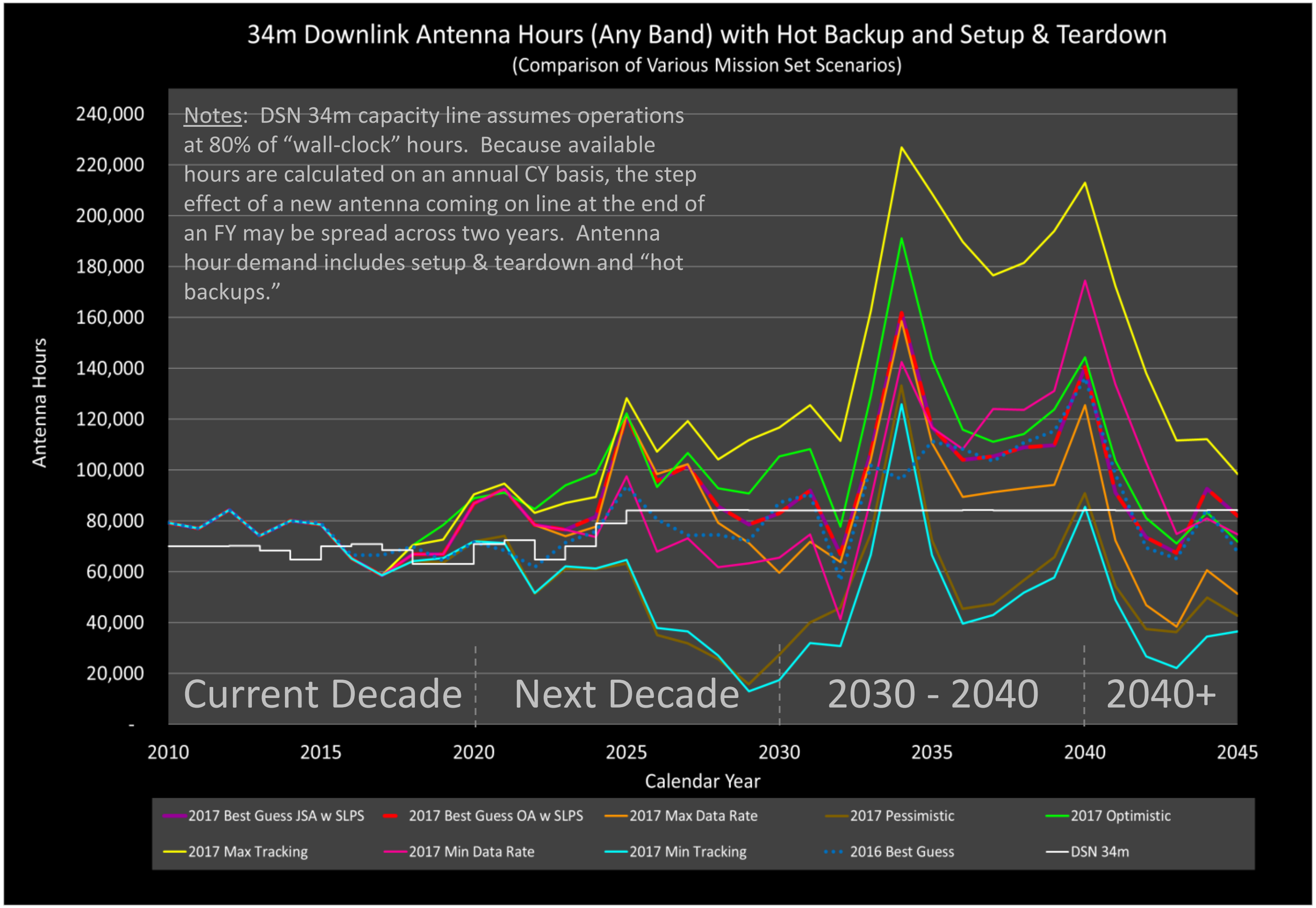
On average, DSN antennas are used at ~75-80% of available "wall-clock" hours.

Antenna-Hour Demand (2/5)



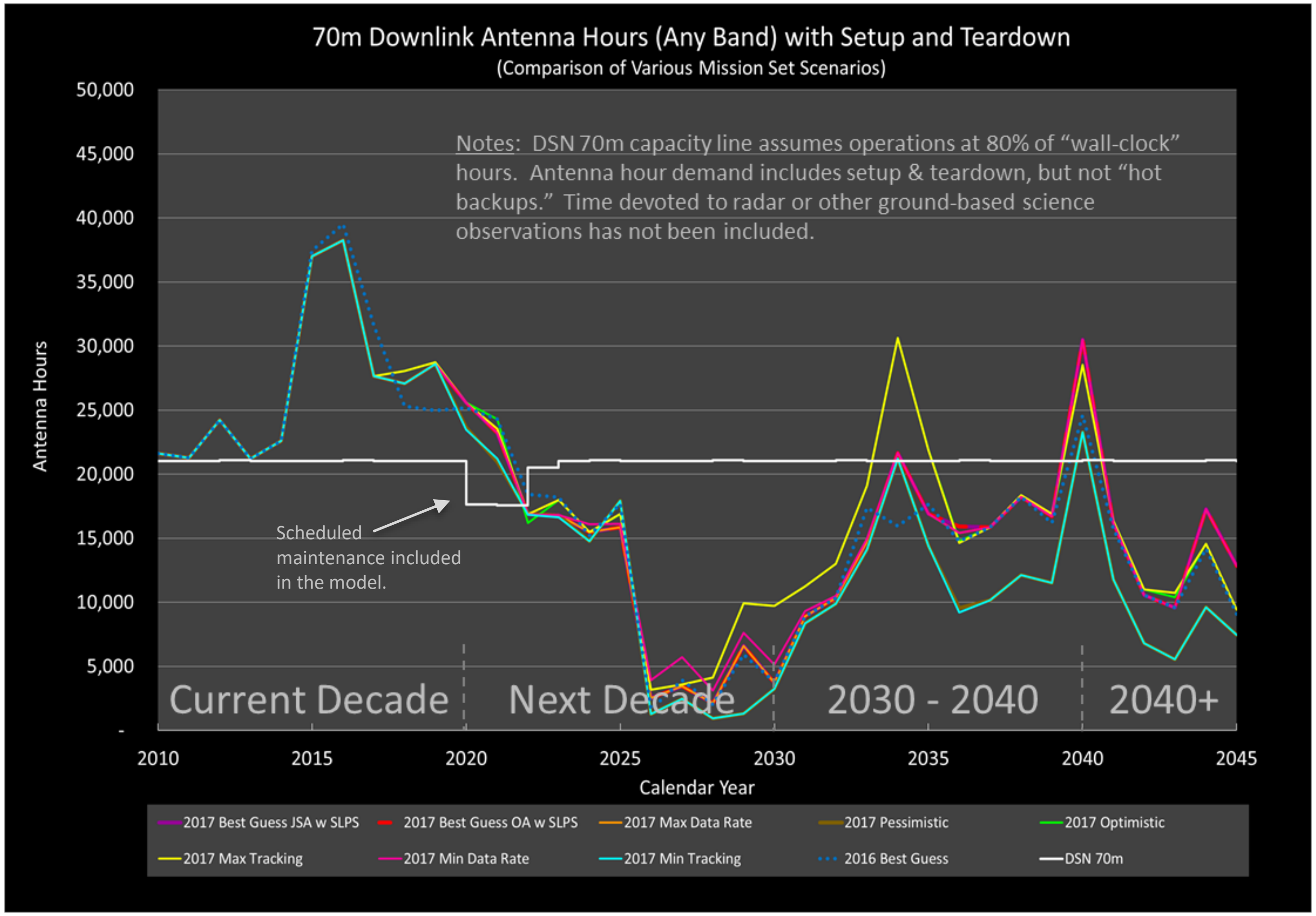
In most scenarios, downlink-antenna-hour demand appears to exceed supply in the 2020's, until DAEP is completed. Arrayed antenna demand from human exploration in the 2030's and beyond completely overwhelms supply at the DAEP level.

Antenna-Hour Demand (3/5)



For most of the scenarios, 34m downlink-antenna-hour demand exceeds supply until at least DAEP completion. For several of the scenarios, demand exceeds supply through 2027. In the 2030s and beyond, human exploration's need for arrayed antennas completely overwhelms supply at the DAEP level.

Antenna-Hour Demand (4/5)



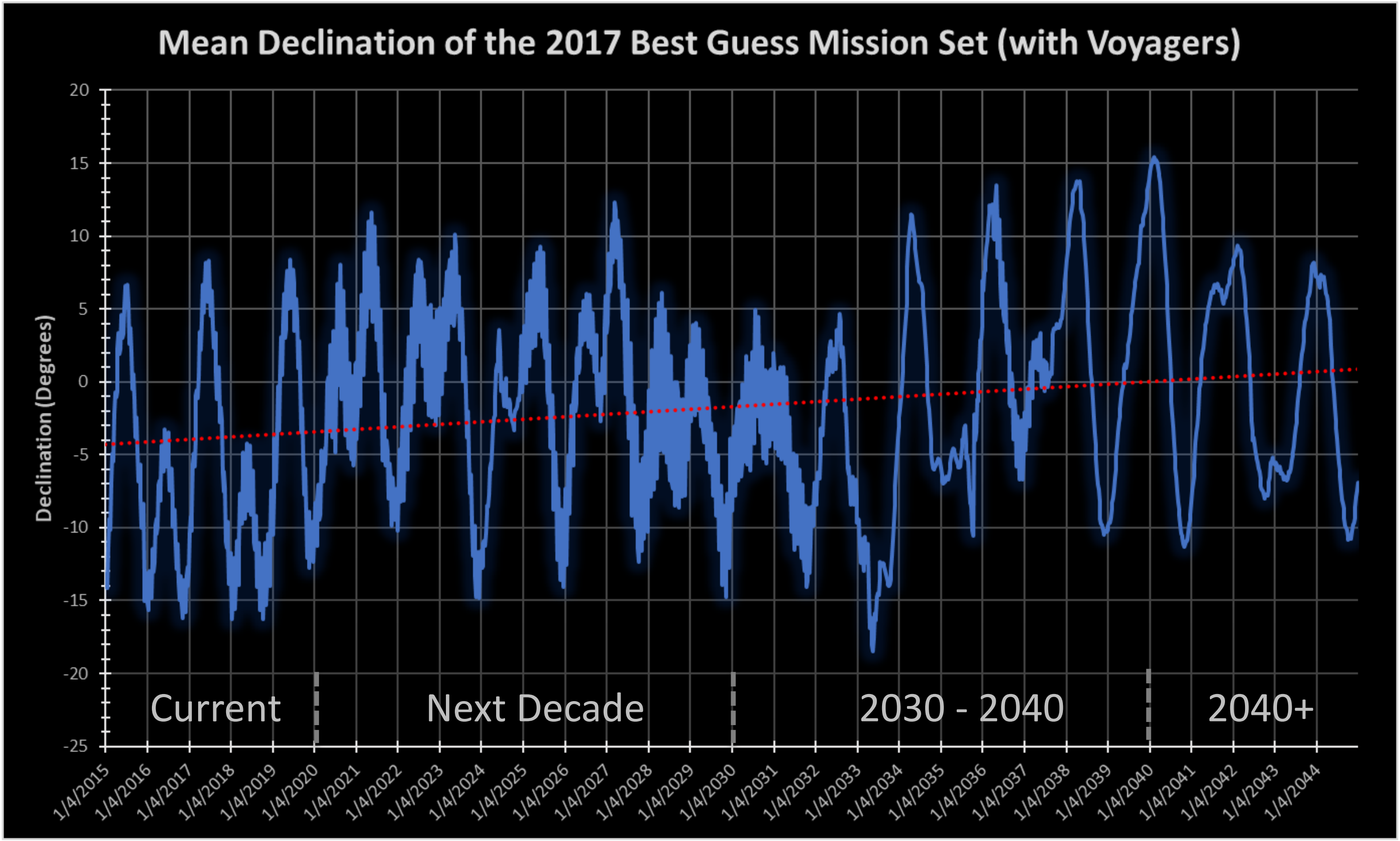
Note scale change from prior slides. 70m demand currently exceeds supply. Surplus capacity is likely next decade due to SMD's "single 34m only for routine support" policy – though, this could change somewhat if New Horizons pursues a 2nd KBO encounter. Mission-critical events drive remaining demand. Full-capacity demand returns in the 2030's due to human Mars exploration.

Antenna-Hour Demand (5/5)

Takeaways:

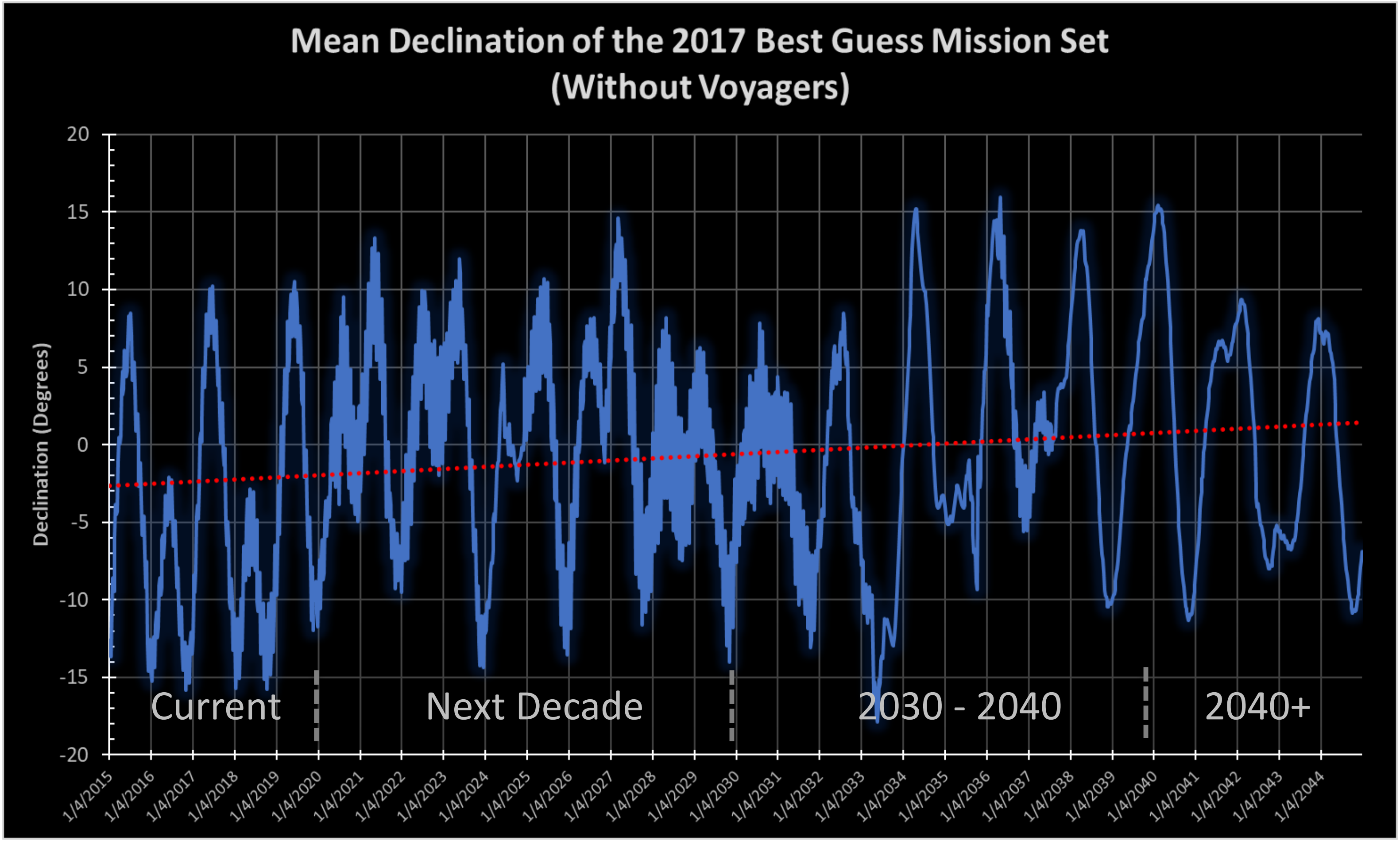
- The DSN is already operating at capacity and is projected to continue doing so for most of the next decade.
  - Oversubscription is being handled by “downsizing” mission customer “requirements” during the RAP process.
  - The DAEP buildout is essential to keep pace with this already “downsized” demand.
- Post-DAEP DSN assets are insufficient for meeting the demands of the human Mars exploration era.
  - 34m antenna-hour demand “skyrockets” in the 2030s and beyond due to the need to array up antennas in order to meet human mission downlink and/or uplink rate requirements at Mars distances. (See “Deep Space Capacity Study” recommendations for minimizing the needed arraying.)
  - Critical event support and human Mars exploration support require 70m-equivalent capability. Attempting to provide such support via only arrayed 34m antennas would severely exacerbate the 34m insufficiency discussed above.

Antenna Asset Visibilities (1/8)



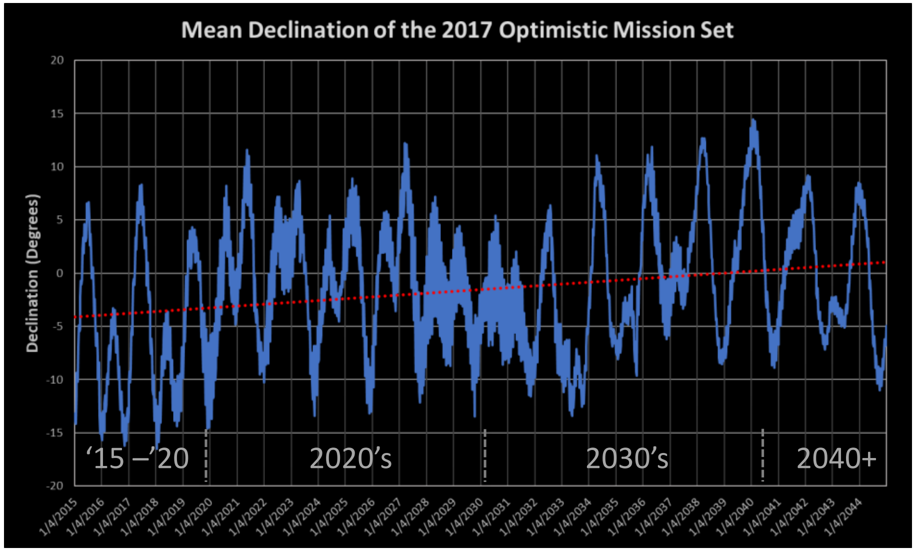
Currently, the mean mission set declination is, on average, southern biased. In 2020, that bias becomes less apparent and does not significantly resurface until 2027. It then fades away again in 2034. The annual cyclical variations tend to be driven by Mars's visibility.

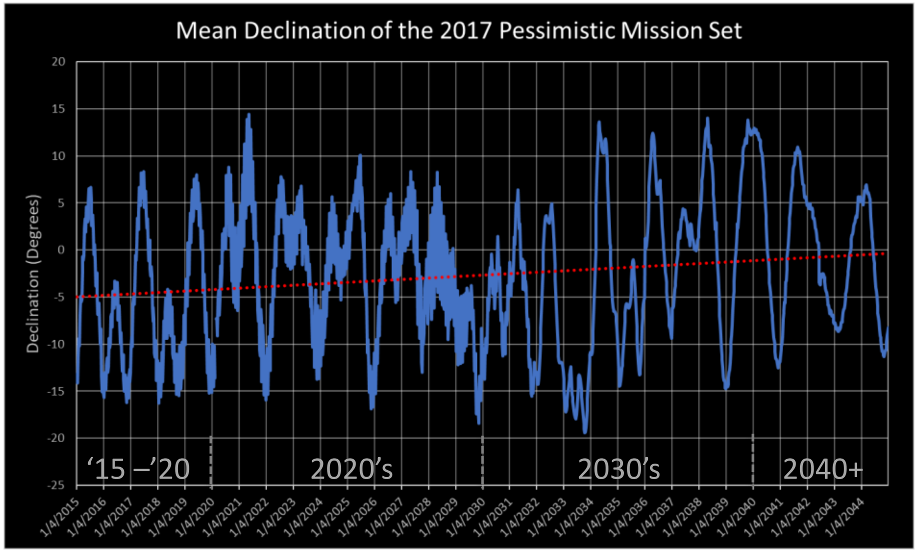
Antenna Asset Visibilities (2/8)



While deletion of the Voyager spacecraft slightly reduces the extent of the southern declination bias, it does not appreciably change the observations noted on the prior slide.

Antenna Asset Visibilities (3/8)





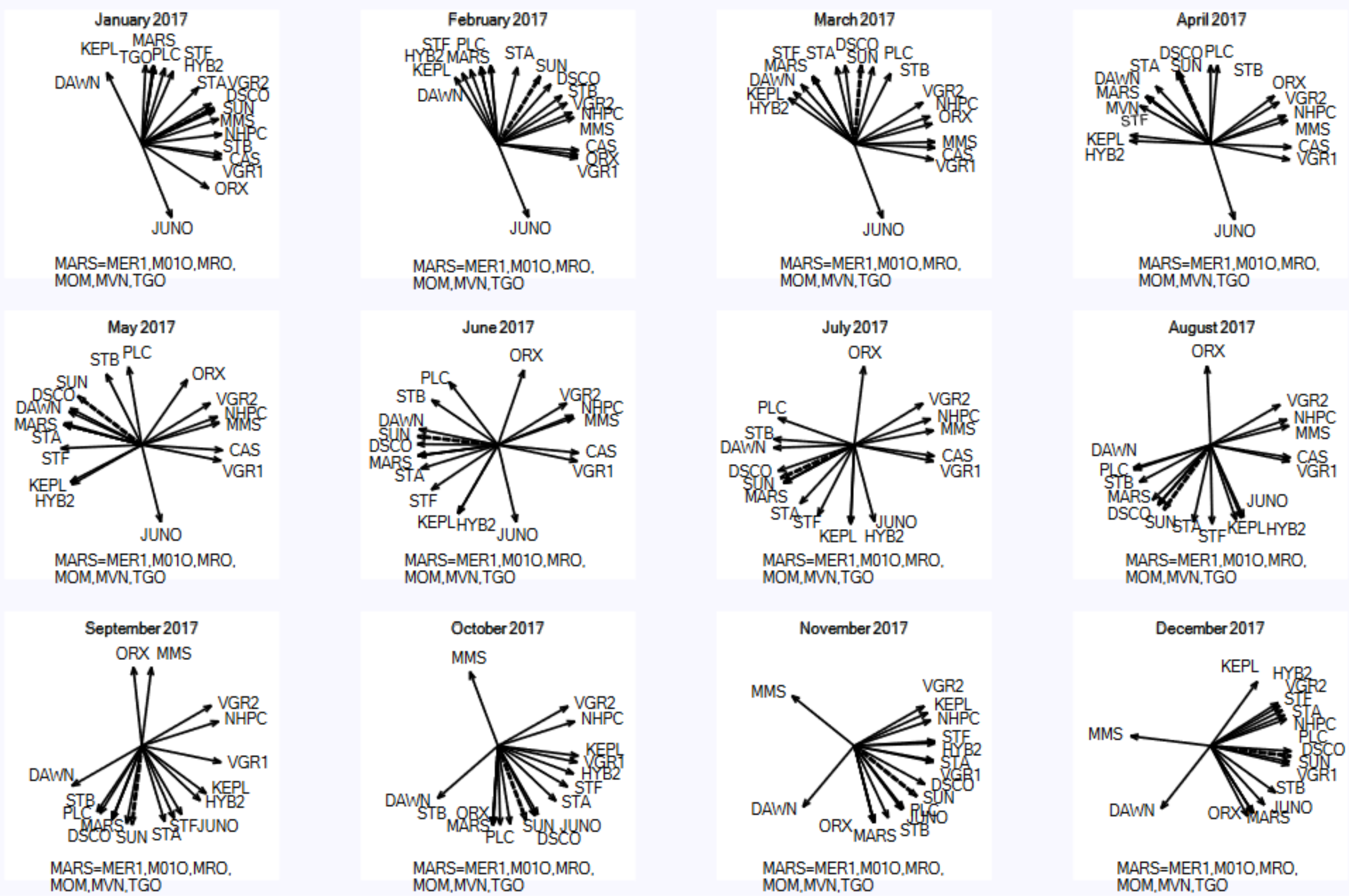
- The 2017 Optimistic Mission Set Scenario is characterized by a declination profile that is very similar to the 2017 Best Guess profile.

- The 2017 Pessimistic Mission Set Scenario is also characterized by a declination profile that is very similar to the 2017 Best Guess profile.

Antenna Asset Visibilities (4/8)

Credit: DSN Scheduling, RAPWEB.

Spacecraft Right Ascension
2017



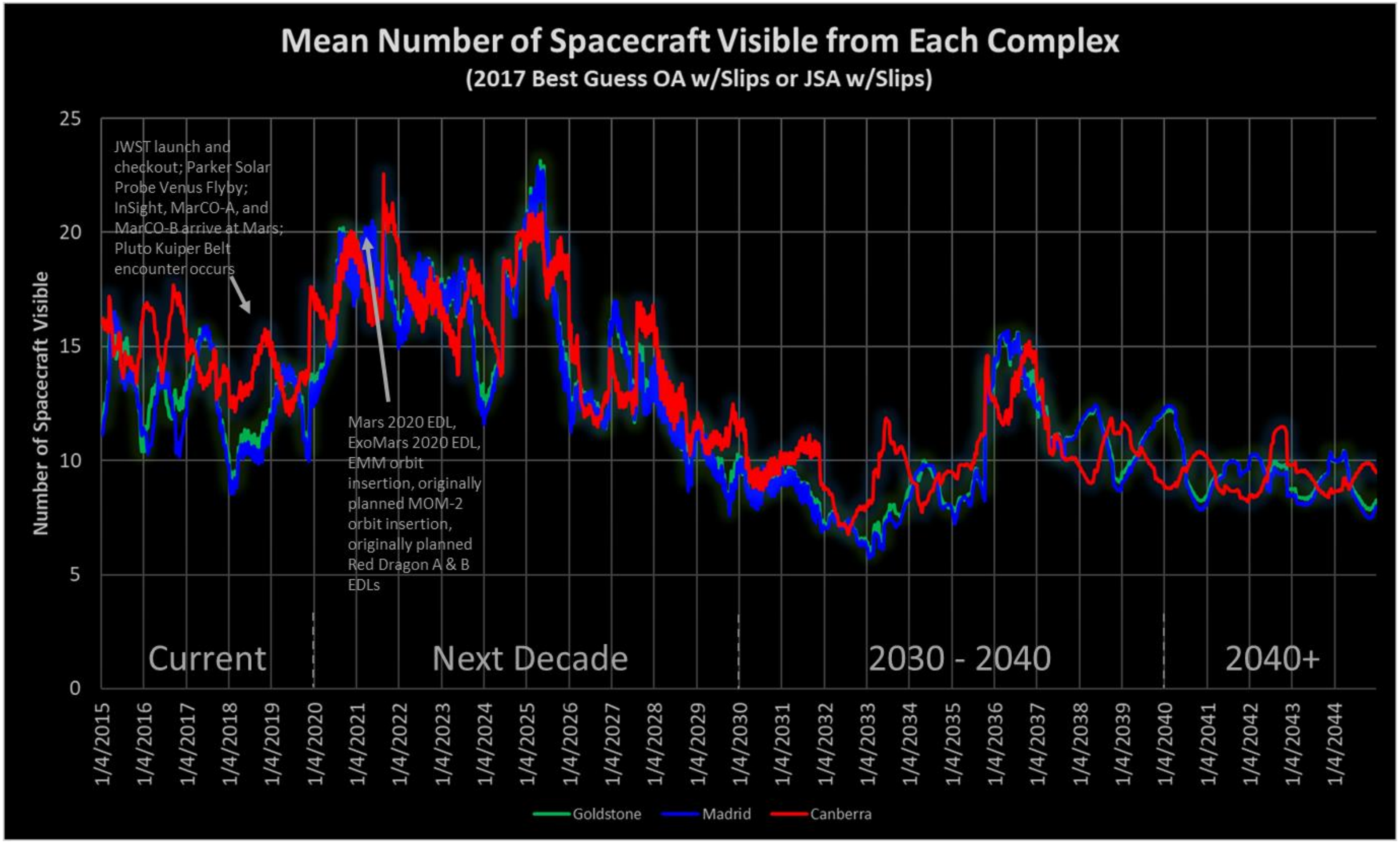
As of May 2017

The spacecraft right ascension figures show the positions of the spacecraft in the sky relative to each other on the 15th of each month for the year indicated. Right ascension is commonly measured in hours, with 1 hour = 15 degrees. The arrow indicates the center of a spacecraft view from earth. Extend 60 degrees on both sides of the arrow to calculate an eight (8) hour view period.

The aggregate mission set can also have a highly variable right ascension bias.

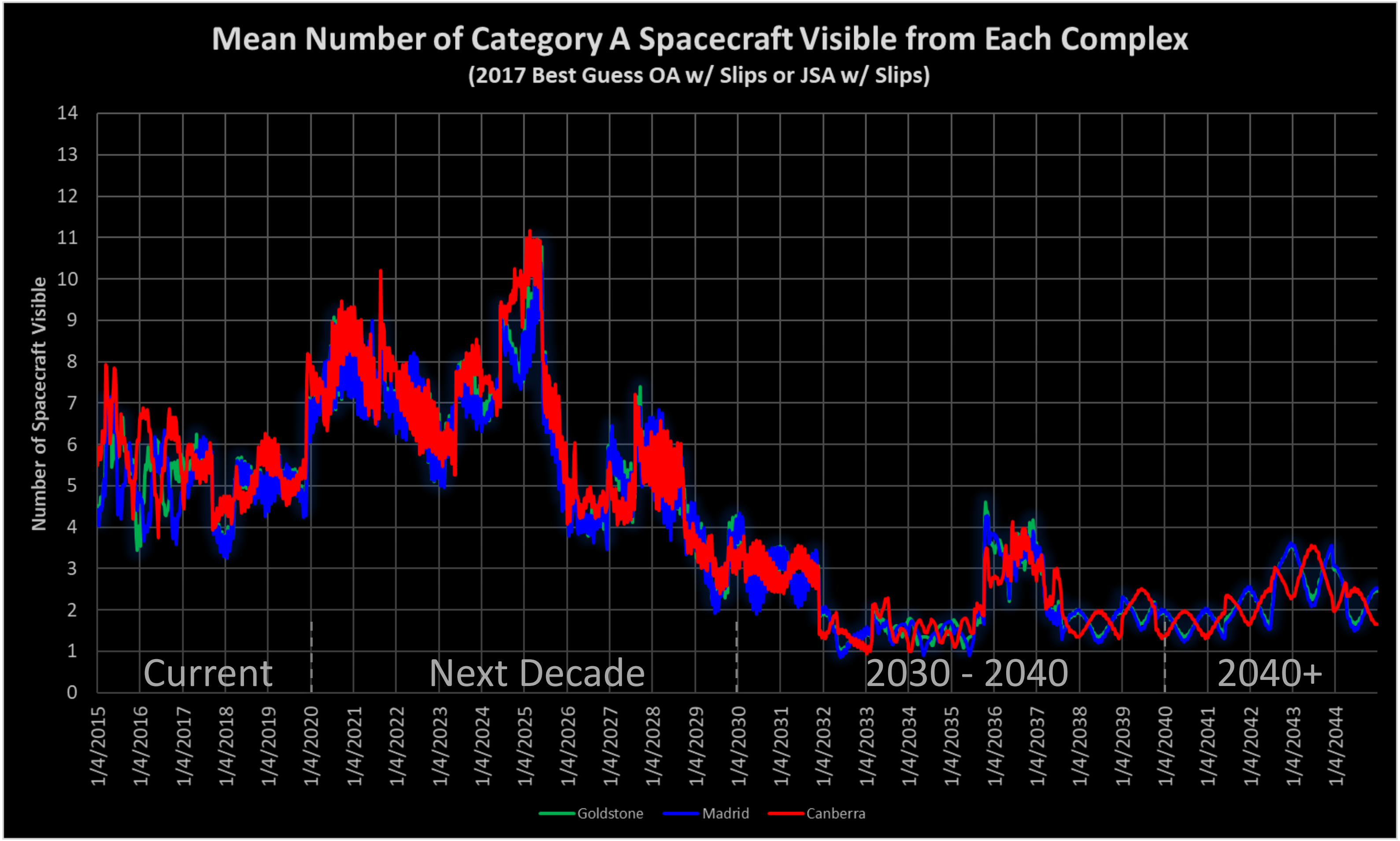
At selected times, the bulk of the missions may be visible from just one or two complexes at a time.

Antenna Asset Visibilities (5/8)



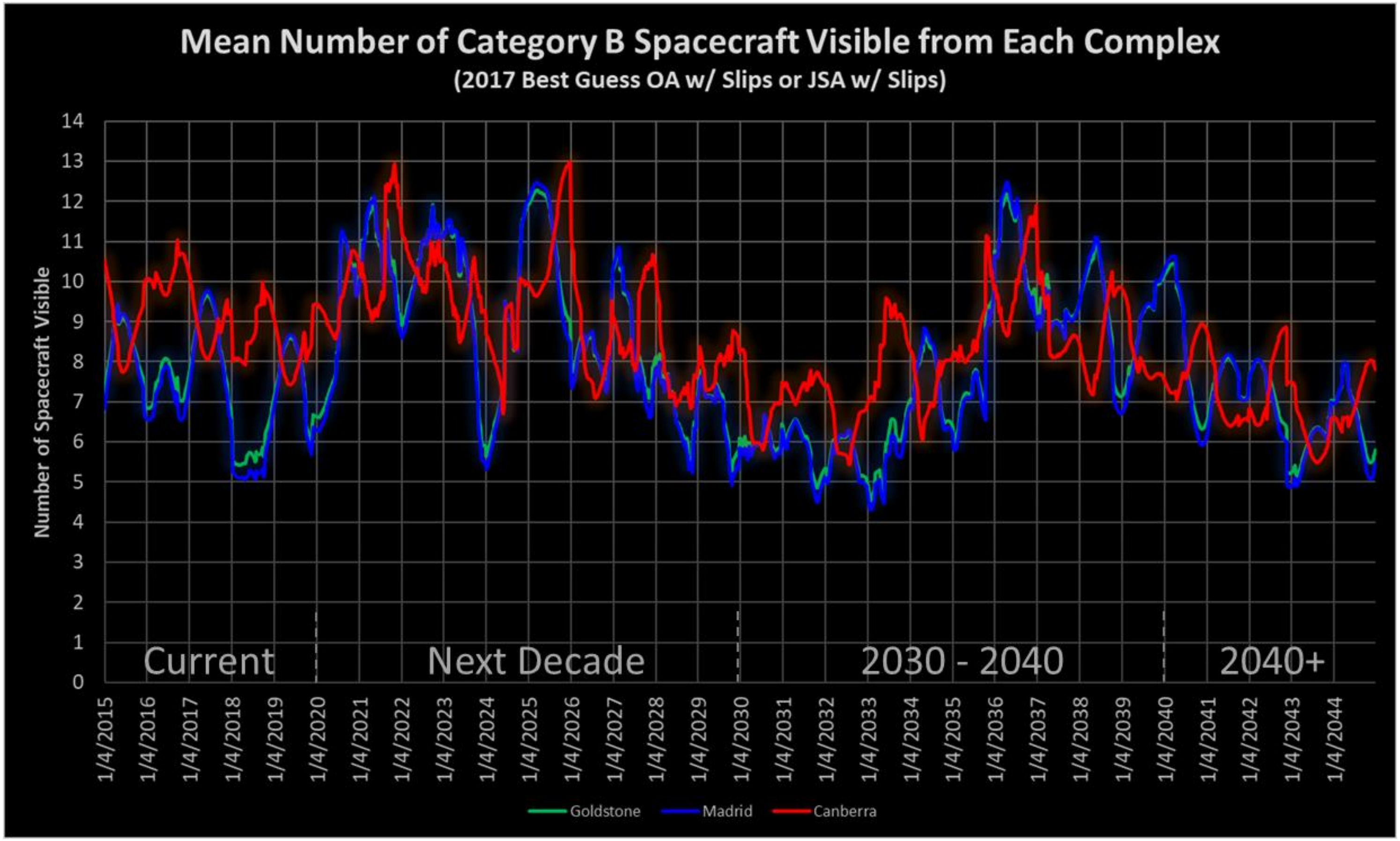
This plot combines declination and right ascension information. While Canberra tends to see the most spacecraft, Madrid and Goldstone also have visibility maximums on occasion, sometimes during a key confluence of critical spacecraft events. Having two Complexes most in view during a peak demand period can lead to less asset contention than when only one Complex is most in view.

Antenna Asset Visibilities (6/8)



With few exceptions, Canberra has the best view of the anticipated Category A spacecraft for roughly the next 10 years. Similar results are obtained when looking at the 2017 Optimistic and Pessimistic cases.

Antenna Asset Visibilities (7/8)



Category B spacecraft visibilities change more slowly with time, giving the curves a less "noisy" appearance. Peak spacecraft visibility tends to alternate between Canberra and the other two Complexes more than it did for the Category A spacecraft. Note, however, the dominance of Canberra during the beginnings of the human Mars exploration era (circa 2027 – 2034). Similar results occur for the 2017 Optimistic and Pessimistic cases.

Antenna Asset Visibilities (8/8)

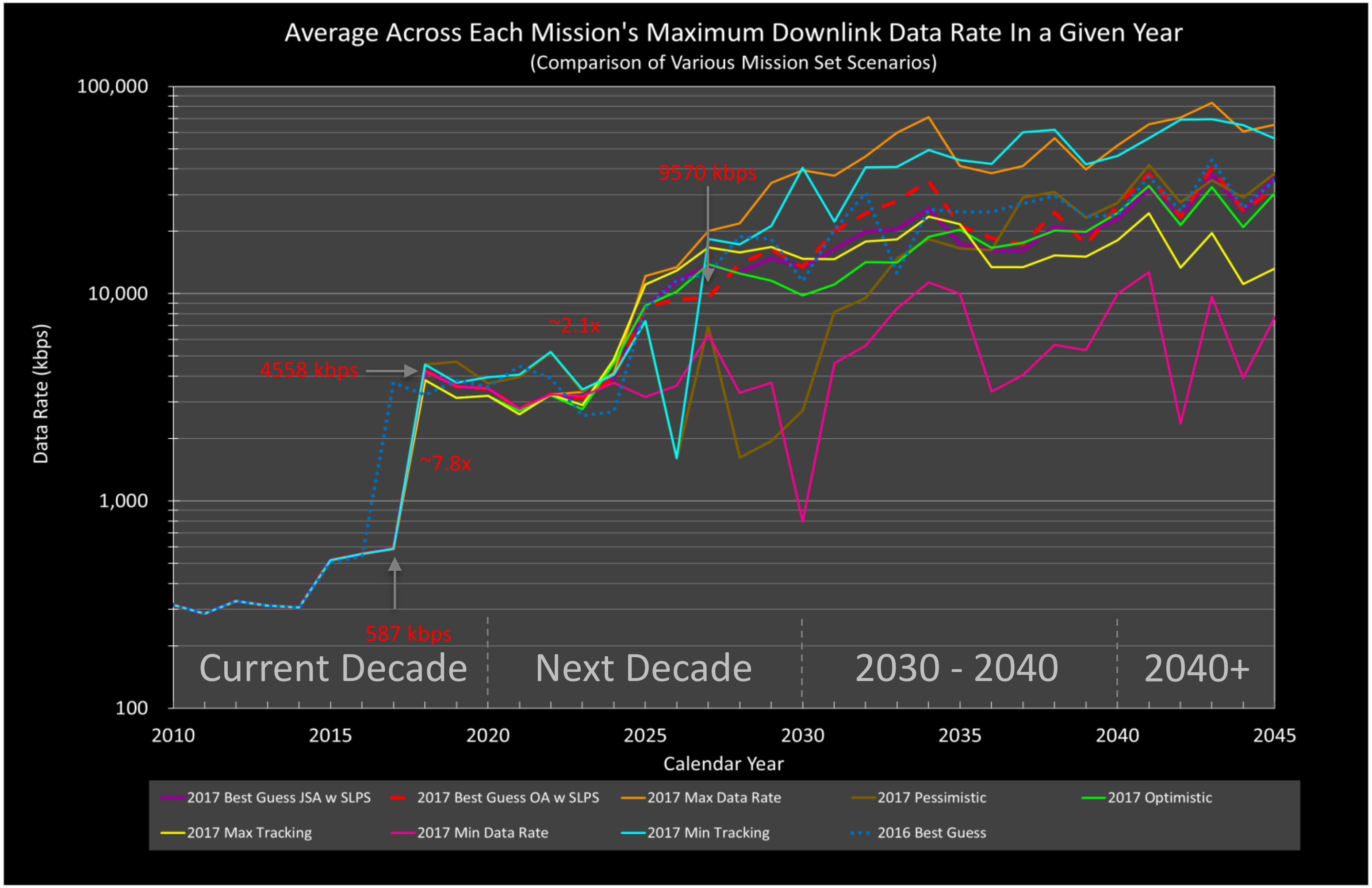
Takeaways:

- Canberra will have more customer spacecraft visibility, on average, than the other two complexes, from now through the early 2030's.
  - Over the next 10 years Category A spacecraft will likely have the greatest visibility from Canberra.
  - After that, up to about 2034, Category B spacecraft will likely have the greatest visibility from Canberra.
- One should not lose sight of the fact the above bullets are "on average." Large cyclical variations in visibility occur each year.
  - When peak visibilities favor Madrid and Goldstone together, a large confluence of spacecraft (e.g., 2021 Mars arrivals) are more readily accommodated than when the peak visibility favors Canberra alone.
- Pursuing greater asset representation in the Southern Hemisphere would likely benefit Category A customers (e.g., human lunar exploration) over the next 10 years and Category B customers (e.g., human Mars exploration) after that.

Topics

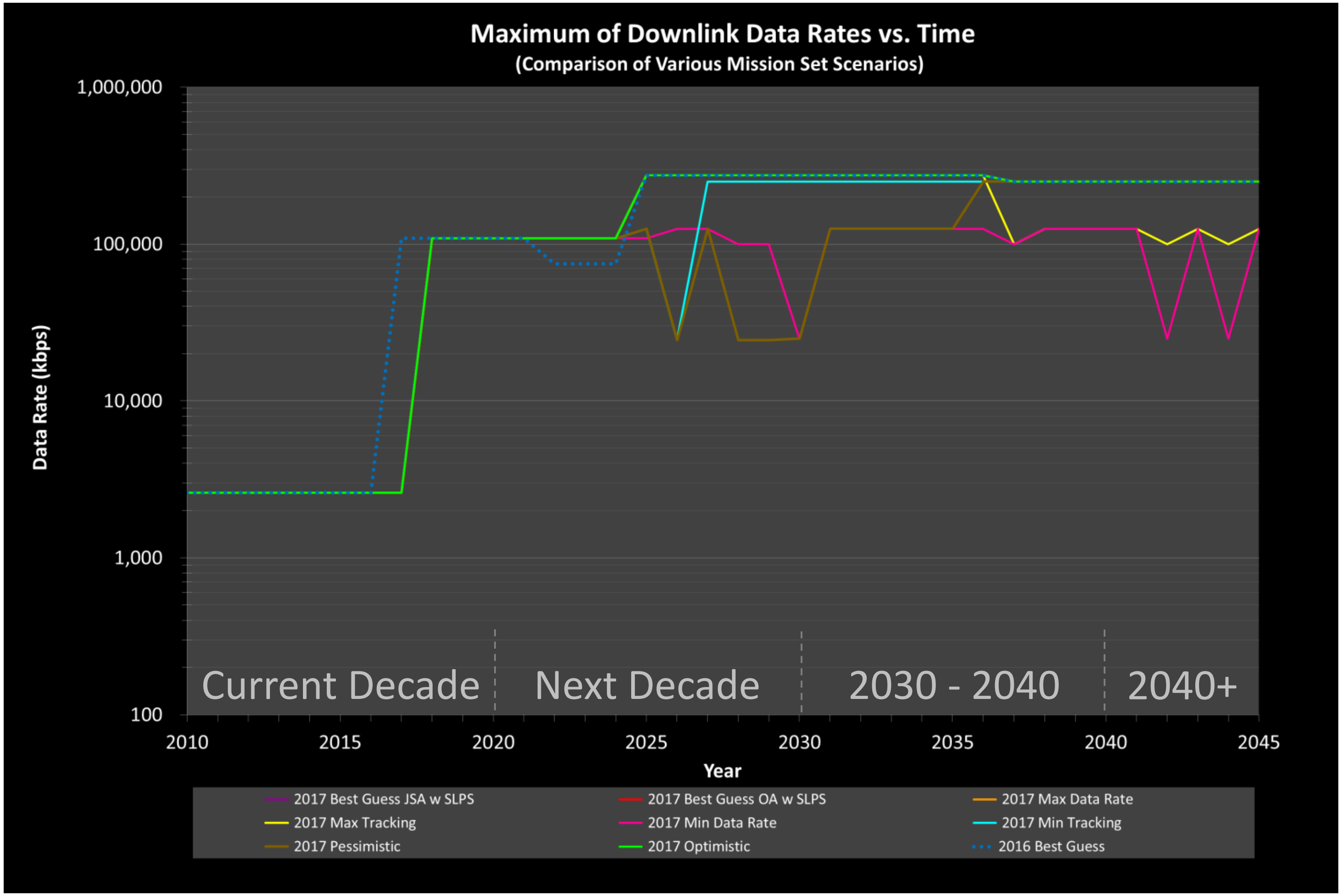
- **Factors Shaping the Anticipated Future Mission Set**: The Budget Situation, Uncertainty & Shifting Priorities for Human Exploration, and Increasing Globalization and Commercialization of Space Exploration Beyond GEO
- **Future Mission Set Analysis Methodology**: Definition of Mission Set Scenarios, Key Items Not Yet In Scenarios, Mission Set Analysis Process, Other Assumptions, and Interpretation of Results
- **Selected Mission Set Analysis Results**
  - **Capacity:** Anticipated Customer Base, Antenna-Hour Demand, and Antenna Asset Visibilities
  - **Capability**
    - **Downlink**: Average Rates, Maximum Rates, Rate Drivers, Data Volumes, Mission Set Range, End-to-End Downlink Difficulty, Maximum Individual G/T, and Aggregate G/T
    - **Uplink:** Average Rates, Maximum Rates, Rate Drivers, Maximum Individual EIRP, and Aggregate EIRP.
  - **Spectrum:** Downlink Count, Downlink Antenna Hours, Uplink Count, and Uplink Antenna Hours
  - **Loading Simulation Results:** “Requested” Downlink Hours Realized, “Requested” Downlink Data Volume Realized, “Requested” Uplink Hours Realized, and “Requested” Uplink Data Volume Realized
- **Implications**: The Next 10 Years and The Human Mars Exploration Era

Average Downlink Rates



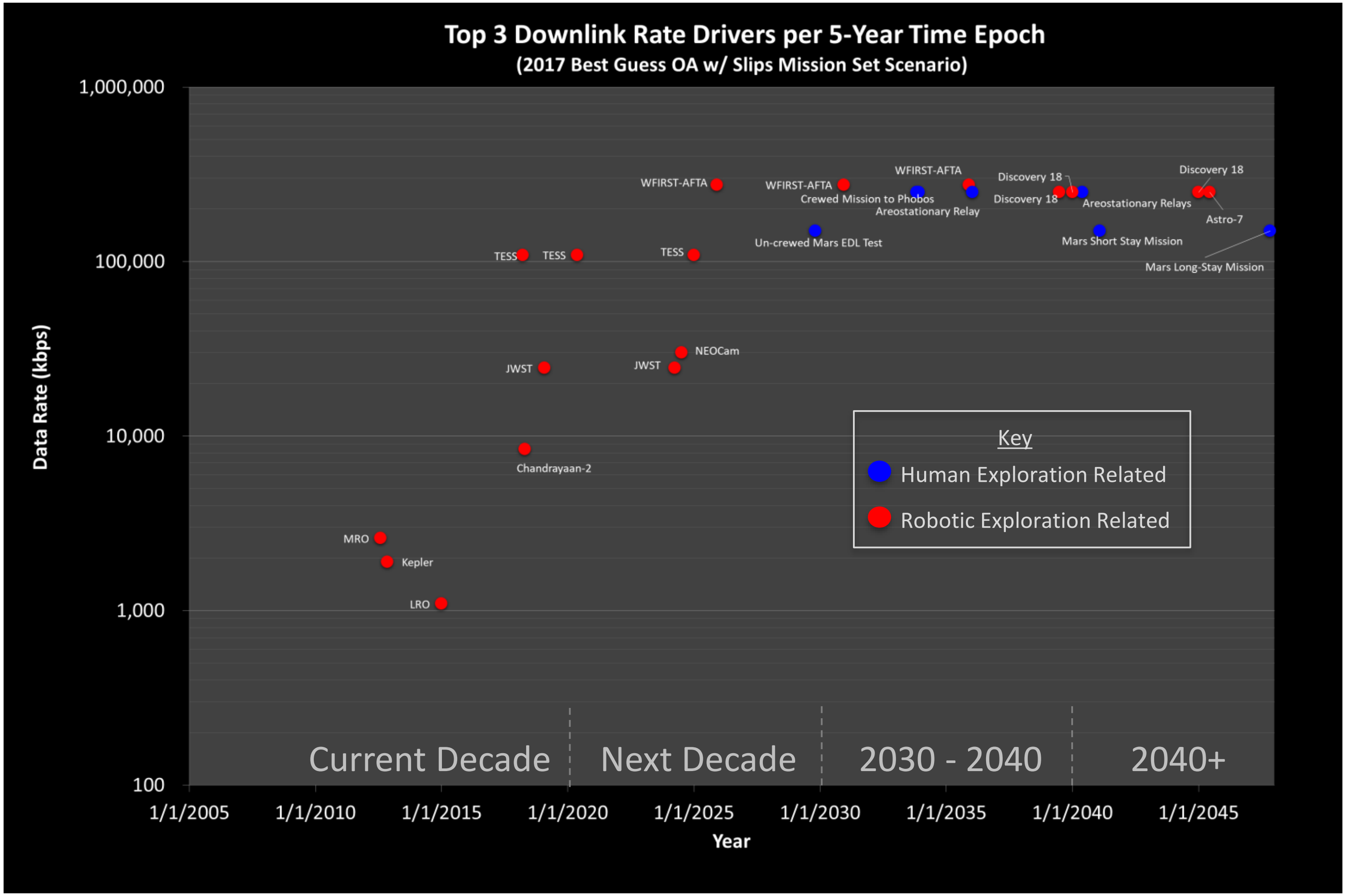
Most mission set scenarios entail average downlink-rate increases of roughly two orders of magnitude. Most of this increase, ~16x, is projected to occur over the next 10 years.

Maximum Downlink Rates



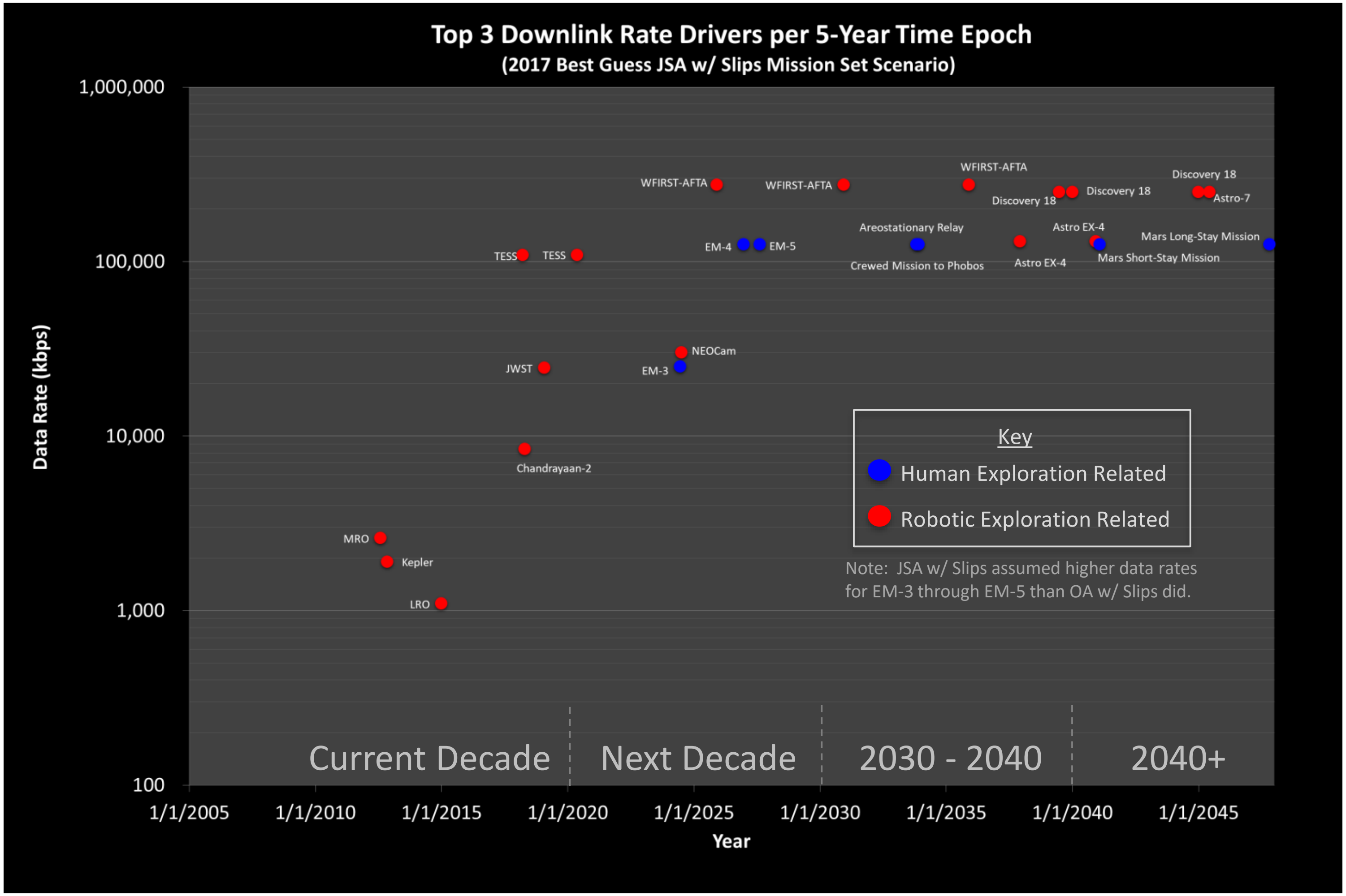
For most mission set scenarios, maximum downlink rates increase sharply over the next 10 years and then level off at between 100 and 300 Mbps. This data rate plateau may at least partially be due to allocated RF spectrum bandwidth limitations (e.g., 500 MHz at 32 GHz).

Downlink Data Rate Drivers (1/2)



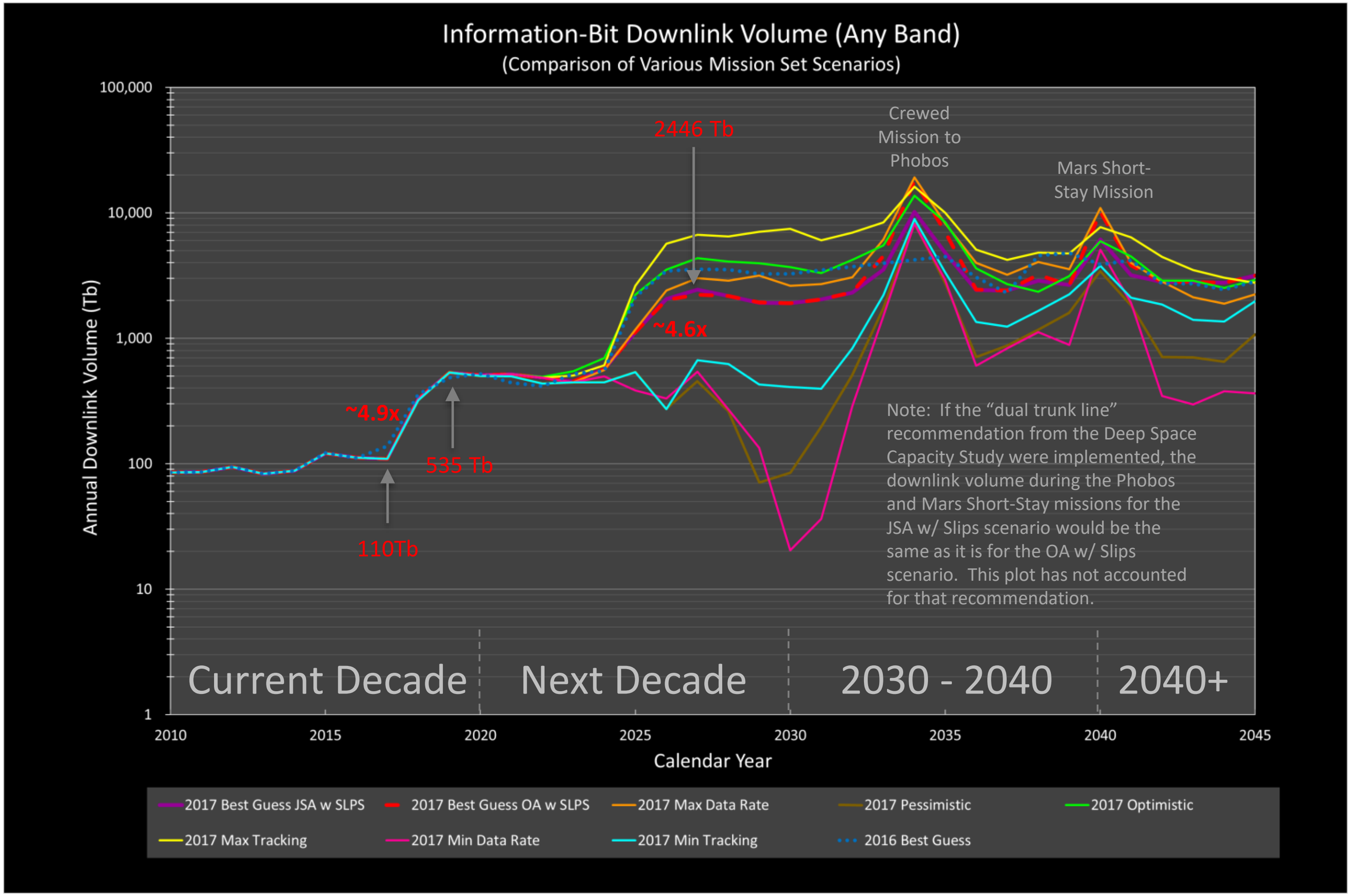
In the 2017 Best Guess OA w/ Slips scenario, observatory-class missions drive the steep increase in downlink rates over the next 10 years. After that, human Mars exploration missions become some of the key downlink rate drivers.

Downlink Data Rate Drivers (2/2)



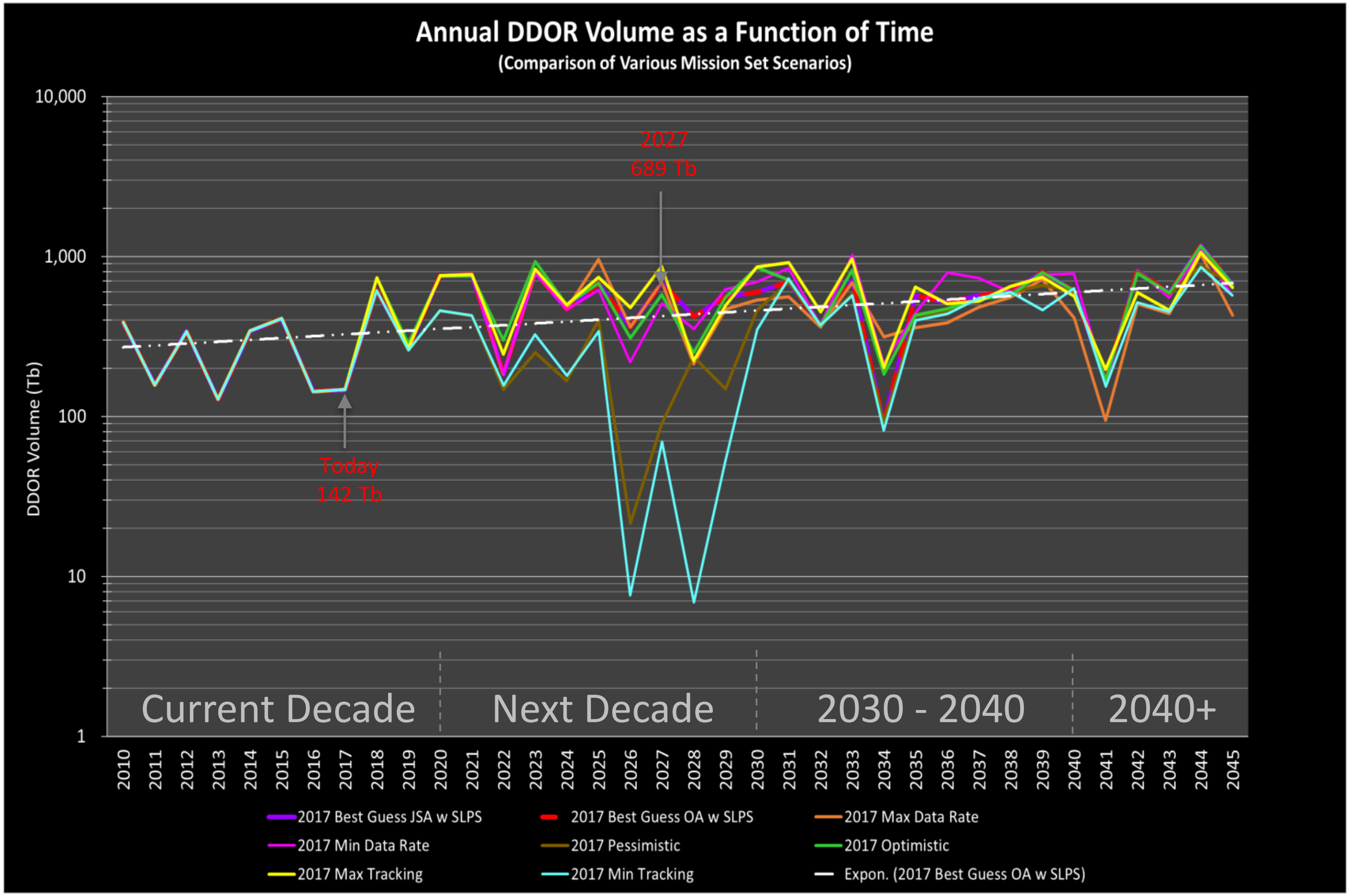
In the 2017 Best Guess JSA w/ Slips scenario, in the human Mars exploration era, rates are lower than in the "OA w/ Slips." The "Deep Space Capacity Study, Pass-2" recommendation of a "dual trunk link" approach to returning data enables a halving of the downlink rates to achieve a proportional decrease in required ground aperture.

Annual Downlink Data Volume



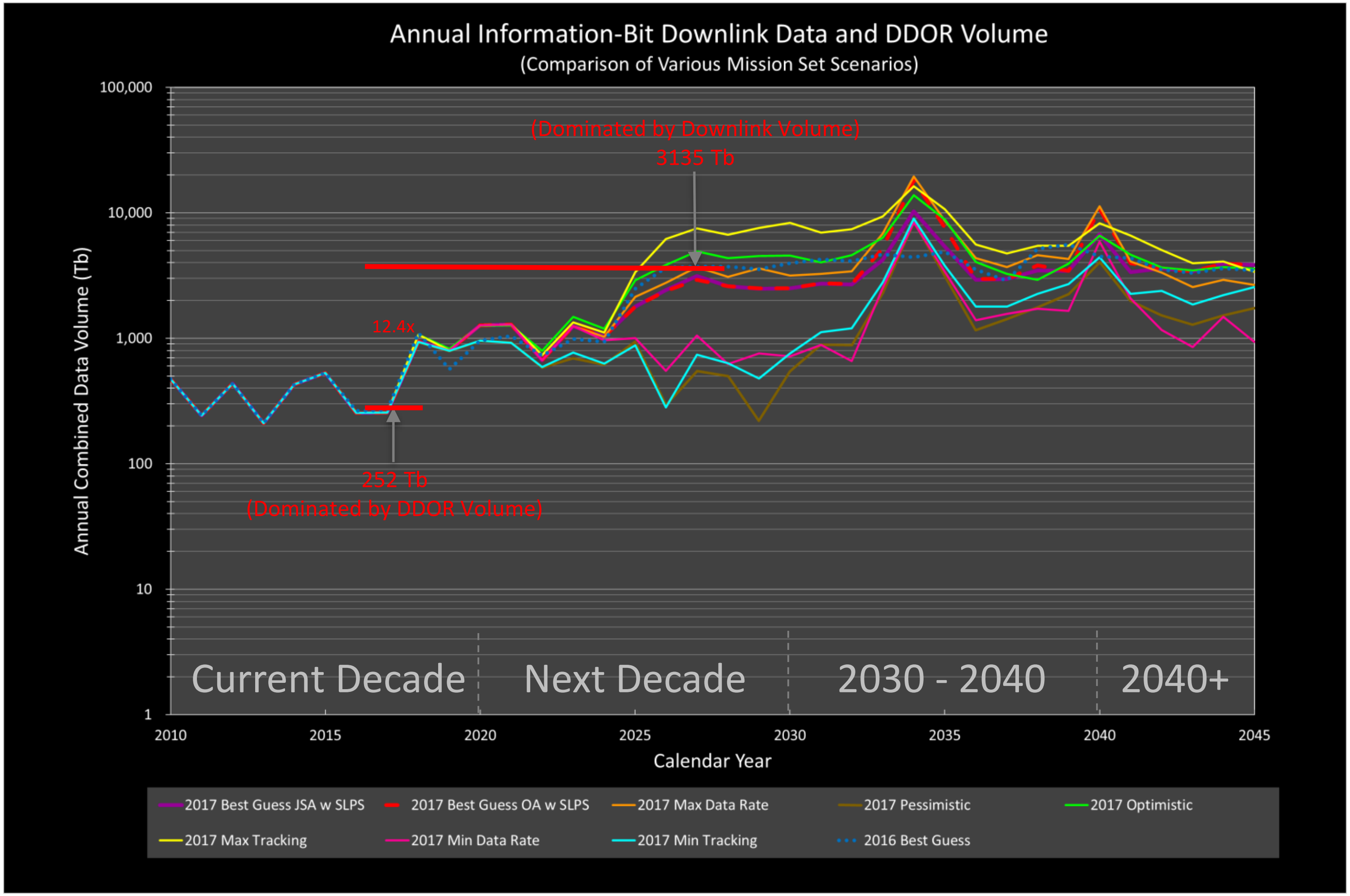
Over the next 10 years, downlink data volume (in terms of information bits) is projected to increase by a factor of ~22. This increase in downlink volume slightly outpaces the increase in average downlink rates projected over the same period, suggesting a concomitant net increase in required antenna time.

Annual Delta-DOR Data Volume



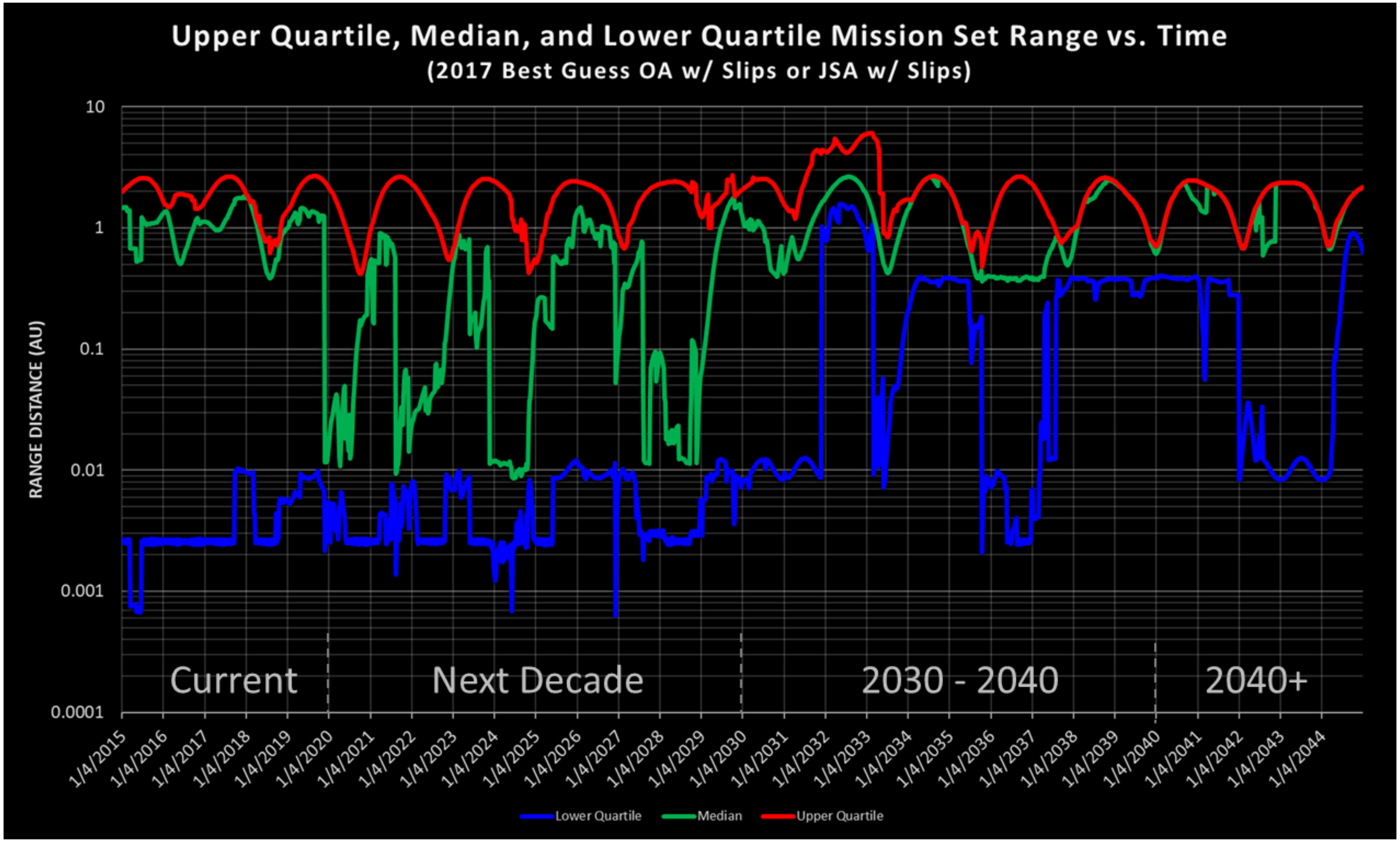
The general upward trend in DDOR data volume suggests a gradual increase in the number of DDOR users over time.

Combined DDOR and Downlink Volume



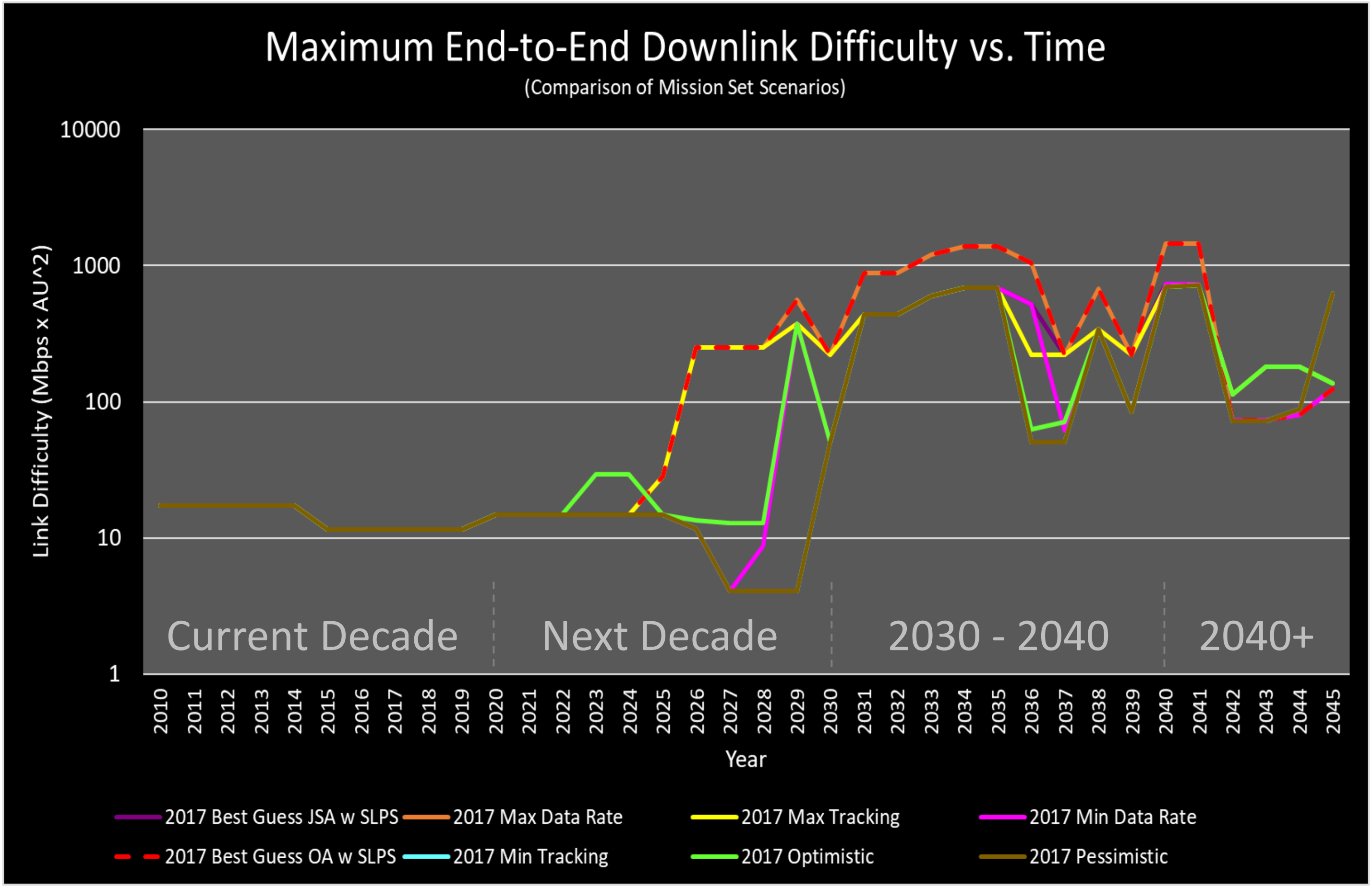
In the next 10 years, downlink volume is projected to exceed DDOR volume as the bandwidth driver for data transport from the Complexes to JPL Central. Note that the plot actually underestimates this volume because it is partially derived from information-bit rates and not the symbol rates.

Mission Set Range



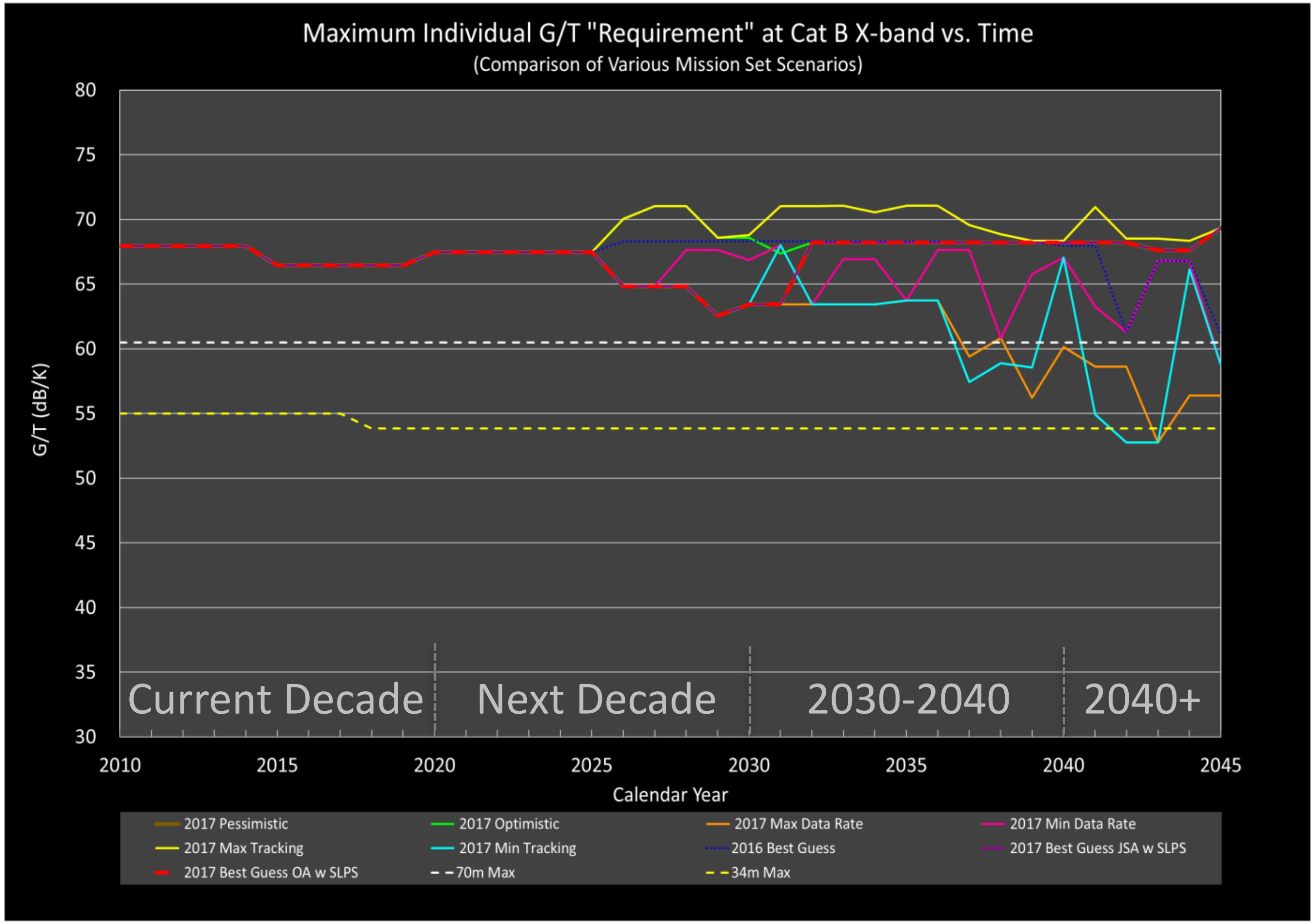
Over the next decade, ~25% of the spacecraft are projected to be at SEL range or less. ~50% are forecast to be between SEL range and Mars range. And, ~25% are projected to be at or beyond Mars range. In the human Mars exploration era, spacecraft at SEL ranges or less will likely comprise a much smaller percentage of the overall customer set. (This is less the case in the Optimistic scenario.)

End-to-End Downlink Difficulty



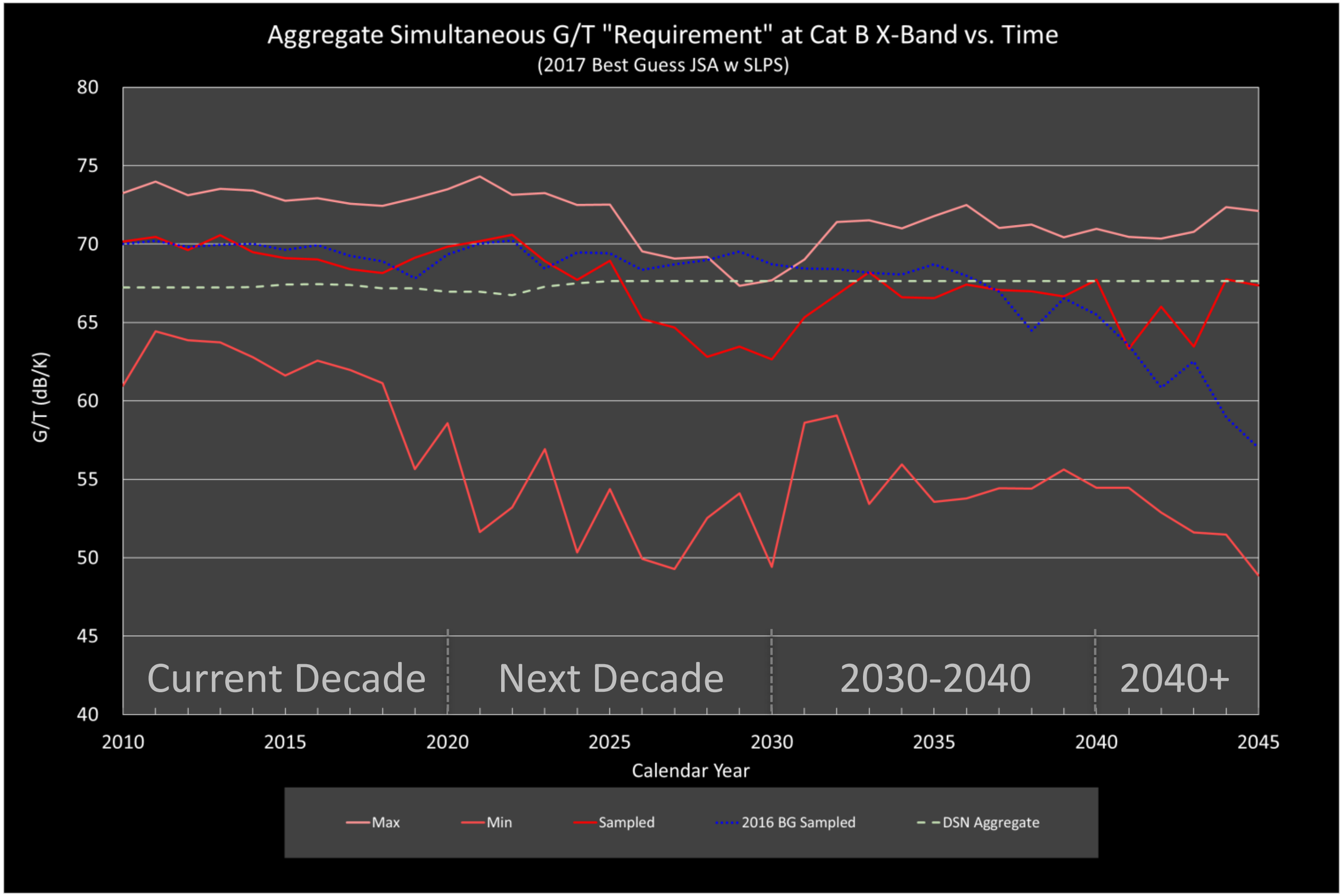
Human Mars exploration's combination of high data rates and relatively long link distances drives up end-to-end link difficulty between 1 and 2 orders of magnitude, depending upon mission set scenario.

Maximum Individual X-band G/T



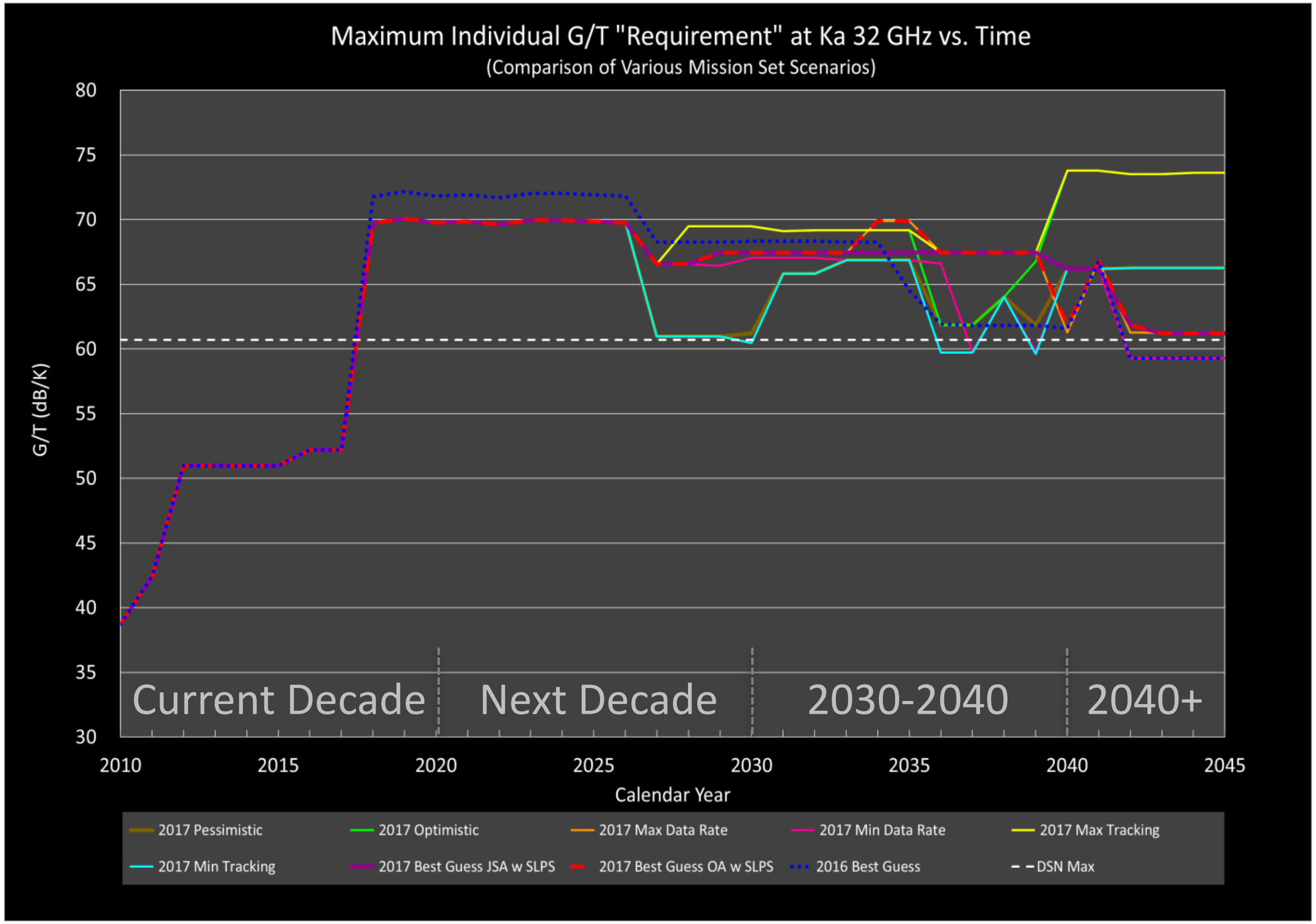
Currently, variable-range Cat. B X-band missions (e.g., Mars missions) can drive G/T requirements beyond 70m capability, but typically lower their data rates instead. Future human exploration missions may not be so flexible.

Aggregate X-band G/T



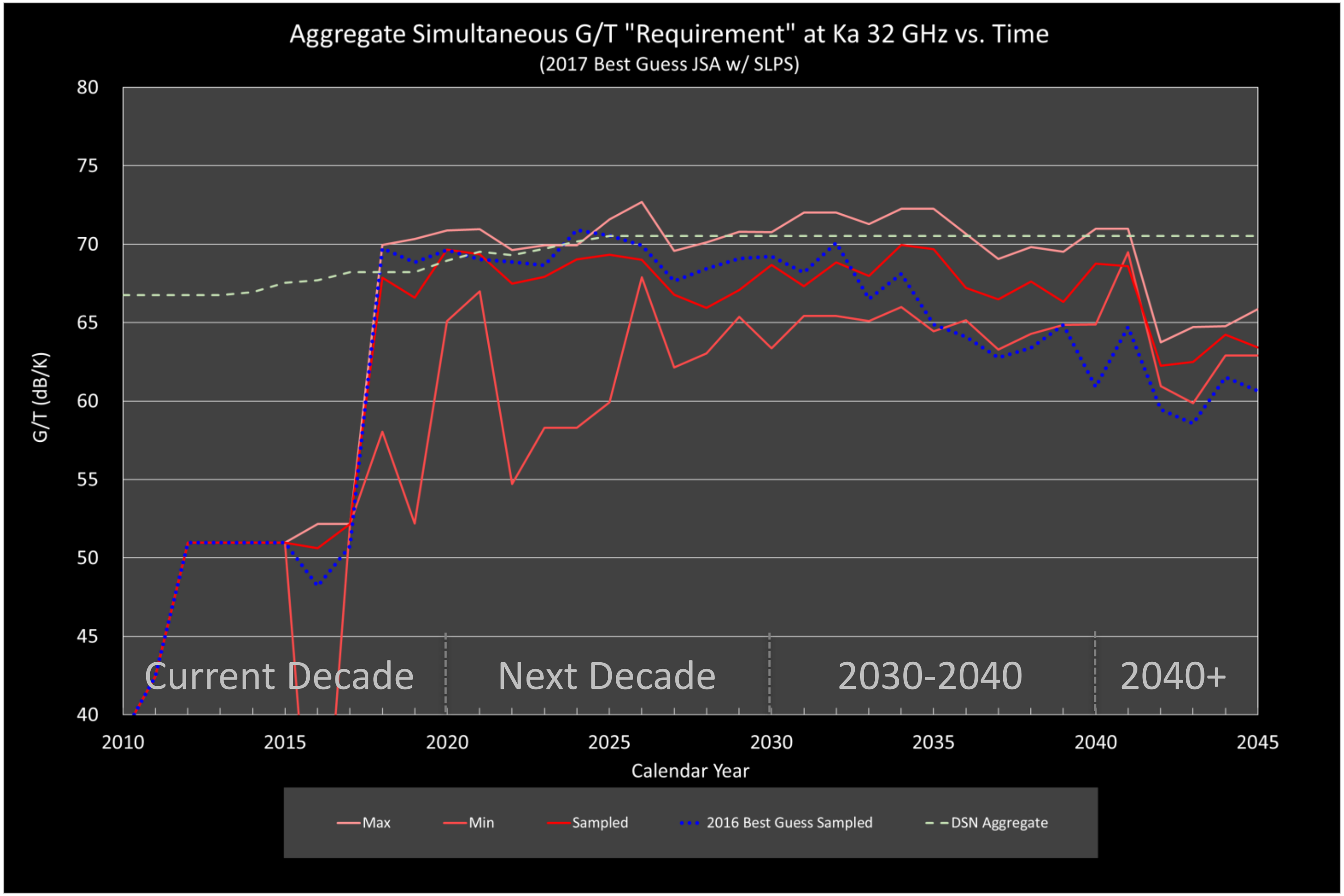
For the next 8 years, "average" aggregate X-band demand appears to exceed supply. After that, assuming completion of the DAEP and continued operation of the 70m antennas, aggregate X-band capability appears to be sufficient for "average" demand. Note that aggregate G/T demand says nothing about aggregate antenna-hour demand – the metrics are not interchangeable.

Maximum Individual Ka 32 GHz G/T



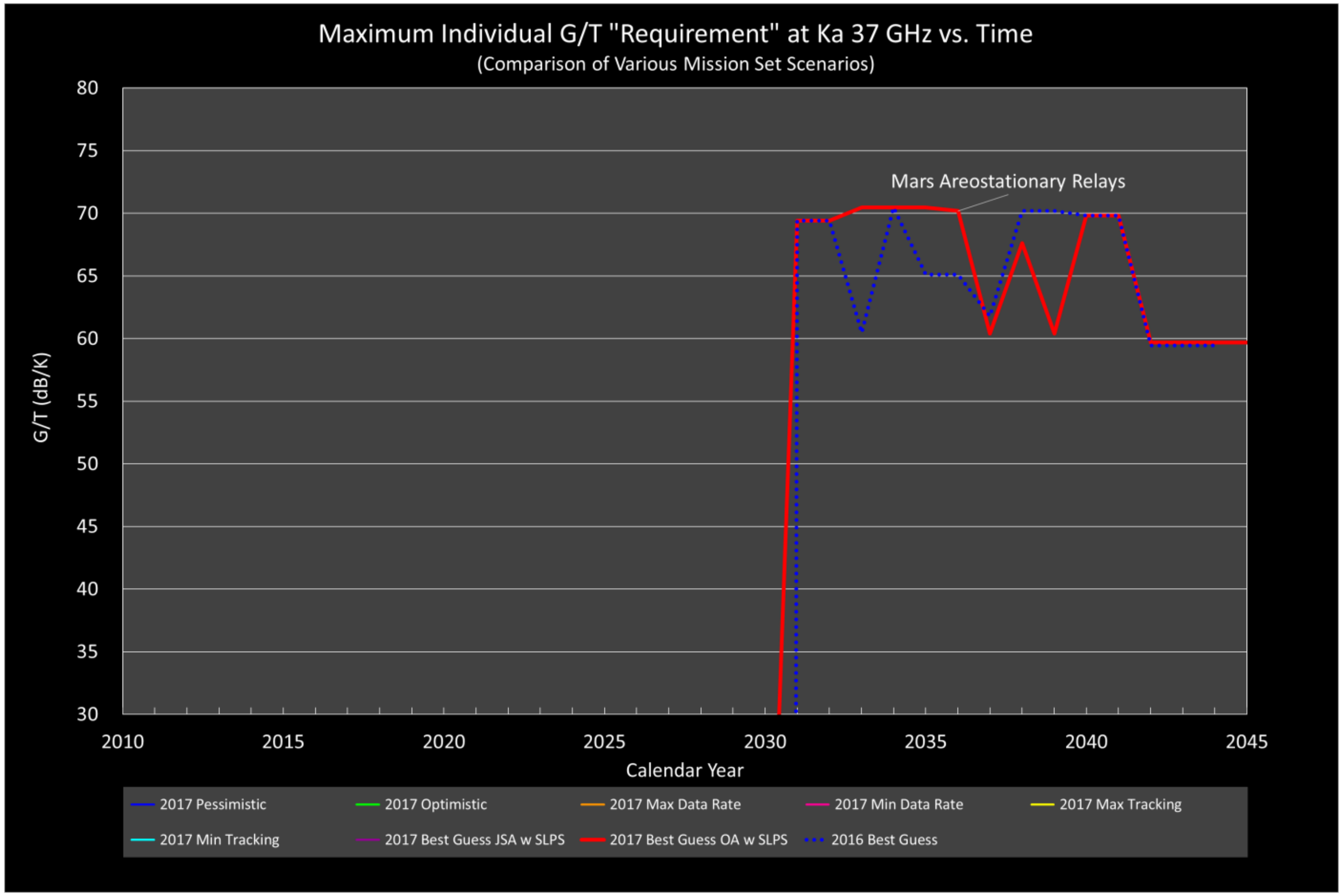
As with X-band, a number of variable-range Ka 32 GHz missions (e.g., Parker Solar Probe, Mars-24, etc.) can drive G/T requirements, if they don't drop their data rates with increasing range. Human Mars missions may not be as flexible.

Aggregate Ka 32 GHz G/T



Assuming a “dual trunk link” approach to human Mars exploration and completion of DAEP, planned 32 GHz capability appears capable of meeting “average” aggregate demand after 2020-2021. Again, note that aggregate G/T capability is not a substitute measure for antenna-hour capacity.

Maximum Individual Ka 37 GHz G/T



The "Deep Space Capacity Study, Pass-2" recommendations call for moving the Mars Areostationary Relay capability from 40/37 GHz to 34/32 GHz and adopting a dual-trunk line approach to halving data rates. In the 2017 Best Guess OA w/ Slips scenario where these recommendations do not apply, human Mars exploration uplink rates drive a large 37 GHz G/T "requirement."

Downlink Capability Demand (1/2)

Takeaways:

- Over the next 10 years, observatory-class missions my drive up average downlink rates by a factor of ~16.
- In the 2030s and '40s, projected maximum downlink rates ultimately level out at between 100 and 300 Mbps, depending upon the mission set scenario. This may at least partially be the result of allocated RF spectrum bandwidth limitations constraining the communications rates assumed in mission concept designs.
- Over the next 10 years, projected increases in downlink data volume, combined with DDOR data, translate into more than an order of magnitude increase in ground data volume. Two factors drive this:
  - An increase in average downlink rates
  - An increase in the number of DSN users, particularly those relying on DDOR
- Until the 2030's, ~75% of the mission set will be located roughly within 1 AU from the Earth, leading to a flat trend in end-to-end link difficulty until human Mars exploration begins.

Downlink Capability Demand (2/2)

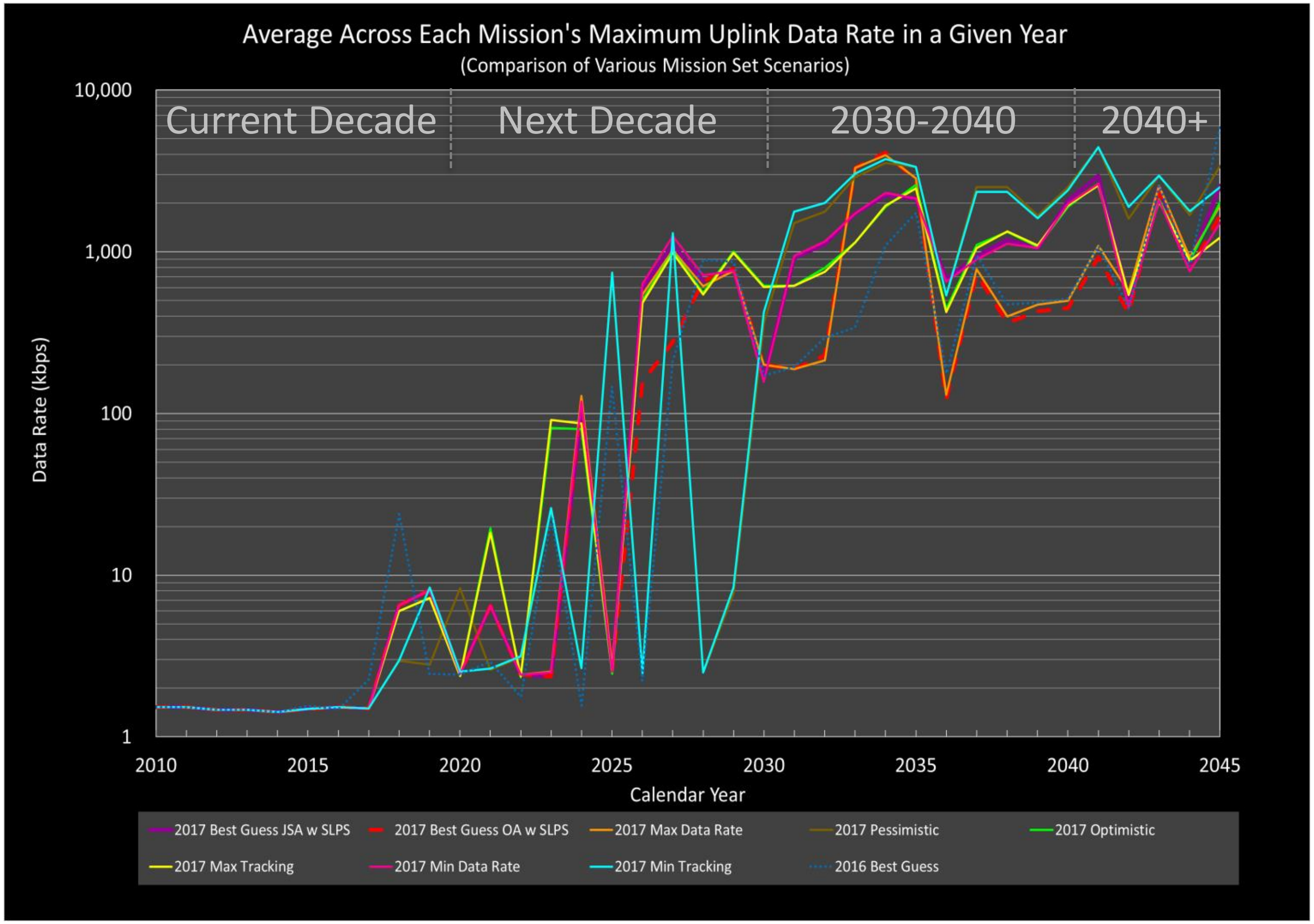
Takeaways: (Continued)

- Despite the flat trend in end-to-end link difficulty, “average” demand in terms of the projected aggregate X-band G/T requirement exceeds supply through ~2027.
  - This aggregate G/T capability is not a substitute measure for antenna-hours capacity – though a shortfall in the former can lead to a shortfall in the latter.
- After 2021, aggregate Ka32 GHz G/T capability appears sufficient to meet “average” demand, assuming DAEP completion and a “dual trunk line” approach to downlink from human Mars exploration.
  - Again, however, the aggregate G/T capability is not a substitute measure for antenna-hours capacity – a shortfall in the latter was identified in earlier slides, driven by the number of hours over which all of the missions’ G/T’s are actually needed.

Topics

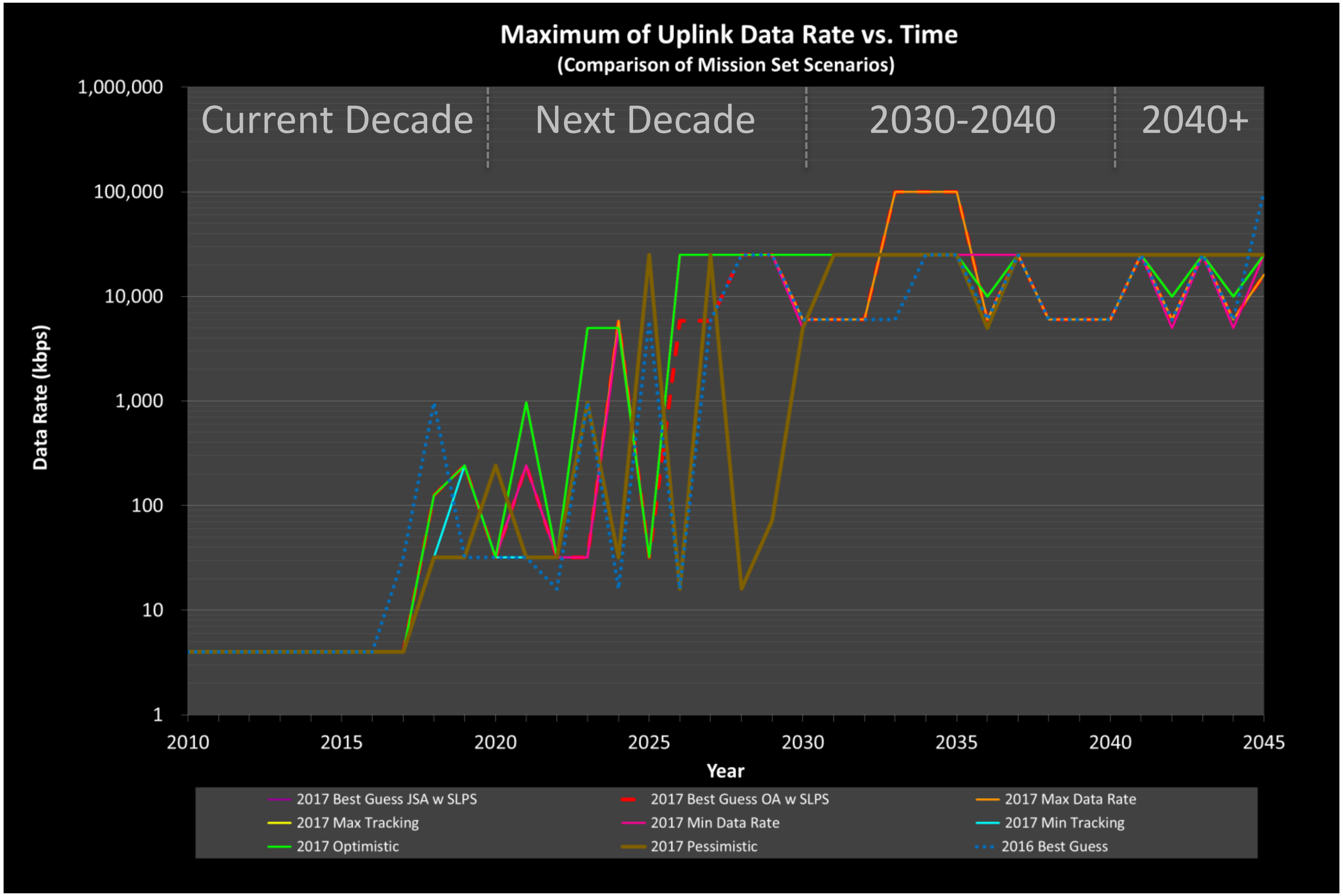
- **Factors Shaping the Anticipated Future Mission Set**: The Budget Situation, Uncertainty & Shifting Priorities for Human Exploration, and Increasing Globalization and Commercialization of Space Exploration Beyond GEO
- **Future Mission Set Analysis Methodology**: Definition of Mission Set Scenarios, Key Items Not Yet In Scenarios, Mission Set Analysis Process, Other Assumptions, and Interpretation of Results
- **Selected Mission Set Analysis Results**
  - **Capacity:** Anticipated Customer Base, Antenna-Hour Demand, and Antenna Asset Visibilities
  - **Capability**
    - **Downlink**: Average Rates, Maximum Rates, Rate Drivers, Data Volumes, Mission Set Range, End-to-End Downlink Difficulty, Maximum Individual G/T, and Aggregate G/T
    - **Uplink:** Average Rates, Maximum Rates, Rate Drivers, Maximum Individual EIRP, and Aggregate EIRP.
  - **Spectrum:** Downlink Count, Downlink Antenna Hours, Uplink Count, and Uplink Antenna Hours
  - **Loading Simulation Results:** "Requested" Downlink Hours Realized, "Requested" Downlink Data Volume Realized, "Requested" Uplink Hours Realized, and "Requested" Uplink Data Volume Realized
- **Implications**: The Next 10 Years and The Human Mars Exploration Era

Average Uplink Rates



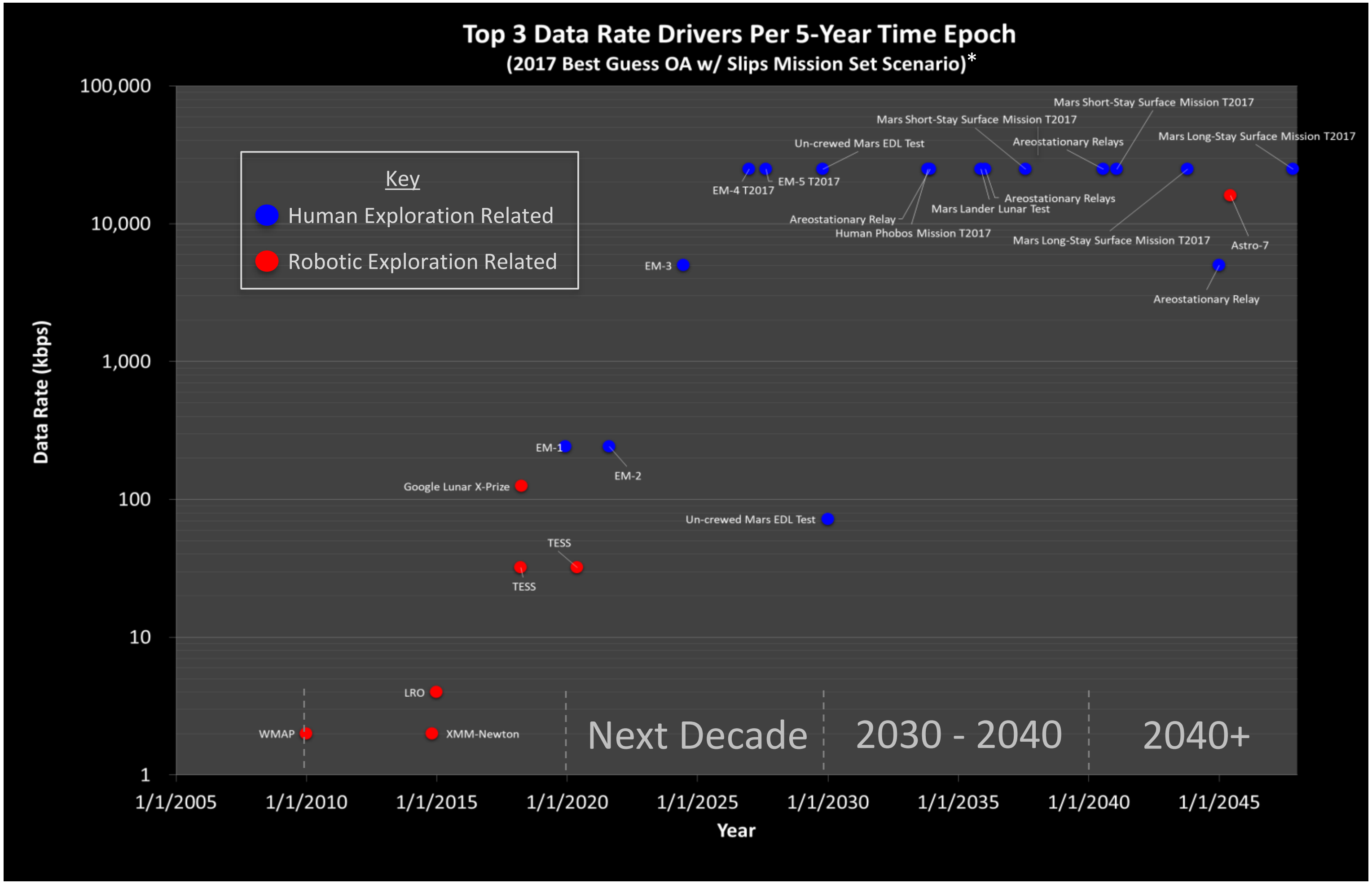
Depending upon the mission set scenario, average uplink rates increase almost 3 orders of magnitude within the next 10 years.

Maximum Uplink Rates



In some scenarios, maximum uplink rates increase more than 4 orders of magnitude over the next 20 years, with most of the increase occurring in the next 10. Rates level off at 25-100 Mbps, due primarily to the lack of any identified higher rate requirements.

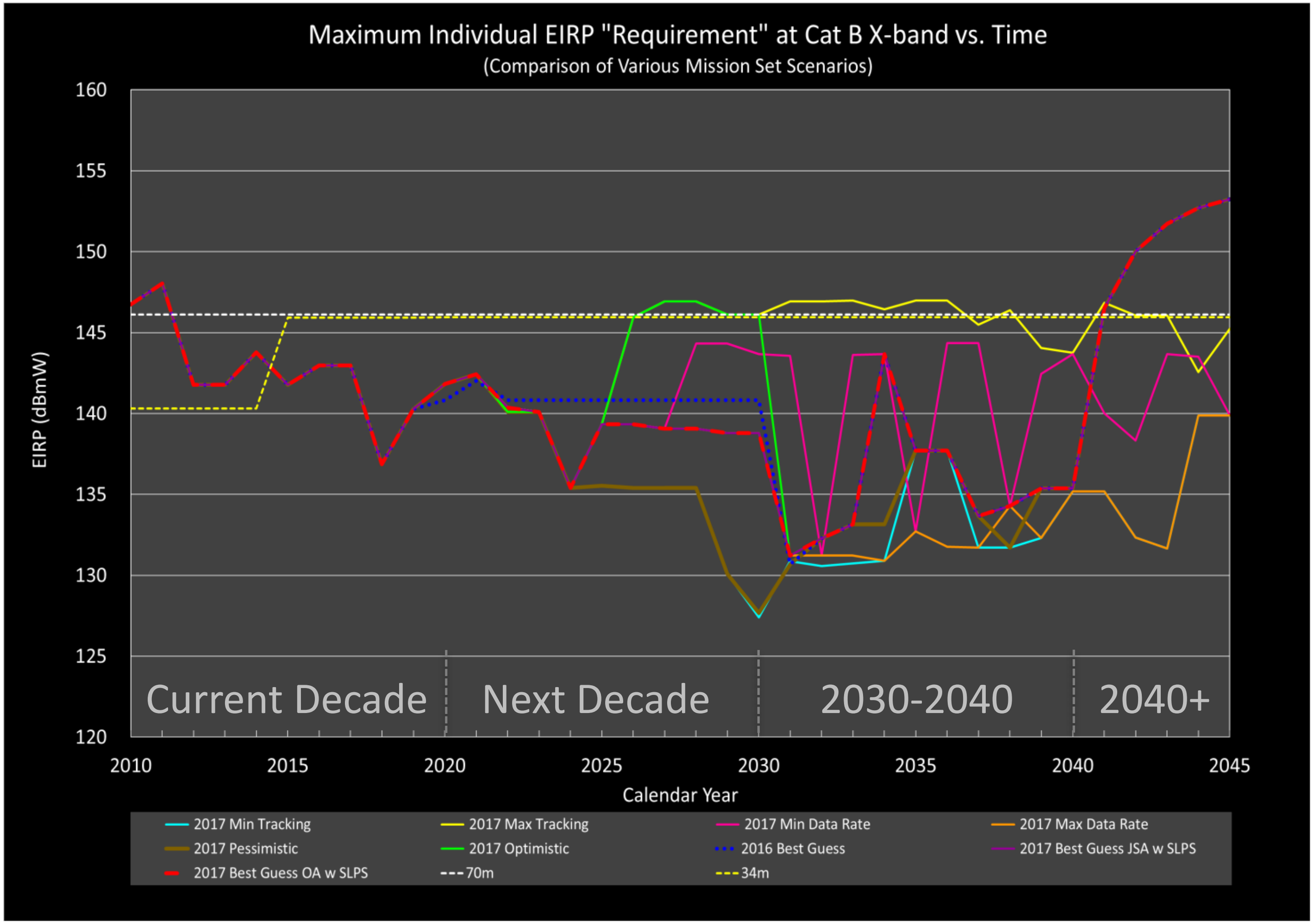
Uplink Data Rate Drivers



Robotic missions tend to dominate uplink rates this decade. In the decades that follow, human exploration missions will likely drive the uplink rates.

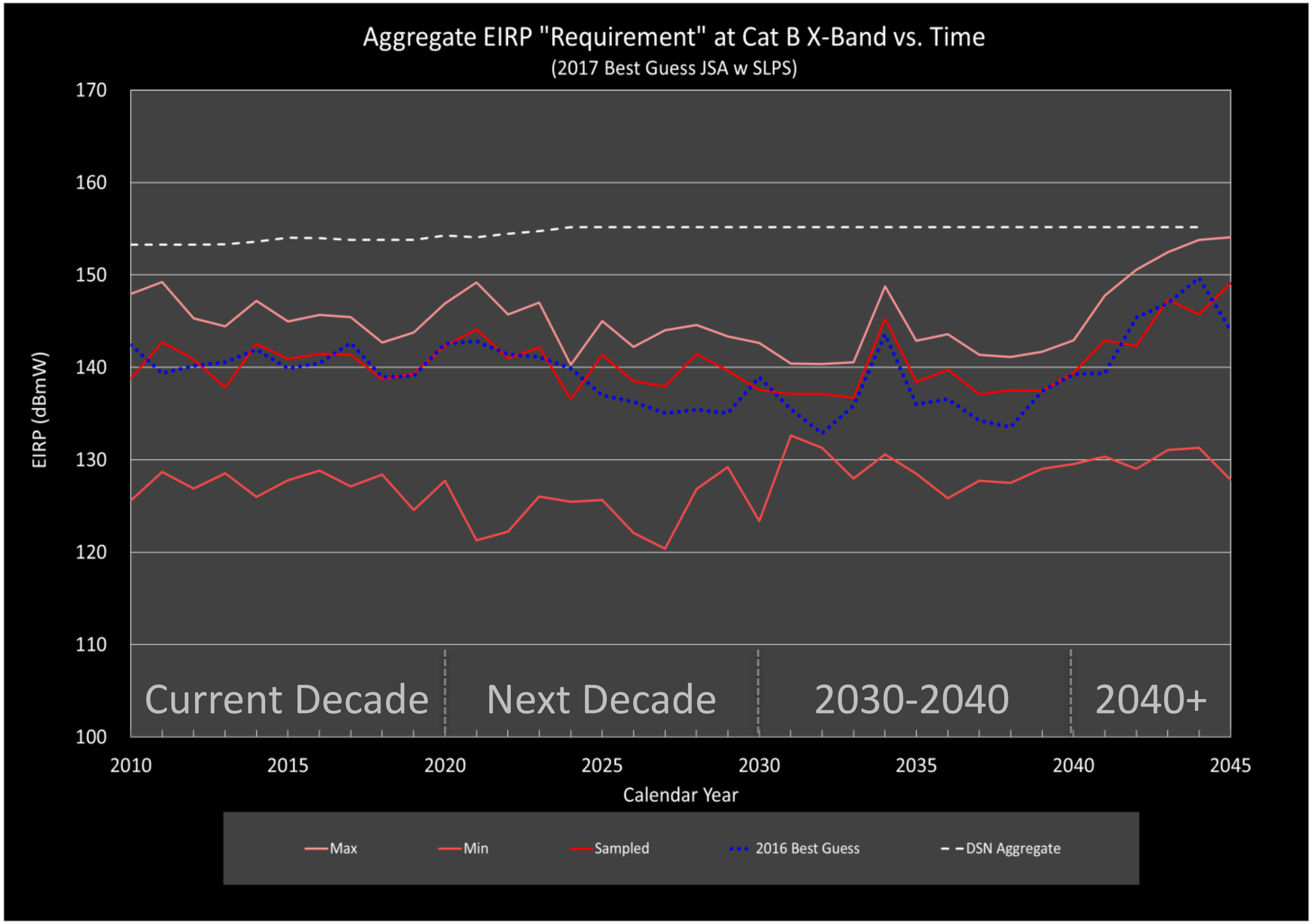
*For uplink, 2017 Best Guess JSA w/ Slips has an identical set of drivers.

Maximum Individual X-band EIRP



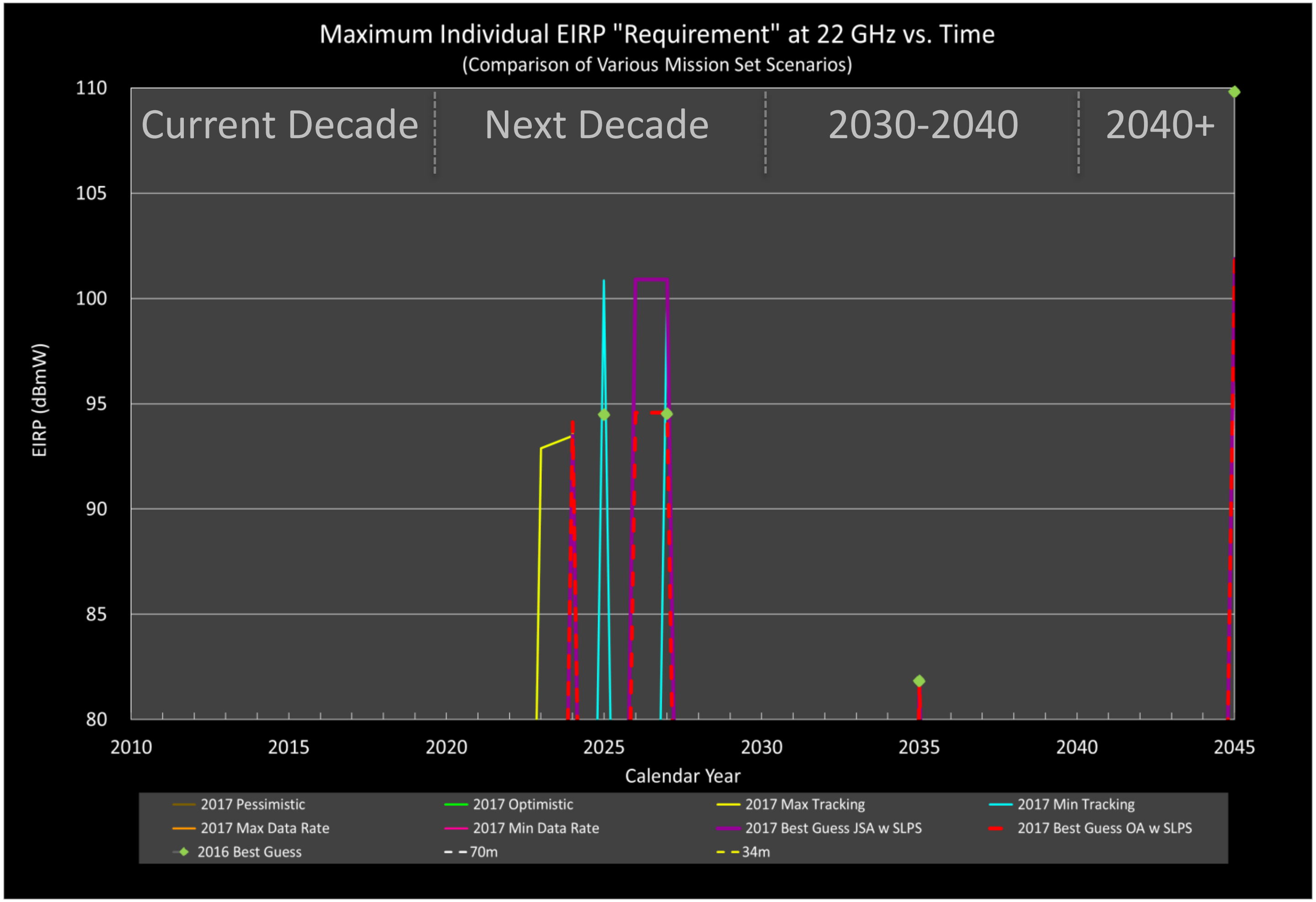
In all but the most extreme scenarios, the 70m-20kW and 34m-80 kW capabilities will likely satisfy the non-emergency maximum individual X-band EIRP "requirement" through about 2040.

Aggregate X-band EIRP



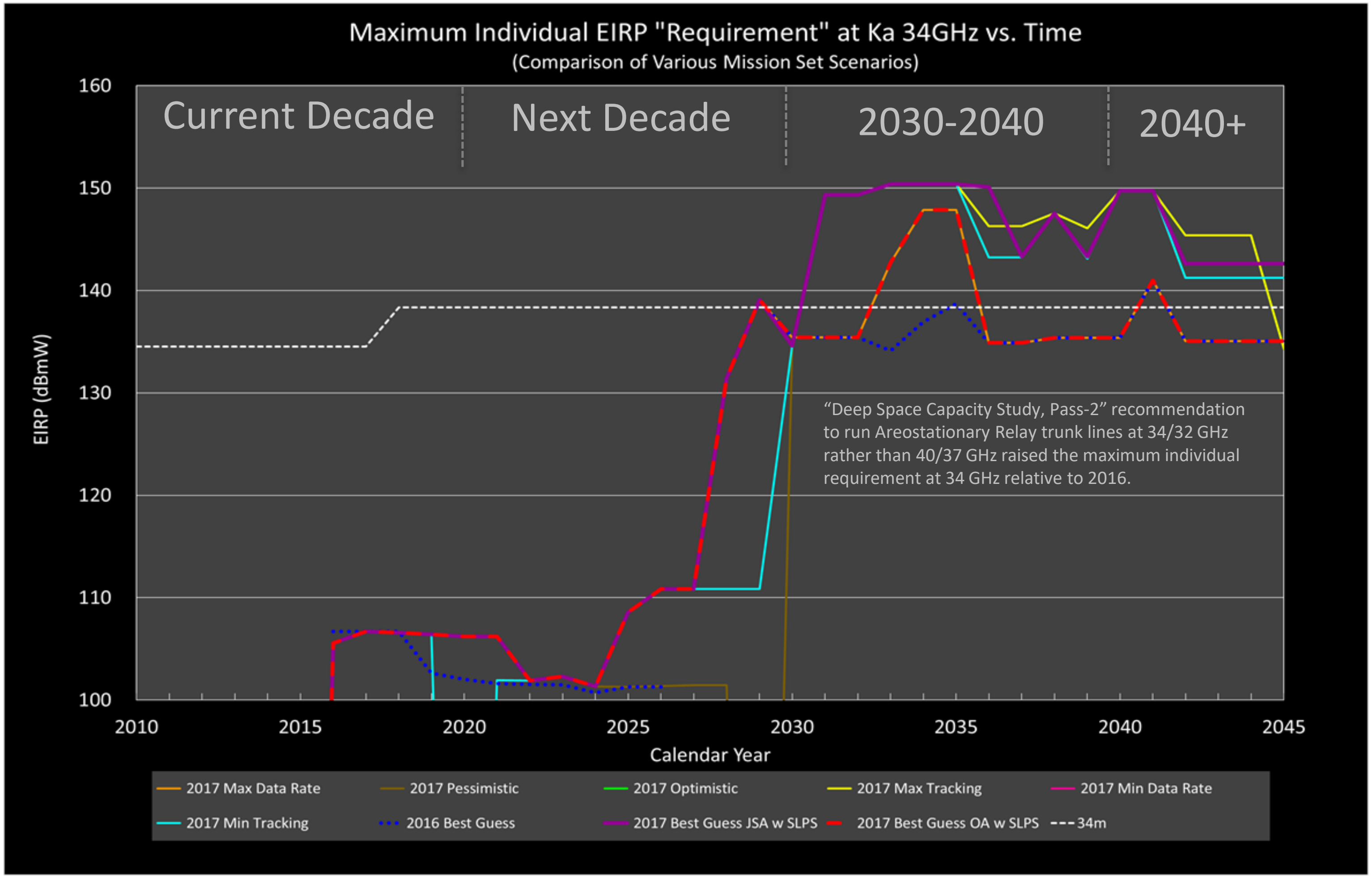
Assuming the DAEP buildout with selected 80 kW antennas and continued availability of the 70m antennas, aggregate Cat. B X-band EIRP looks adequate for the foreseeable future.

Maximum Individual Ka 22 GHz EIRP



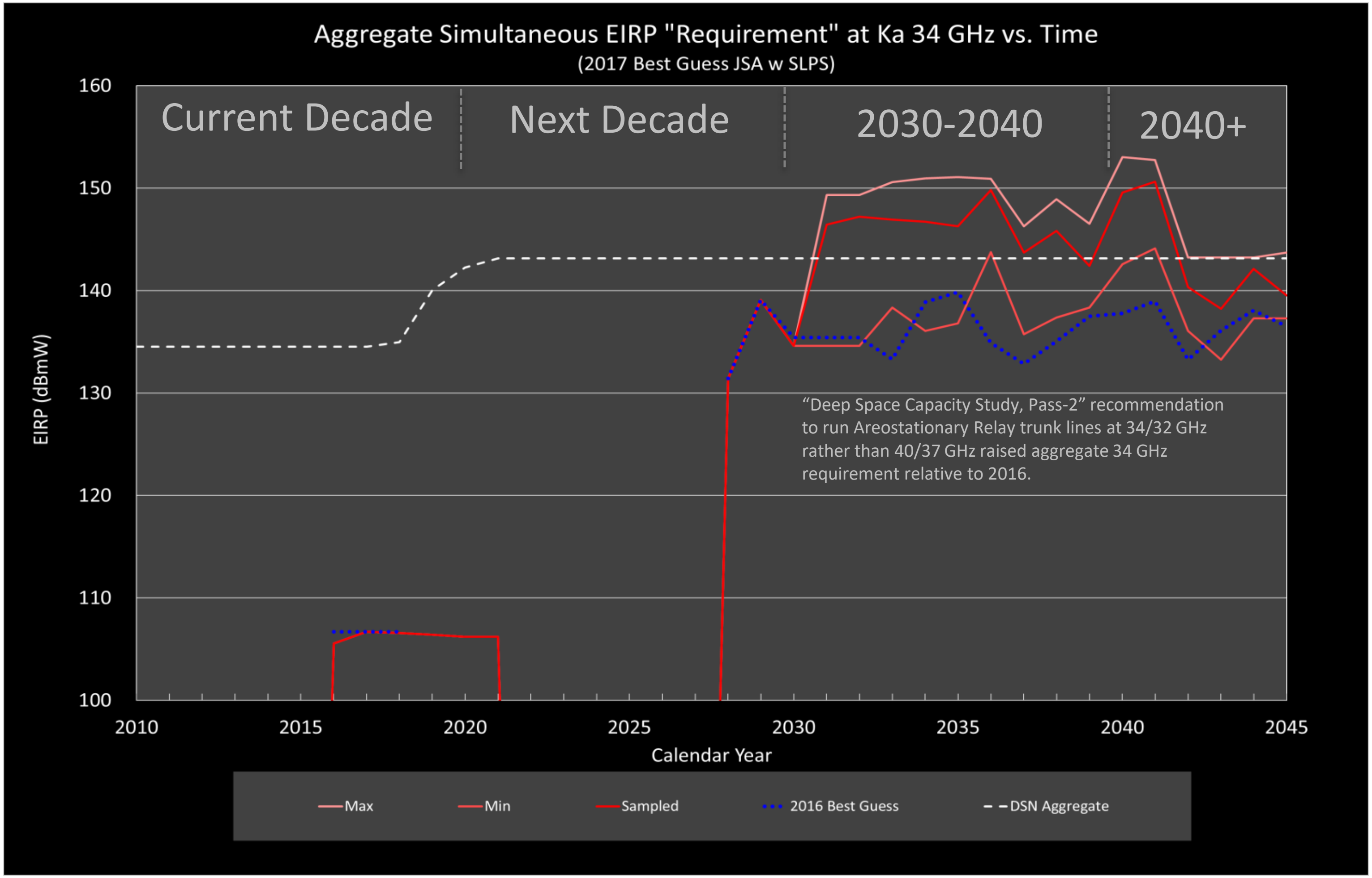
With NASA plans for the next decade now focused on a cislunar Deep Space Gateway, 22 GHz may be needed even more than what is indicated by these curves (which predate announcement of the concept). An EIRP capability of ~102 dBmW would appear to encompass the foreseeable individual mission need.

Maximum Individual Ka 34 GHz EIRP



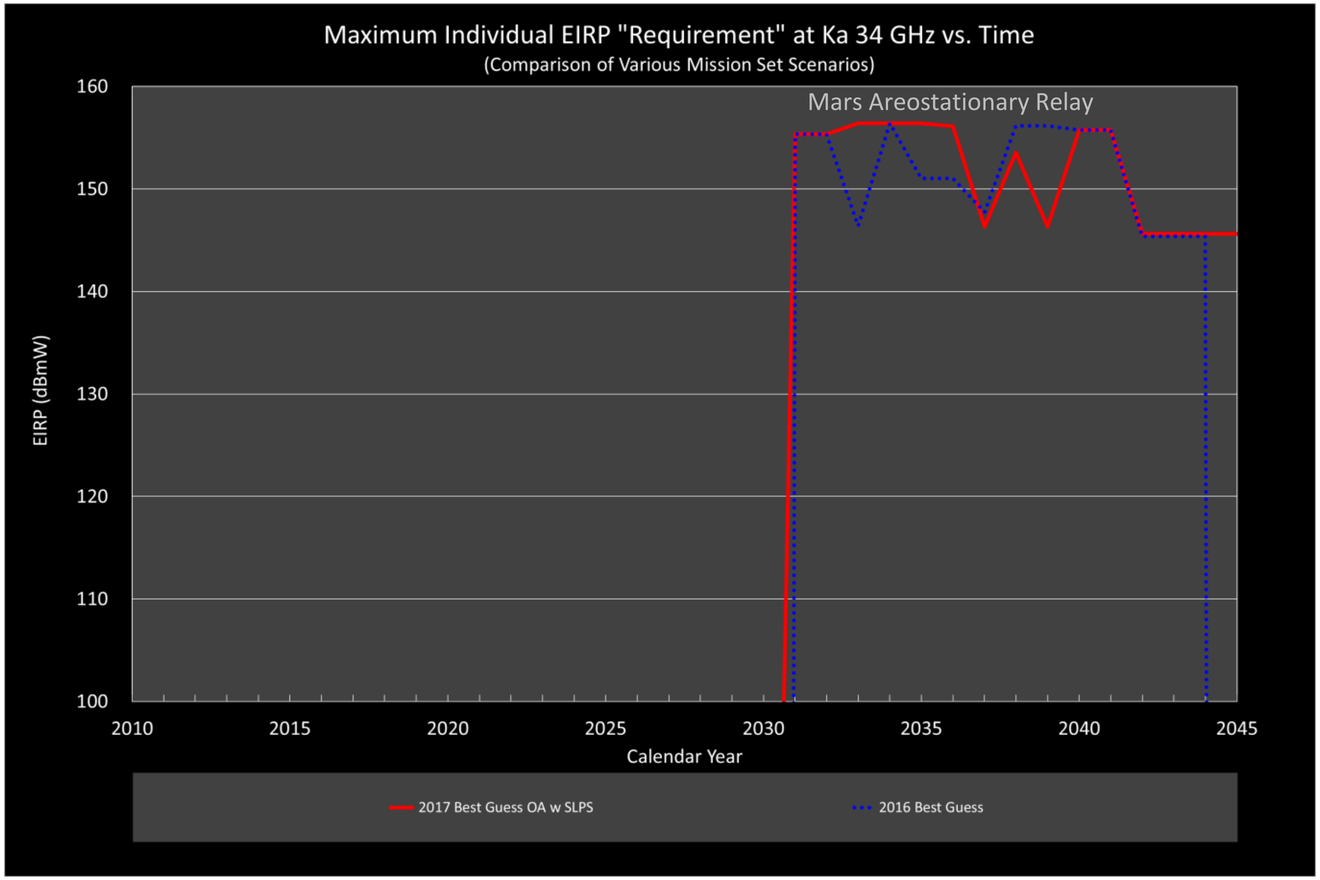
The 1 kW 34 GHz capability planned for later this decade will likely meet the maximum individual EIRP requirement until around 2030. After that, a significant increase in EIRP capability is needed to meet human Mars exploration needs. (See "Deep Space Capacity Study, Pass-2" recommendations.)

Aggregate Ka 34 GHz EIRP



Planned aggregate 34 GHz EIRP will likely only be adequate through the end of the next decade. Additional capability will be needed at each Complex, particularly since the majority of the users will all be in the same part of the sky (i.e., at Mars).

Maximum Individual Ka 40 GHz EIRP



The “Deep Space Capacity Study, Pass-2” recommendations call for moving the Mars Areostationary Relay capability from 40/37 GHz to 34/32 GHz and adopting a dual-trunk line approach to halving data rates. In the 2017 Best Guess OA w/ Slips scenario where these recommendations do not apply, human Mars exploration uplink rates drive a large 40 GHz EIRP “requirement.”

Uplink Capability Demand

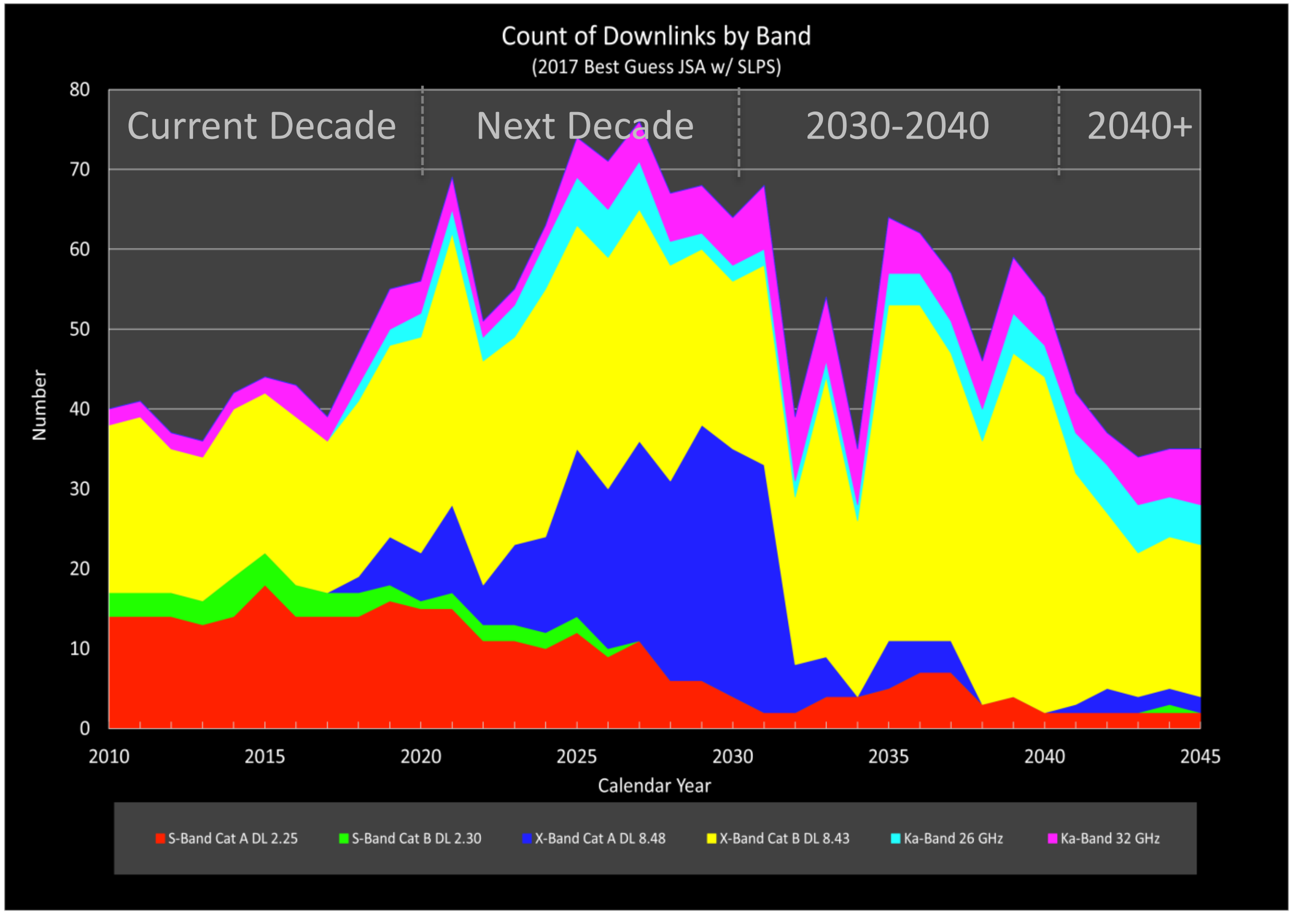
<u>Takeaways</u>:

- Human exploration missions drive up maximum uplink rates nearly 4 orders of magnitude over the next 20 years, with most of the increase occurring in the next 10 years.
- The DSN's maximum and aggregate EIRP capabilities at X-band should be adequate for non-emergency demand through 2040, assuming continued operation of the 70m antennas and continued deployment of the 80 kW transmitters on the 34m antennas, per the DAEP plan.
- The DSN currently lacks 22 GHz capability for next-decade, cislunar human exploration missions.
- The DSN's maximum and aggregate EIRP capabilities at Ka 34 GHz should be adequate to ~2030. After that, it will need to increase significantly to support human exploration at Mars.
    - Based on "Deep Space Capacity Study" recommendations for uplink.
    - Otherwise, Ka 40 GHz capability needed in addition to the planned 34 GHz capability.

Topics

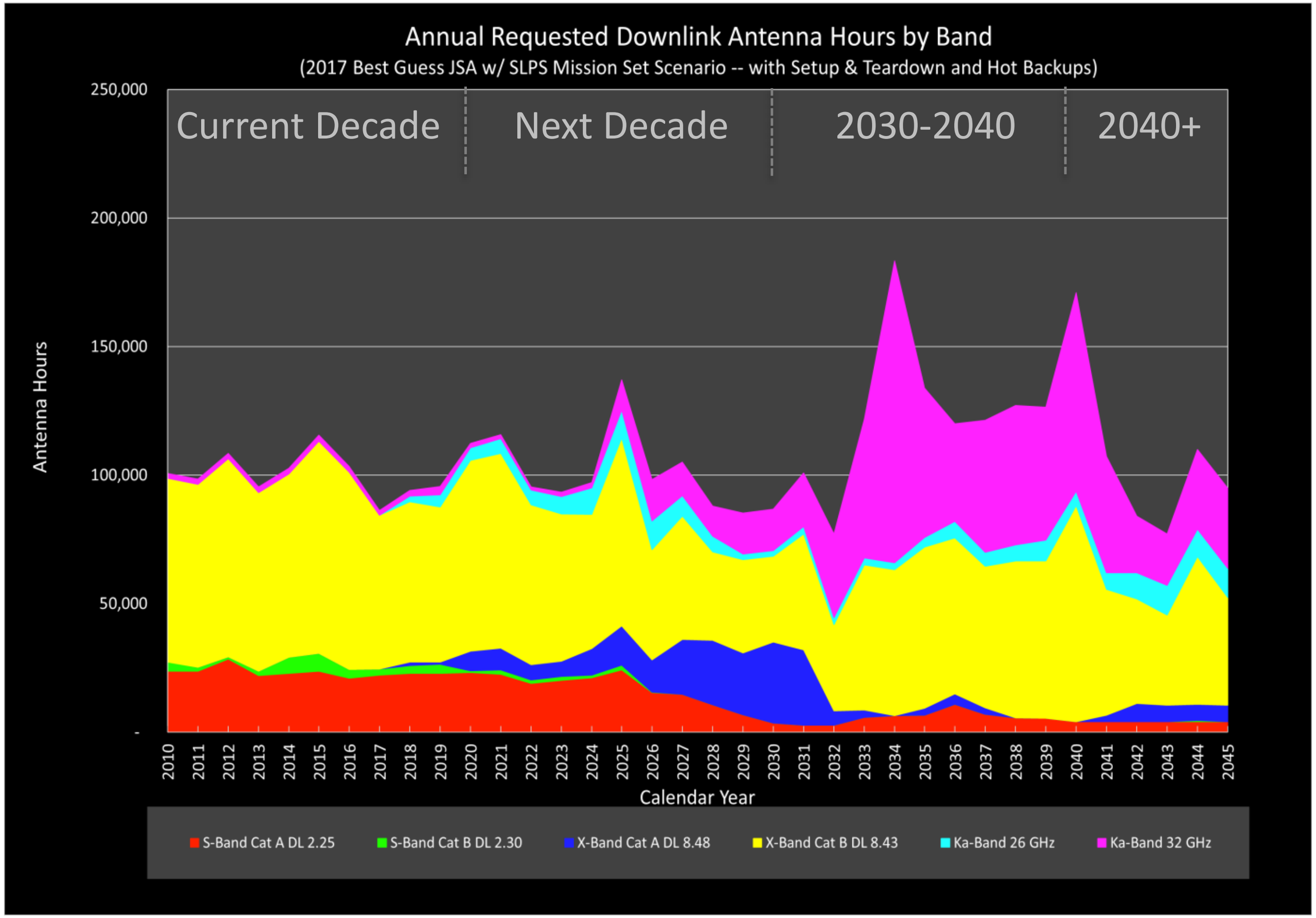
- **Factors Shaping the Anticipated Future Mission Set**: The Budget Situation, Uncertainty & Shifting Priorities for Human Exploration, and Increasing Globalization and Commercialization of Space Exploration Beyond GEO
- **Future Mission Set Analysis Methodology**: Definition of Mission Set Scenarios, Key Items Not Yet In Scenarios, Mission Set Analysis Process, Other Assumptions, and Interpretation of Results
- **Selected Mission Set Analysis Results**
  - **Capacity:** Anticipated Customer Base, Antenna-Hour Demand, and Antenna Asset Visibilities
  - **Capability**
    - **Downlink**: Average Rates, Maximum Rates, Rate Drivers, Data Volumes, Mission Set Range, End-to-End Downlink Difficulty, Maximum Individual G/T, and Aggregate G/T
    - **Uplink:** Average Rates, Maximum Rates, Rate Drivers, Maximum Individual EIRP, and Aggregate EIRP.
  - **Spectrum:** Downlink Count, Downlink Antenna Hours, Uplink Count, and Uplink Antenna Hours
  - **Loading Simulation Results:** "Requested" Downlink Hours Realized, "Requested" Downlink Data Volume Realized, "Requested" Uplink Hours Realized, and "Requested" Uplink Data Volume Realized
- **Implications**: The Next 10 Years and The Human Mars Exploration Era

Spectrum Demand by Downlink Count



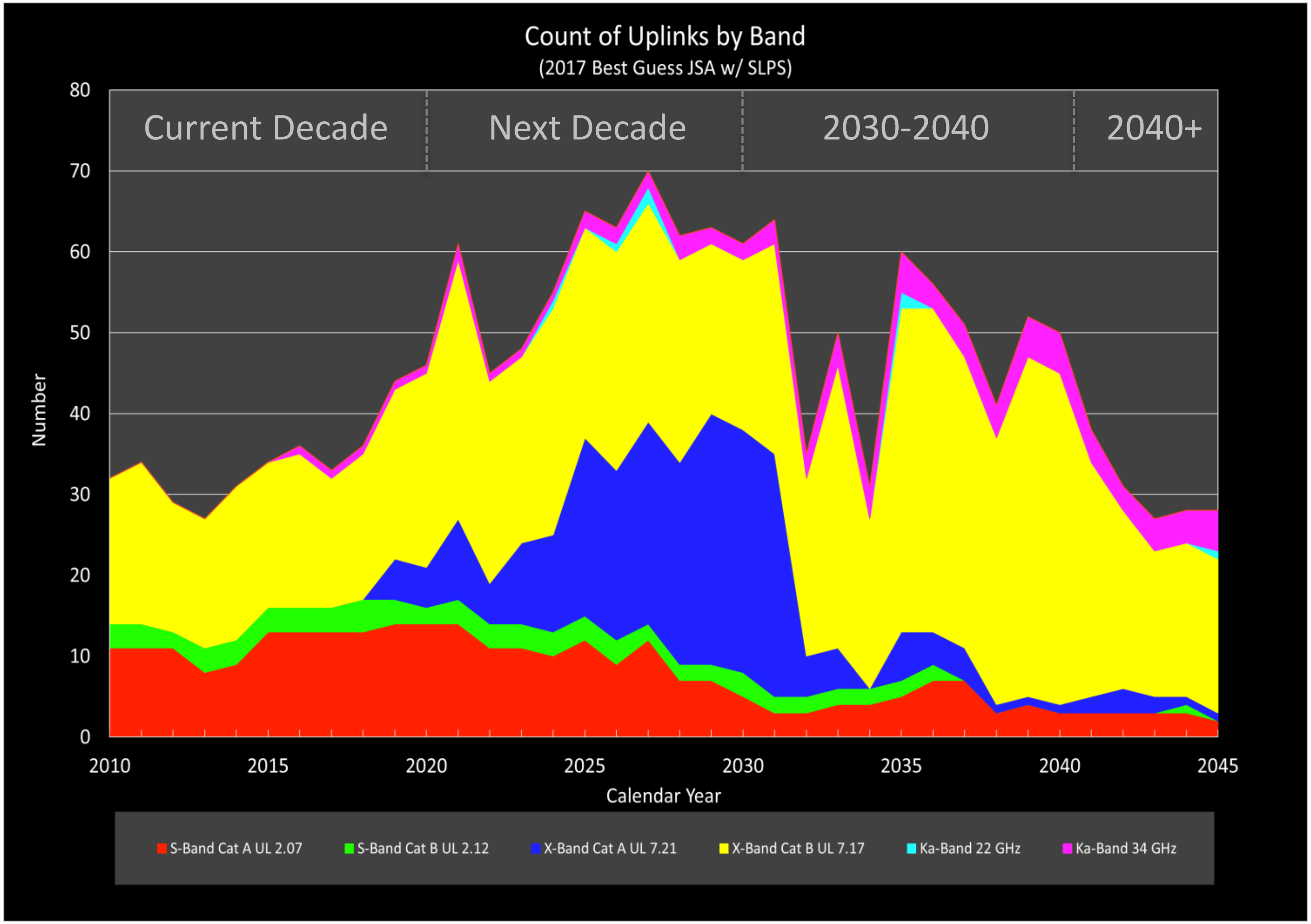
Current heavy use: Cat B X-band and Cat A S-band. **Next Decade growth:** Cat. A X-band, Ka 26 GHz, and Ka 32 GHz. **2030-2040:** Ka 32 GHz, assuming "Dual Trunk Link" approach for human Mars relay applications. Both Cat. A and Cat. B S-band fade in usage. Note that the increasing number of X-band users at Mars may be at risk of depleting the 8 MHz channels available in the 50 MHz allocation.

Spectrum Demand by Total Downlink Antenna Hours



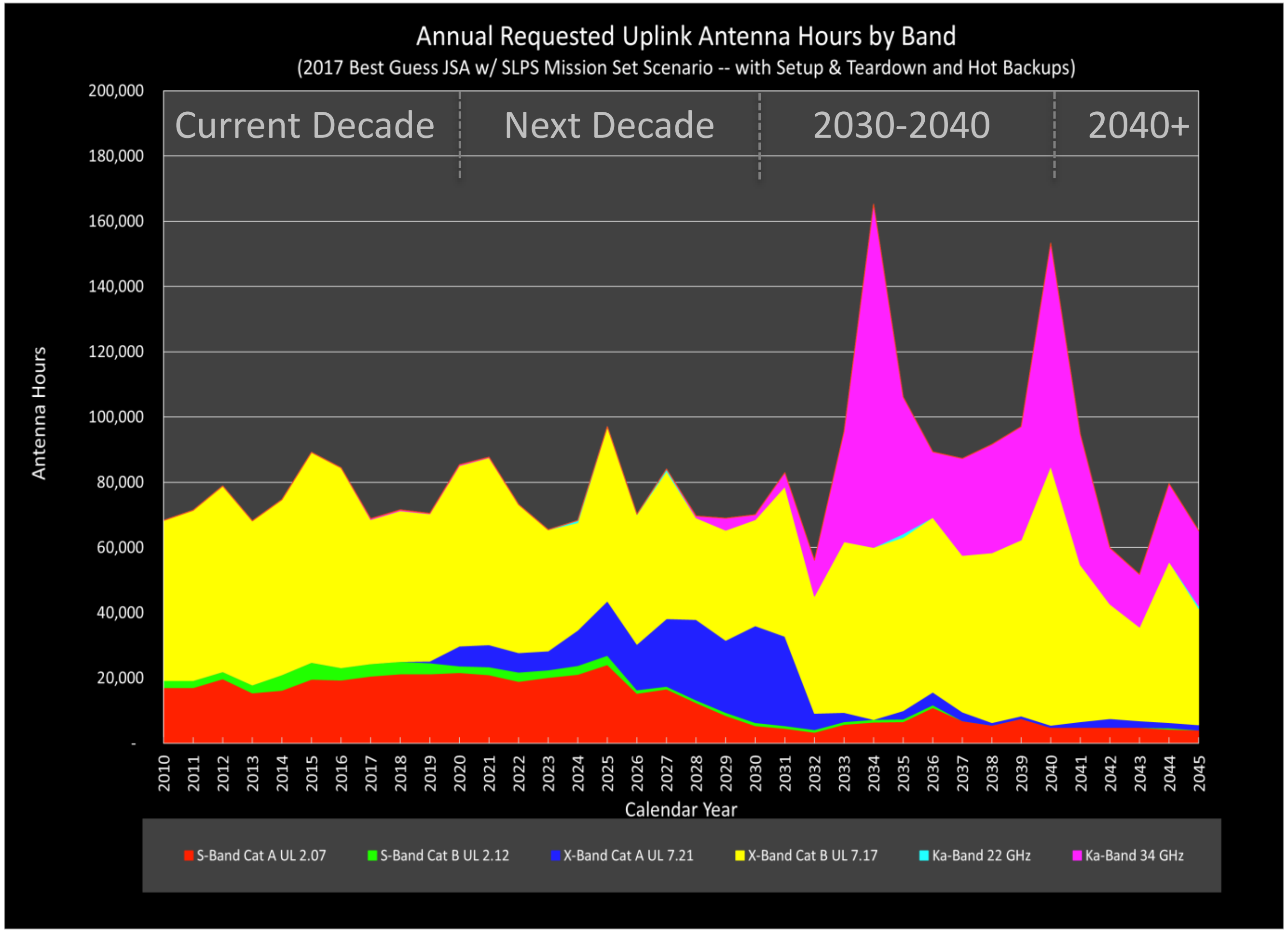
From a total antenna hour standpoint, band-use projections are similar to those associated with downlink count until the 2030's, when human Mars exploration reliance on 32 GHz becomes a dominant feature (see "Deep Space Capacity Study Recommendations, Pass-2").

Spectrum Demand by Uplink Count



While similar to spectrum demand by downlink count, Cat. B S-band demand is more apparent for uplink due to Voyager 2's requirement through 2036. Given recent DSG developments not reflected in this study, 22 GHz demand may be understated.

Spectrum Demand by Total Uplink Antenna Hours



Human Mars exploration drives a substantial uptick in 34 GHz antenna hours, even though the number of supported links is relatively small. (See "Deep Space Capacity Study, Pass-2" for details on the uplink recommendations.) As noted for uplink count by band, recent DSG developments suggest that 22 GHz demand may be understated.

Spectrum Summary

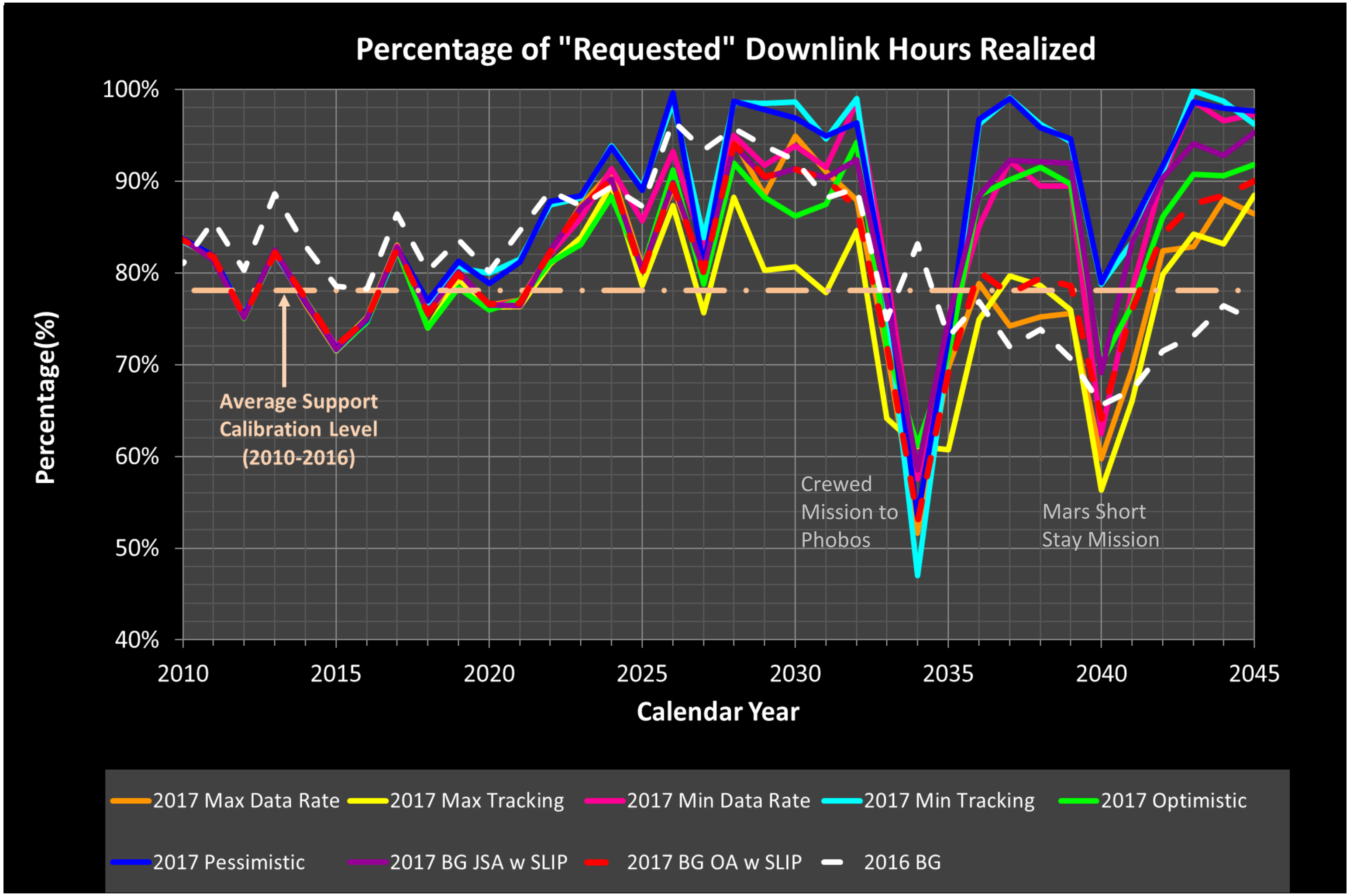
Takeaways:

- The DAEP buildout will address most of the spectrum demand areas over the next 10 years.
  - All of the new antennas are being equipped with Cat A and Cat B X-band and 32 GHz downlink.
  - 26 GHz, another important growth area, is planned on one additional antenna per complex.
  - 34 GHz transmitters are planned on one antenna per complex.
- X-band demand at Mars may be at risk of exceeding the 50 MHz worth of 8 MHz channels as the number of spacecraft operating there increase.
- Because recent DSG developments have not been incorporated into this study, 22 GHz demand may be understated.
  - The DSN does not currently have any 22 GHz capability, nor is any currently planned.
- In the human Mars exploration era, longer range and more bandwidth-intensive links tend to cause S-band use to fade.
- Consistent with the "Deep Space Capacity Study, Pass-2," human Mars exploration will require 34/32 GHz capability in excess of what will be emplaced through the DAEP.
  - The amount of additional capability needed will depend on whether an "optical and RF" or "RF-only" option is to be pursued. (See "Deep Space Capacity Study, Pass-2.")

Topics

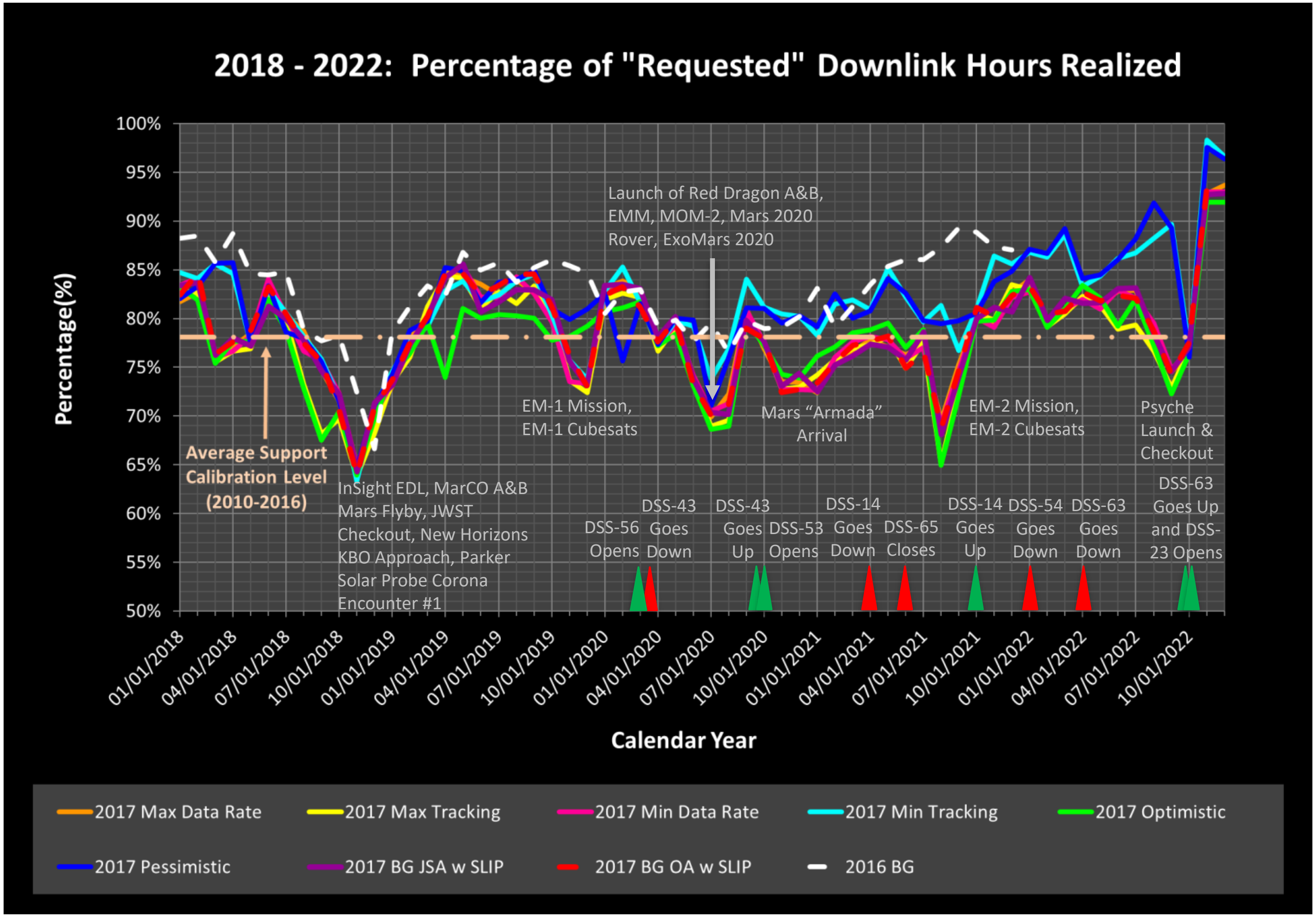
- **Factors Shaping the Anticipated Future Mission Set**: The Budget Situation, Uncertainty & Shifting Priorities for Human Exploration, and Increasing Globalization and Commercialization of Space Exploration Beyond GEO
- **Future Mission Set Analysis Methodology**: Definition of Mission Set Scenarios, Key Items Not Yet In Scenarios, Mission Set Analysis Process, Other Assumptions, and Interpretation of Results
- **Selected Mission Set Analysis Results**
  - **Capacity:** Anticipated Customer Base, Antenna-Hour Demand, and Antenna Asset Visibilities
  - **Capability**
    - **Downlink**: Average Rates, Maximum Rates, Rate Drivers, Data Volumes, Mission Set Range, End-to-End Downlink Difficulty, Maximum Individual G/T, and Aggregate G/T
    - **Uplink:** Average Rates, Maximum Rates, Rate Drivers, Maximum Individual EIRP, and Aggregate EIRP.
  - **Spectrum:** Downlink Count, Downlink Antenna Hours, Uplink Count, and Uplink Antenna Hours
  - **Loading Simulation Results:** "Requested" Downlink Hours Realized, "Requested" Downlink Data Volume Realized, "Requested" Uplink Hours Realized, and "Requested" Uplink Data Volume Realized
- **Implications**: The Next 10 Years and The Human Mars Exploration Era

Loading Simulation Results (1/8)



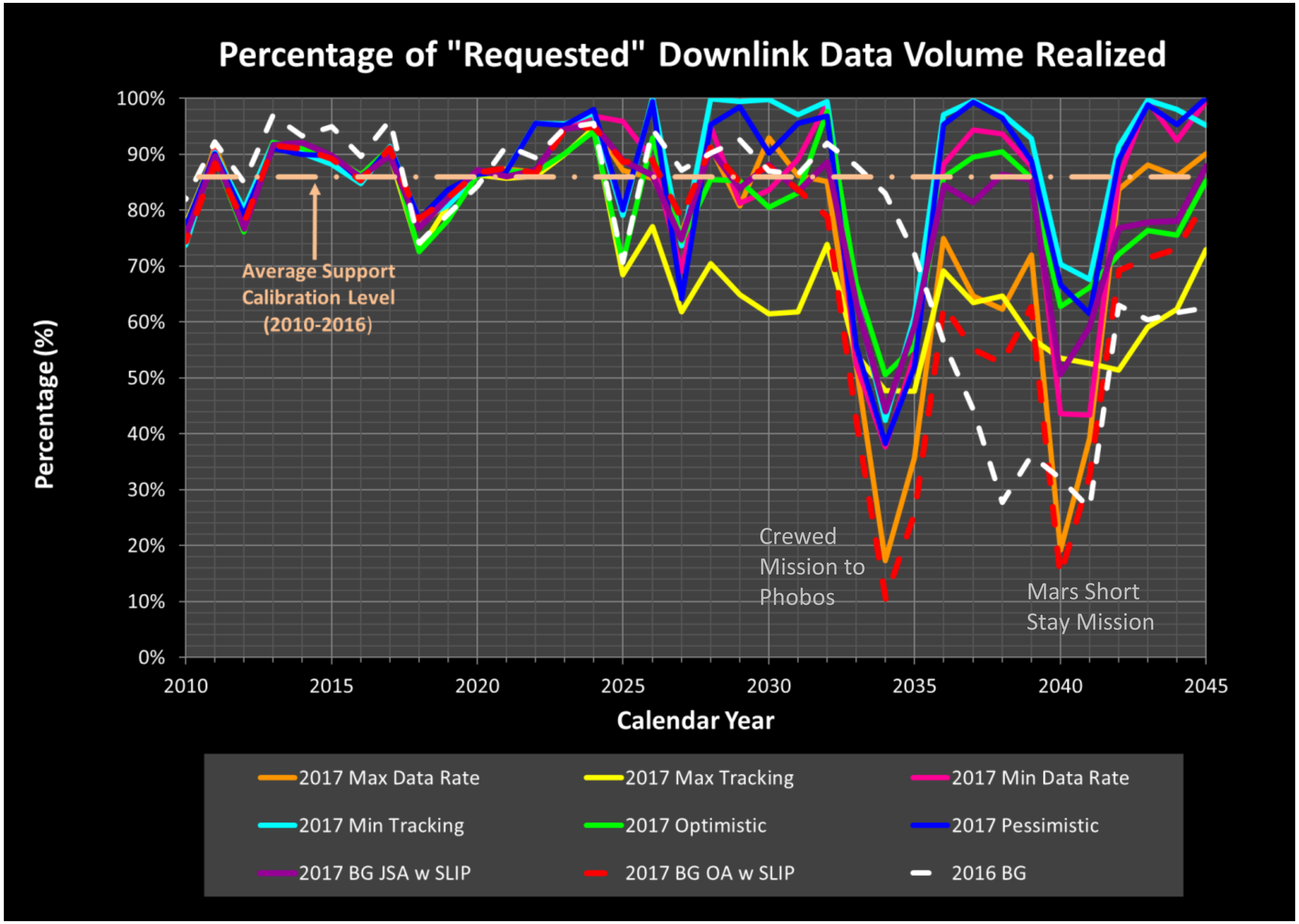
On an average annual basis, the future mission set looks supportable until the era of human Mars exploration, given the baseline assumptions for the DSN's evolution.

Loading Simulation Results (2/8)



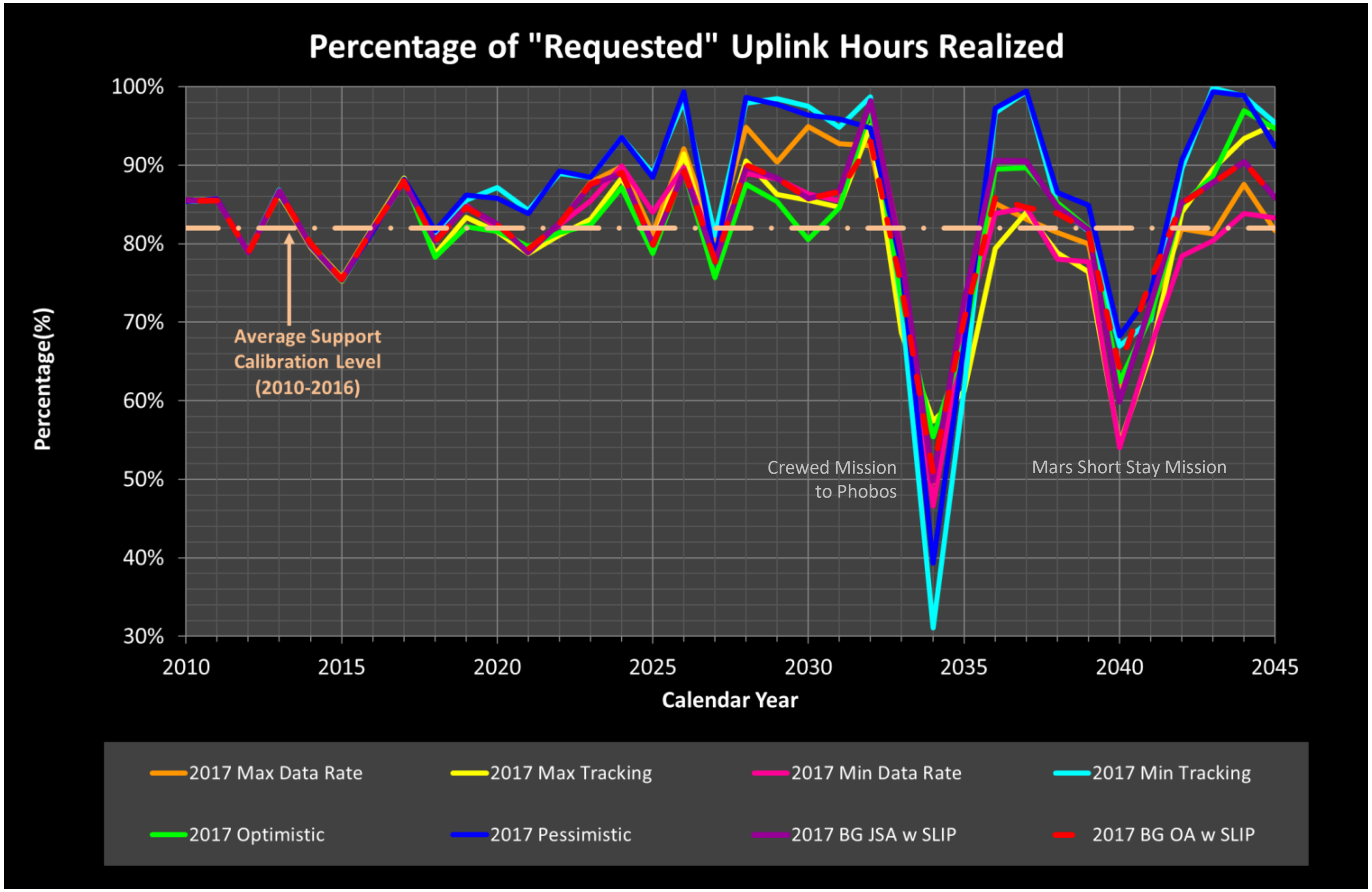
Periods of peak asset contention become more visible when looking on a monthly basis. Mission notations apply to the 2017 Best Guess (BG) scenarios. Mission changes have been occurring post-analysis that may further slip certain key dates to the right.

Loading Simulation Results (3/8)



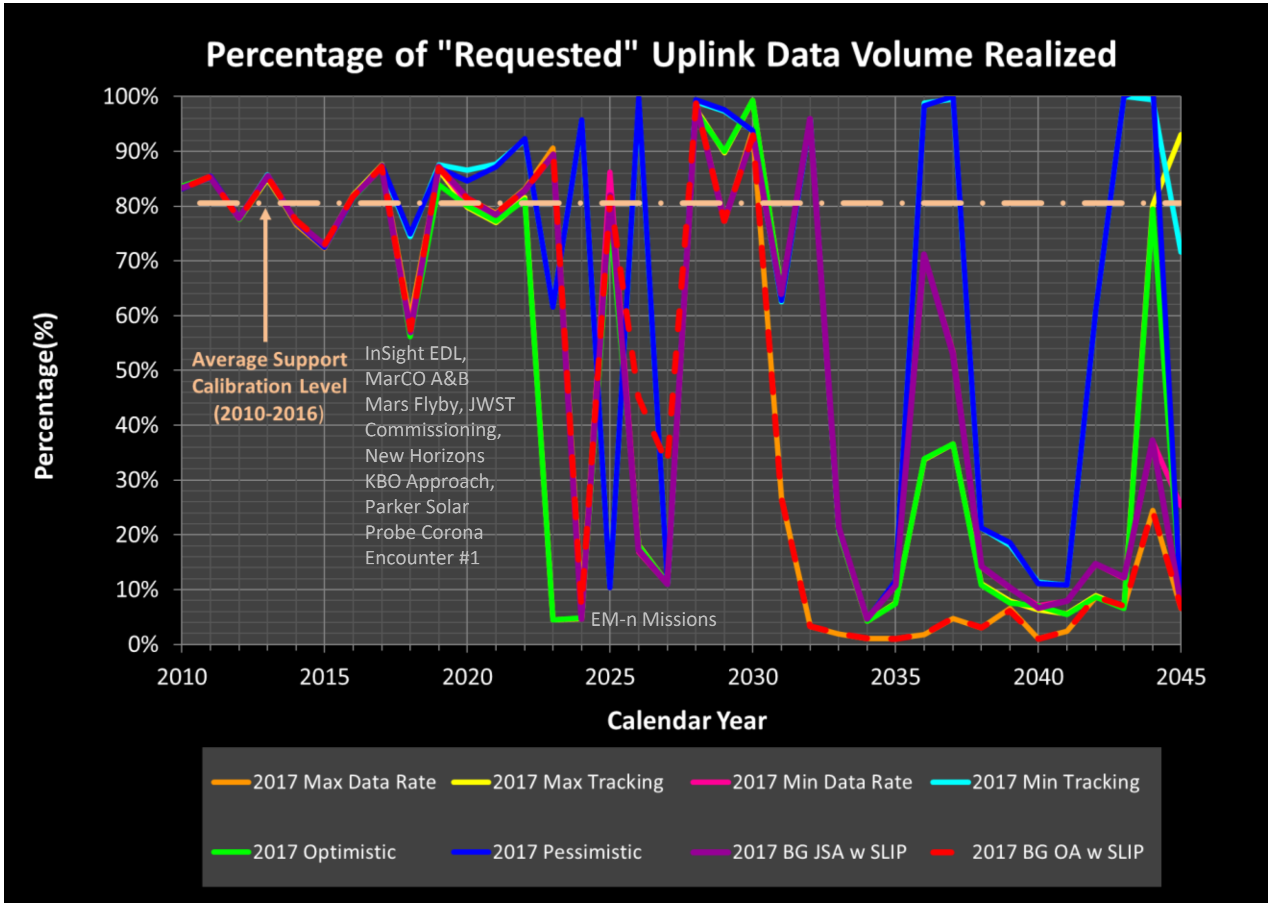
Under the baseline DSN assumptions, significant shortfalls in data volume return occur in the human Mars exploration era. Scenarios (e.g., JSA) which assume a "dual trunk link," 32 GHz (as opposed to 37 GHz) approach to relay data return from Mars, return significantly more data volume than those that do not.

Loading Simulation Results (5/8)



Not surprisingly, the uplink antenna-hour realization is similar to that for the downlink. The largest issues arise in the human Mars exploration era due to a lack of sufficient 34 GHz uplink capacity (or 40 GHz in the case of the OA and Max Data rate cases). For scenarios involving fewer overall missions, the percentage shortfall, of course, can appear greater.

Loading Simulation Results (6/8)



Analysis of uplink data volume realization further highlights the potential impact of not having the required uplink frequencies available. While the human Mars exploration era shortfalls show up at 34 or 40 GHz, the lack of 22 GHz during the EM-n mission era also shows up. To the extent that the EM-n missions are relatively short, they do not significantly impact the uplink-hour plot. But, their relatively high uplink rates make their uplink volume impacts very apparent.

Loading Simulation Results (7/8)

Takeaways:

- Simulations may show contention that simple antenna-hour supply vs. demand plots cannot -- since not all antennas share the same downlink frequency band capabilities, nor do they all share the same transmit capabilities.
- Simulations viewed on a monthly basis reveal more peak asset contention than when viewed on an annual basis.
  - Peak asset contention is particularly pronounced in 2018 due to a host of mission-critical events occurring within the same timeframe.
  - Somewhat less pronounced peak asset contention periods occur during the 2019 EM-1 mission timeframe, the 2020 Mars opportunity when several missions launch to Mars, the 2021 Mars arrival timeframe when those same missions all arrive at Mars, and the 2021 EM-2 mission timeframe.
- The simulations clearly show downlink-hour and downlink-volume shortfalls in the timeframes corresponding to the Crewed Mission to Phobos and the Mars Short-Stay Mission.
  - Because of the large G/T requirements of these missions, antenna arraying becomes necessary -- which leaves less antennas available to service the rest of the missions.

Loading Simulation Results (8/8)

Takeaways (Continued…):

- The JSA scenario loads better than the OA scenario in these simulations because its “dual-trunk-link” approach allows a lower data rate -- thereby necessitating a reduced number of arrayed antennas (see Deep Space Capacity Study, Pass-2).
- The JSA scenario also loads better than the OA scenario because it assumes that the relays operate at 32 GHz (which is currently in plan up to the number of antennas in the DAEP buildout), while the OA scenario assumes that the relays operate at 37 GHz (which is not at all in plan).

- Uplink-hour shortfalls are similarly pronounced in the human-Mars exploration timeframe.
    - Large EIRP requirements drive some uplink arraying which then reduces the number of antennas available for servicing the rest of the mission set.
    - Uplink-volume shortfalls also tend to be driven by weakly supported, or unsupported bands, such as 34 GHz and 22 GHz, respectively.

Topics

- **Factors Shaping the Anticipated Future Mission Set**: The Budget Situation, Uncertainty & Shifting Priorities for Human Exploration, and Increasing Globalization and Commercialization of Space Exploration Beyond GEO
- **Future Mission Set Analysis Methodology**: Definition of Mission Set Scenarios, Key Items Not Yet In Scenarios, Mission Set Analysis Process, Other Assumptions, and Interpretation of Results
- **Selected Mission Set Analysis Results**
  - **Capacity:** Anticipated Customer Base, Antenna-Hour Demand, and Antenna Asset Visibilities
  - **Capability**
    - **Downlink**: Average Rates, Maximum Rates, Rate Drivers, Data Volumes, Mission Set Range, End-to-End Downlink Difficulty, Maximum Individual G/T, and Aggregate G/T
    - **Uplink:** Average Rates, Maximum Rates, Rate Drivers, Maximum Individual EIRP, and Aggregate EIRP.
  - **Spectrum:** Downlink Count, Downlink Antenna Hours, Uplink Count, and Uplink Antenna Hours
  - **Loading Simulation Results:** "Requested" Downlink Hours Realized, "Requested" Downlink Data Volume Realized, "Requested" Uplink Hours Realized, and "Requested" Uplink Data Volume Realized
- **Implications**: The Next 10 Years and The Human Mars Exploration Era

Implications: The Next 10 Years (1/7)

- Environment
  - Budget-constrained – no significant new money for NASA; human exploration consuming an increasing portion of the overall NASA budget; smallsats playing an increasing role in space science as budgets are squeezed.
  - Shifting Priorities – while Mars remains the ultimate objective for human exploration, the focus is now on and around the Moon. Asteroids are out, except with respect to commercial robotic and space science interests.
  - Increasing Globalization & Commercialization of Exploration Beyond GEO – as spacecraft get cheaper to build and launch, and as more avenues for access to space open up, more international and commercial players are likely to appear.
    - This growing international and commercial mission set may not be subject to the same budgetary constraints as NASA's missions.
    - This growing number of mission players may foster additional foreign and commercial communications infrastructure, generating additional international cross-support opportunities and the potential for limited commercial service availability.

Implications: The Next 10 Years (2/7)

- Customer Base
  - <u>Significant Growth</u> – over the next 10 years the DSN will need to service roughly double the number of links that it services today.
    - Between 10 and 40 percent of these links will be associated with smallsats (but with only 5-10% of the antenna-hours going to them).
    - Human exploration missions will be an important new component of the customer base -- with each mission involving multiple links, some of them requiring very high reliability (e.g., "hot backup" antennas).
  - <u>Category B Dominant</u> -- Roughly 25% of all the missions will be operating between GEO and SEL1 or SEL2 distances; 50% between SEL1 or SEL2 distance and Mars distance; and, 25% at or beyond Mars distance.
    - Some of the highest visibility missions (e.g., human cislunar exploration, JWST), however, will be Category A.
    - The majority of smallsats will also operate in Category A space.
    - New Horizons, Osiris-REx, the Mars 2020 Lander, Europa Clipper, Lucy, and Psyche are all examples of prominent Category B missions that would be operating during this time period.

Implications: The Next 10 Years (3/7)

- Capacity
  - <u>Oversubscription</u> – over the next 10 years the DSN will be operating at capacity, with multiple periods in which demand will exceed supply.
    - During the next 10 years antenna-hour demand during peak contention periods increases as much as 54% and, at the end of the period, is ~17% higher than it is today.
    - Oversubscription is being handled by "downsizing" mission customer "requirements" during the RAP process.
  - <u>Asset Contention</u> – loading simulations that already assume the full DAEP buildout, the addition of 26 GHz on 3 more antennas, and reliance on 4-MSPA suggest that there will be recurrent periods of asset contention over the next 10 years.
    - The DAEP buildout is essential to minimizing the number and extent of asset contention periods.
    - Some of the asset contention periods occur prior to completing the buildout.
      - Developing large antenna cross-support agreements, new MSPA techniques (e.g., OMSPA, n-MSPA), and a new Multiple Uplinks Per Antenna (MUPA) capability might help mitigate such periods.
    - Depending upon how NASA's DSG&T evolve, instituting a 22 GHz uplink capability on the 26 GHz downlink assets might also prove important.

Implications: The Next 10 Years (4/7)

- Capacity (Continued…)

  - <u>Asset Visibility</u> – peak asset contention can be more manageable when the contention period corresponds to the northern hemisphere being most in view.

    - Hemispheric visibility to the mission set tends to be driven by a combination of Earth's seasons and the relative motion of the other bodies at which the spacecraft reside.

    - Because two of the three complexes are located in the northern hemisphere, there are more antennas in view of the mission set when the northern hemisphere is most in view.

    - This visibility phenomenon partially contributes to the 2018 contention period which occurs when the southern hemisphere is most in view with only the Canberra antennas. Much of the 2020-2021 contention period tends to occur when the northern hemisphere is most in view with both the Goldstone and Madrid antennas.

    - Over the next 10 years, the aggregate mission set, particularly Category A missions, manifests a slight southern declination bias, suggesting that Canberra, on average, will be most in view.

    - To the extent that human cislunar exploration drives an additional southern hemisphere site for coverage reasons, such a site would also help minimize peak asset contention when the southern hemisphere is most in view.

Implications: The Next 10 Years (5/7)

- Capability
  - “Skyrocketing” Data Rates – average downlink rates increase by ~16x over the next 10 years; average uplink rates increase ~1000x.
    - Downlink rates are largely driven by high-rate observatory-class missions.
      - While initial human cislunar exploration mission concept data rates have not been high enough to be drivers, the new DSG&T concepts may entail higher, more driving rates.
    - Uplink rates are almost entirely driven by human cislunar exploration missions.
    - Rates will be getting high enough to make Ka-band, and possibly optical, attractive from an allowable spectrum bandwidth limitation standpoint.
  - “Skyrocketing” Downlink Volumes -- Over the next 10 years, downlink volumes increase by ~22x.
    - The steep increases in downlink rates contribute significantly to the increase in downlink volumes. But, the increase in the number of DSN users also contributes.
    - DDOR volumes increase by almost 5x, consistent with an increase in the number of DSN users.
    - The combined downlink and DDOR volumes moving around on the ground will increase by more than an order of magnitude (a conservative estimate since downlink volumes are based on information-bit rates and not symbol rates).
      - Ground data handling and management capabilities will need to grow accordingly.

Implications: The Next 10 Years (6/7)

- Capability (Continued…)
  - Inadequate X-band G/T – maximum individual and "average" aggregate X-band G/T demand exceeds supply over the next 10 years.
    - G/T shortfalls are managed by having missions reduce their data rates when link distances start to demand G/T's in excess of what the antennas can currently support.
      - Continued buildout of the DAEP antennas is essential to minimizing the amount of science data return that has to be sacrificed via such data rate reductions.
    - Mission critical events such as planetary orbit insertions typically require a 70m-equivalent level of G/T because the spacecraft HGA has to go off earth-point during the insertion burn and LGAs or MGAs have to be used instead.
      - Continued buildout of the DAEP antennas is essential to ensuring a temporary backup capability using arrayed 34m antennas, should a 70m malfunction during a critical event.
      - Because the DAEP buildout only enables a total of 4 34m antennas per Complex and it takes 4 34m antennas to equal the G/T capability of a 70m antenna, the DAEP antennas cannot permanently replace a 70m antenna without sacrificing their support to the rest of a Complex's user missions.
  - Adequate X and 34 GHz EIRP – With the assumed DAEP buildout, addition of 80 kW transmitters on selected antennas, continued availability of the 70m antennas, and the addition of 34 GHz capability at each Complex, non-emergency EIRPs should be adequate.

Implications: The Next 10 Years (7/7)

- Spectrum
  - RF Spectrum Contention – significantly higher data rates over the next 10-years may drive channel bandwidth demand to exceed allowable supply.
    - Category B X-band remains the most heavily-used DSN-supported band for the foreseeable future.
    - Spatial reuse of spectrum typically allows those users to fit within the 50 MHz of allocated spectrum.
    - But, at Mars, the number of available 8 MHz channels are diminishing as the number of mission users at that locale grows.
      - Provides an increased impetus to move to Ka-band and/or optical.
  - Human Exploration May Drive New Band Use – The high rate uplink demands of forthcoming cislunar missions may drive 22 GHz Ka-band uplink.
    - Human exploration over the next 10 years is projected to drive a ~1000x increase over today's DSN-supported uplink rates.
      - New DSG&T cislunar "space station" concepts introduced since the conduct of this study could cause those rates to be used on a more sustained basis.
    - Category A S- and X-band allocations for uplink are only 85 MHz and 45 MHz, respectively.

Implications: Preparing for the Human Mars Exploration Era (1/7)

- Environment
  - Still Budget-constrained – new money for NASA still hard to come by; human exploration consuming most of the overall NASA budget; space science missions more challenging but somewhat less numerous than in the prior 10 years.
  - Mars focused – commercial interests dominate the near-Earth environment and NASA's focus is more on putting humans on Mars.
  - Continued Globalization & Commercialization of Exploration Beyond GEO – the sheer cost associated with sustaining a human presence at the Moon and putting humans on Mars necessitates global participation from both government agencies and commercial entities.
    - By this time, commercial entities will have accrued more experience beyond GEO and will be actively lobbying to play a larger role in providing the needed infrastructure, including telecommunications.
    - While NASA will remain a major player, other international entities will be vying for leadership roles in sustaining a continuing human presence at the Moon and blazing the trail to Mars.

Implications: Preparing for the Human Mars Exploration Era (2/7)

- Customer Base
  - <u>Larger than Today, But Less than the Next 10 Years</u> – Beyond 2027, mission numbers will generally return to today's levels; but, the number of uplinks and downlinks requiring DSN support will generally remain 50% - 60% higher than today's.
    - Human exploration missions may absorb much of NASA's budget.
    - Human exploration missions will involve multiple launches of multiple spacecraft, each with multiple uplinks and downlinks associated with them.
    - Human exploration missions will also continue to provide secondary payload opportunities for increasingly challenging smallsat missions.
  - <u>Mars Dominant</u> -- Roughly 25% of all the missions would be operating at less than ~0.4 AU from Earth; 50% would be operating between roughly 0.4 AU and Mars distance; and, 25% at or beyond Mars distance.
    - Results tend to be somewhat scenario dependent.
      - In the Optimistic and Max Tracking scenarios where the DSN supports more foreign-led and commercial-led missions, the bottom quartile resides closer to Earth.
      - In the Pessimistic and Min Tracking scenarios where the DSN supports few foreign-led and no commercial missions (and fewer missions overall), the bottom quartile converges on the median at Mars distance.

Implications: Preparing for the Human Mars Exploration Era (3/7)

- Capacity
  - Fundamentally Inadequate – with just the DAEP buildout of antennas, the DSN will not have enough antennas to array up to meet human Mars mission data rate requirements and still have enough left over to fully service the rest of the mission customers.
    - Results are consistent with "Deep Space Capacity Study" findings.
      - The "Dual Trunk Link" approach to Mars relays during human exploration recommended by the "Deep Space Capacity Study, Pass-2" essentially halves the number of antennas that would otherwise be needed.
      - Loading simulations conducted assuming a combined RF-Optical mission set derived from the 2017 Best Guess JSA w/Slips mission set scenario are contained in a supplement to this document.
    - The recommendations from the "Deep Space Capacity Study, Pass-2" still apply.
  - 34 GHz Uplink Shortage – to the extent that the high uplink rates demanded by human Mars exploration are met by arraying 34 GHz-capable assets, there are not enough of such assets in plan to meet the need (not to mention service other 34 GHz mission customers).
      - Only 1 34 GHz-capable antenna per Complex planned – insufficient for even the "hot backup" requirement.
      - Development of higher power 34 GHz transmitters could reduce the need for uplink arraying.

Implications: Preparing for the Human Mars Exploration Era (4/7)

- Capacity (Continued…)
  - Southern Hemisphere Visibility Still Important – Canberra remains, on average, visible to more spacecraft during the early 2030s.
    - Peak asset contention can be more manageable when the contention period corresponds to the northern hemisphere being most in view.
    - To the extent that NASA decides an additional southern hemisphere site is needed to close coverage gaps for human exploration, ensuring such a site is deep space capable would help reduce potential contention between early human Mars exploration endeavors and other DSN-supported mission set elements.

Implications: Preparing for the Human Mars Exploration Era (5/7)

- Capability
  - <u>Allocated RF Spectrum Constraints Begin to Manifest</u> – maximum RF downlink rates tend to level off at between 100 and 300 Mbps, which for 32 GHz, would use up most of the spectrum allocation.
    - 500 MHz is allocated to Category B missions within the 32 GHz spectrum. Given a QPSK modulation scheme and a rate ½ code, a single mission operating at 250 Mbps could use up the entire spectrum allocation.
      - This may be one of the factors that cause mission designers to be limiting their future mission design concepts to such data rates. (Another might include the increasing difficulty associated with closing the link.)
    - For a location where several high-rate missions may converge, such as Mars, spatial reuse of the spectrum is not an option.
    - Such RF spectrum constraints provide impetus for moving to optical communications.
      - An alternative approach would make use of additional downlink spectrum available at 37-38 GHz. However, this would require significant new receiver upgrades to existing antennas, more antennas, and transmitter upgrades to existing spacecraft radios.
        - Cost-trades relative to combined optical-RF options are contained in the "Deep Space Capacity Study, Pass-2."

Implications: Preparing for the Human Mars Exploration Era (6/7)

- Capability (Continued…)
  - <u>Greater Need for Downlink Arraying at 32 GHz</u> – Maximum G/T shortfalls cannot as easily be resolved by lowering mission data rates, since most of the driver missions in this timeframe involve human exploration.
    - While the DSN's aggregate X-band and 32 GHz G/Ts appear to be adequate in this timeframe for "average" demand, antenna-time analysis and loading simulations suggest that arraying up all of the needed antennas to meet maximum individual G/T requirements cannot be done without impacting available capacity (as noted a couple of slides back).
    - While optical communications could potentially reduce the extent of RF arraying needed, periods when the Sun-Earth-Probe angle is small (e.g., less than 10-12 degrees) will produce outages on the order of a couple of months – necessitating a certain level of 32 GHz arraying during such time periods (please see the "Deep Space Capacity Study, Pass-2" report and recommendations).
  - <u>Inadequate EIRP at 34 GHz</u> – Both the maximum individual and aggregate EIRP requirements for this timeframe cannot be satisfied with the currently planned 1kW, single 34m per Complex capability.
    - Either additional 34m antennas need to be equipped with this capability to enable an arrayed uplink that can satisfy the requirements, or the planned transmit power needs to be increased.
      - As noted in the capacity discussion, a second 34 GHz-equipped 34m antenna per Complex may be needed in any event to satisfy the "hot backup" requirement.

Implications: Preparing for the Human Mars Exploration Era (7/7)

- Spectrum
  - RF Spectrum Allocation Constraints Begin to Manifest – as mentioned in the capability discussion, maximum RF downlink rates tend to level off at between 100 and 300 Mbps, which for 32 GHz, would use up most of the spectrum allocation.
    - Provides an increased impetus to move to optical. (See "Deep Space Capacity Study, Pass-2" recommendation.)
    - Alternatively, NASA could choose to pursue development of 37-38 GHz downlink.
      - Requires more antennas and receiver upgrades.
      - This higher downlink frequency would have to be accommodated on the spacecraft-side as well.
- A Note about Timing
  - While the human Mars exploration era is out beyond the 10-year horizon, the capabilities it requires may take that long to develop and implement. Start now.
    - 32 GHz downlink arraying
    - 34 GHz uplink arraying and/or more powerful transmitters
    - Development and implementation of RF-optical hybrid antennas and/or other array-able ground station assets (per "Deep Space Capacity Study, Pass-2" recommendation).