2016 Future Deep Space Mission Trends & Implications

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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 analysis. And, associated aggregate mission geometry and station visibility analyses.
- **Andy Kwok** – 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 analysis. 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.
- **Janet Wu** – mission data research, mission modeling, model maintenance, and analysis.

Pre-decisional – for Planning and Discussion Purposes Only

Topics

- **Factors Shaping the Anticipated Future Mission Set**: The Budget Situation, Emergence of a Minimal Humans-to-Mars Architecture, and Continued Small Satellite Technology Innovation
- **Future Mission Set Analysis Methodology**: Mission Set Analysis Process, Definition of Mission Set Scenarios, Key Items Not Yet In Scenarios, and Interpretation of Results
- **Selected Mission Set Analysis Results**
  - **Capacity:** Anticipated Customer Base, Antenna-Hour Demand, and Antenna Asset Visibilities
  - **Capability**
    - **Downlink**: Average 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 and "Requested" Downlink Data Volume Realized
- **Implications**: This Decade, Next Decade, and Beyond

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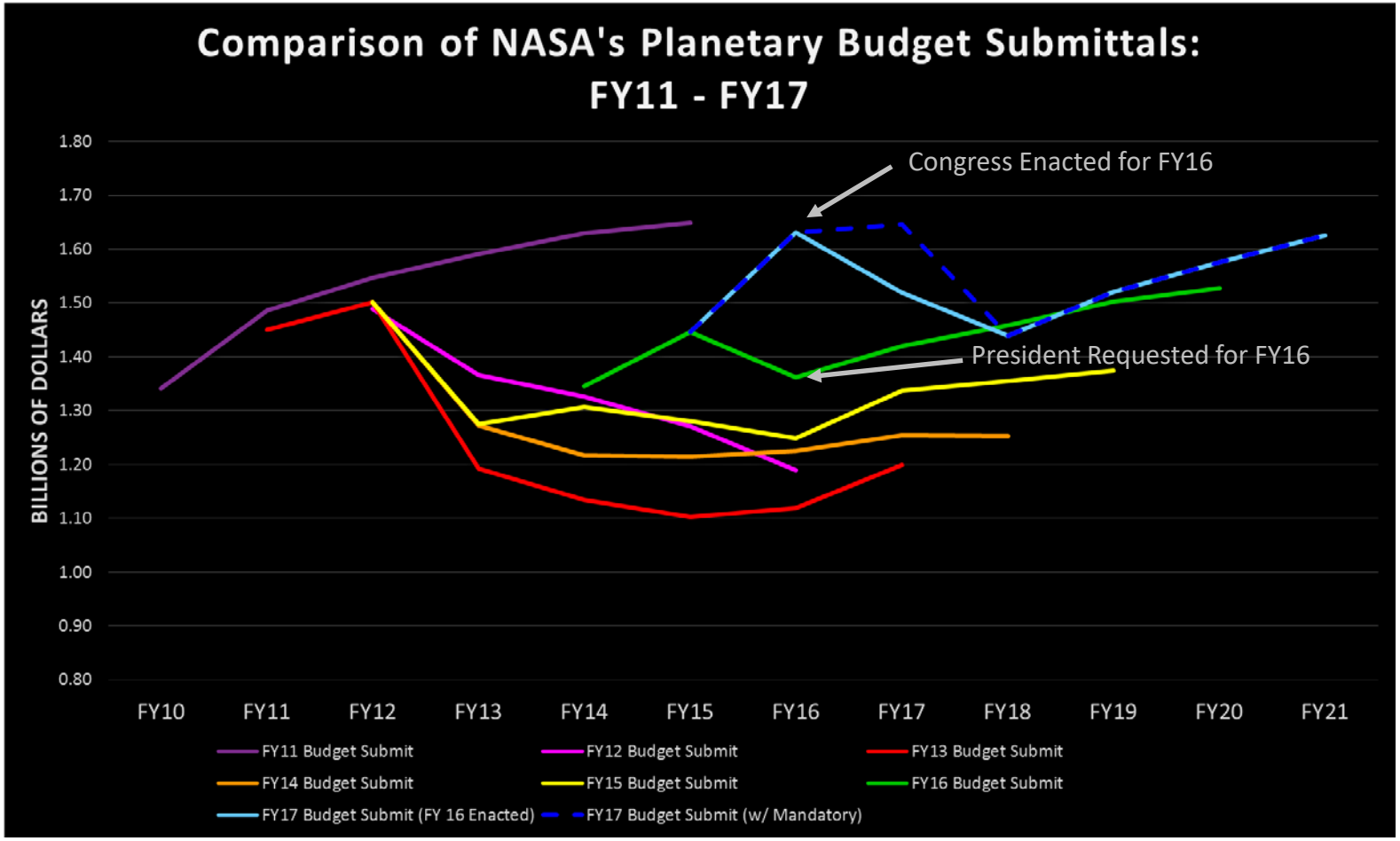
The Budget Situation (1/2)



Recent appropriations have been significantly larger than what was requested. Whether appropriated levels will continue to exceed requested levels in the out-years is an open question.

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The Budget Situation (2/2)

- Some of the noteworthy FY17 Budget Request items include: WFIRST, the Outer Planet and Ocean Worlds program, "accelerated technology development of future power systems and other areas important for future planetary exploration," the CubeSat project, the Small Satellite Constellation Initiative (primarily for Earth Science), and the Asteroid Redirect Robotic Mission.
- Proposed funding levels for SLS and Orion are significantly below FY16 levels.
  - "NASA is on track for a launch capability readiness date of November 2018 for Exploration Mission 1 (EM-1), which will be an un-crewed test of the SLS rocket carrying an Orion capsule."
- The FY17 Budget Request is an election-year budget that will undoubtedly be subject to change.
- Nothing has significantly changed in term's of the Government's long-term budget outlook as reported by the CBO – discretionary spending will continue to be increasingly constrained by growing obligations.

Human exploration and robotic science missions will continue to evolve in a highly constrained budget environment.

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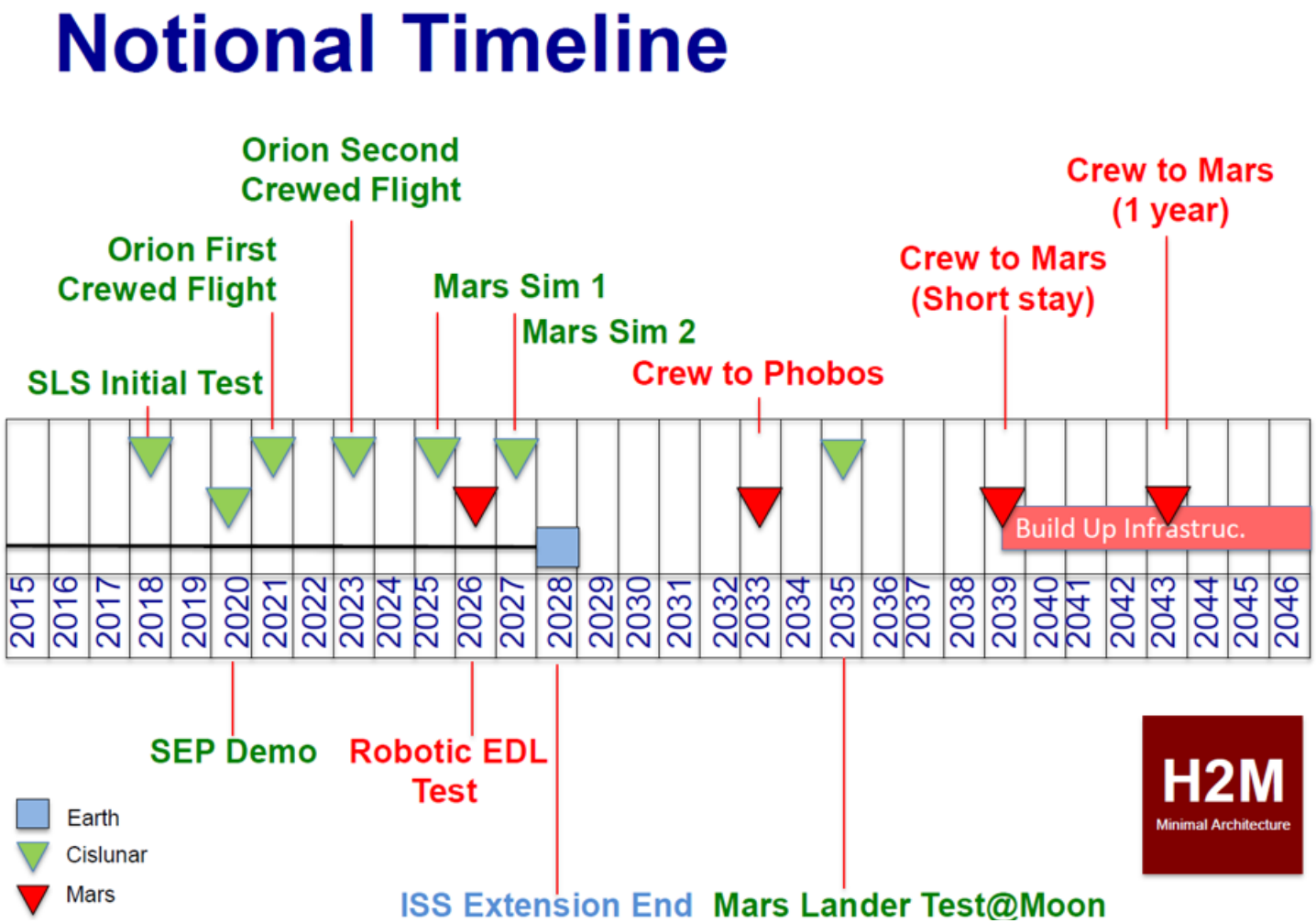
H2M Minimal Architecture (1/2)



More substantive architectures for cost-constrained human Mars exploration are emerging.

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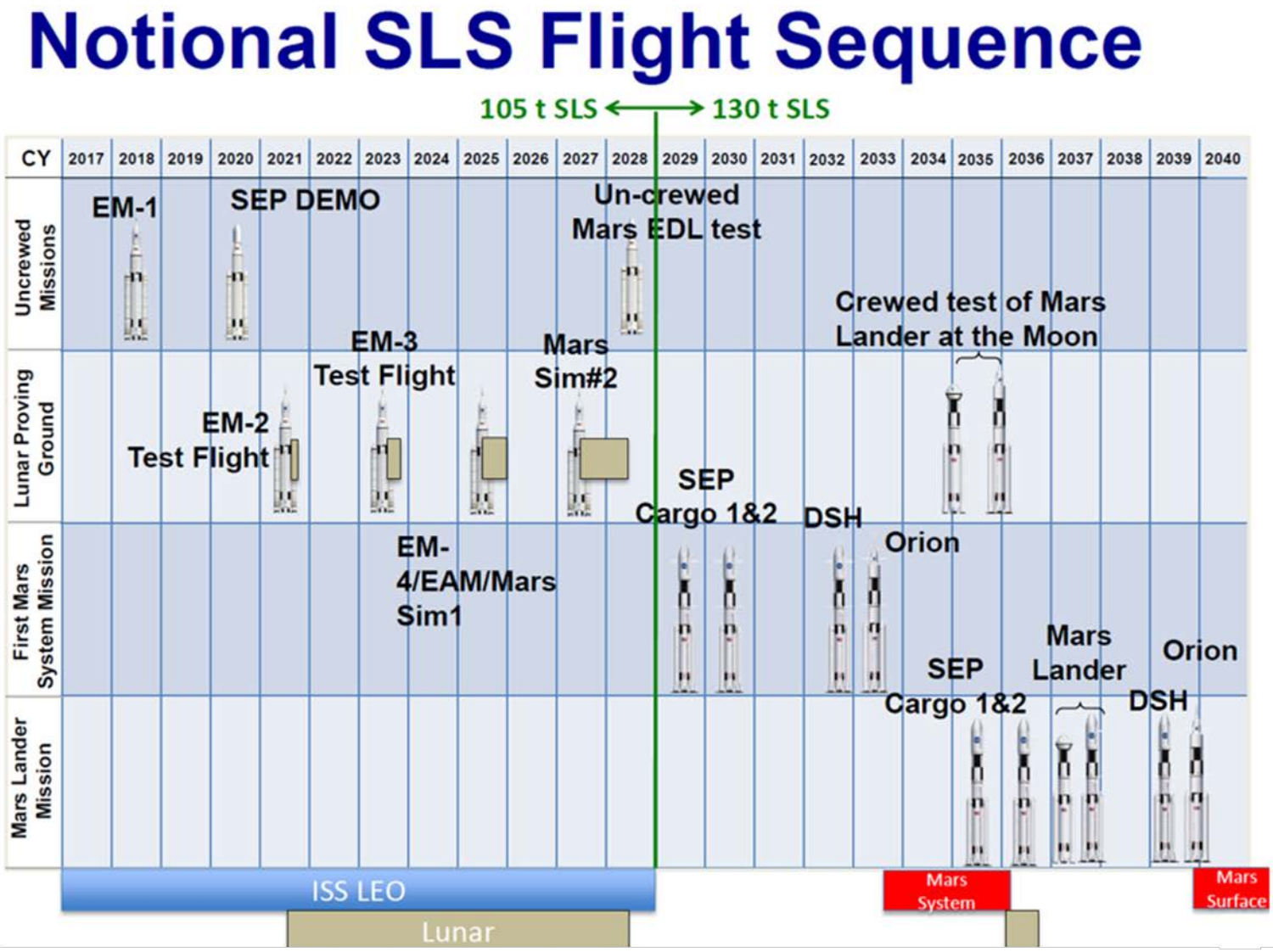
H2M Minimal Architecture (2/2)



The H2M Minimal Architecture involves enough launches to provide ample opportunities for secondary smallsat payloads.

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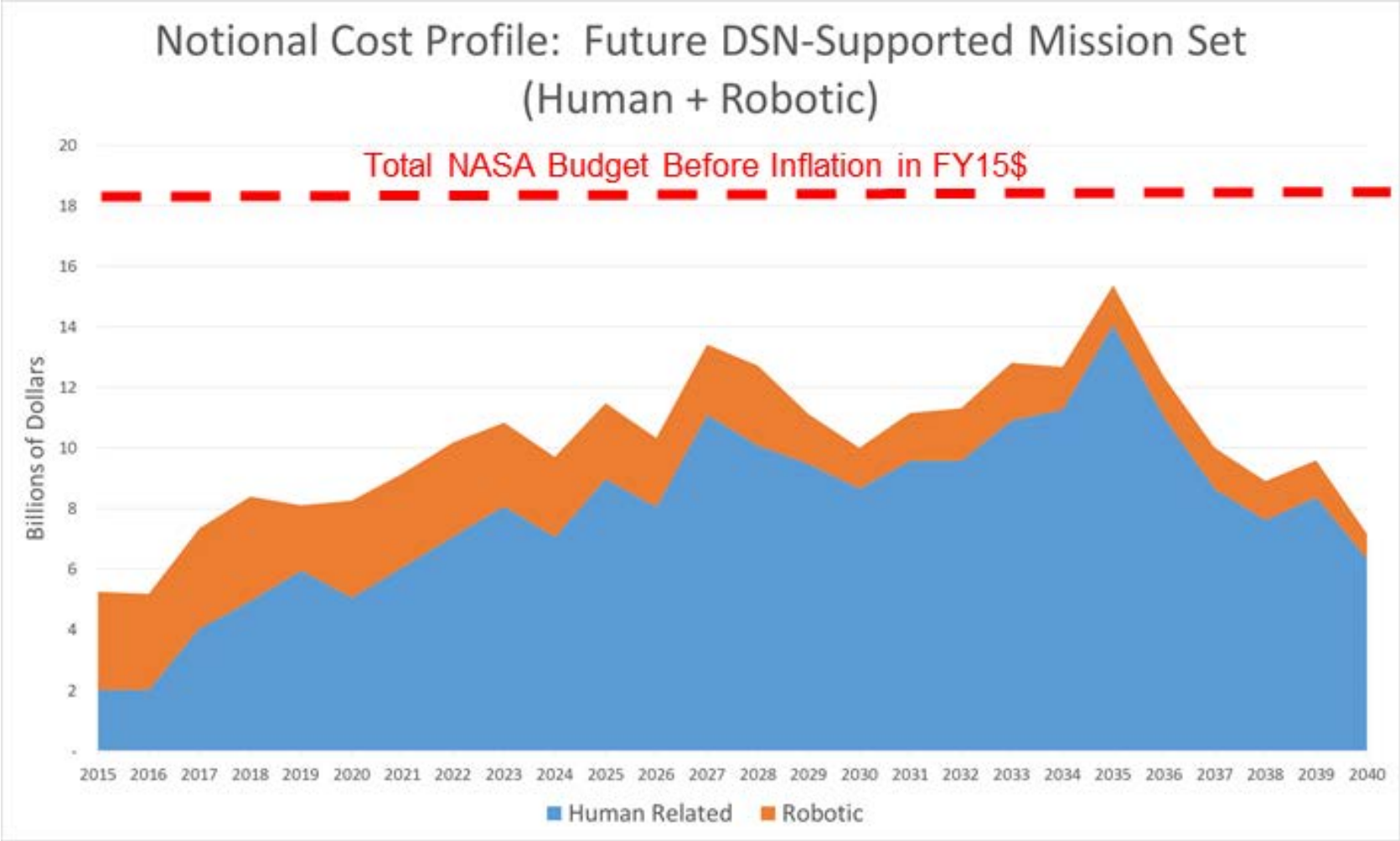
H2M Budget Implications



Even a minimal H2M architecture would strain NASA's budget if it only grows with inflation. Other NASA endeavors would likely be "squeezed."

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Innovation in Small Satellite Technology

Increasing effort is being placed on advancing small satellite technology, paving the way for greater deep space reliance on smallsats in the future.

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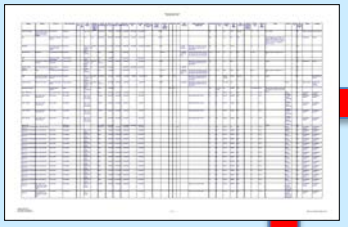
Mission Set Analysis Process

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

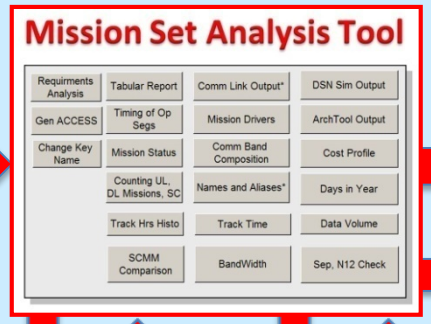
Space Communications Mission Model (SCMM)



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

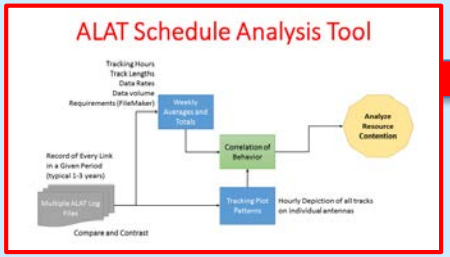
(MSAT)

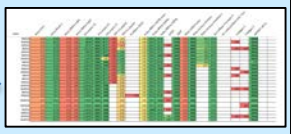
Detailed Mission & Spacecraft Characteristics; RF Link Analyses

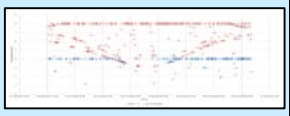


(ASAT)

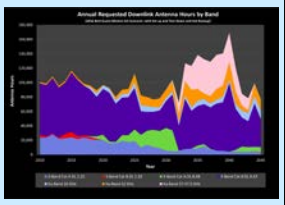
Analyzes simulated schedule output from ALAT to understand underlying resource contention drivers



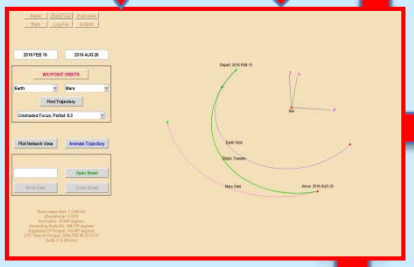




Aggregate Mission Set Trends & Requirements



RF Link Requirements & Associated Spacecraft Telecom & Tracking Requirement Data

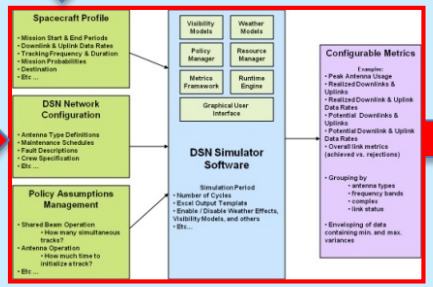


Orbital Trajectory Inference Engine (OTIE)

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

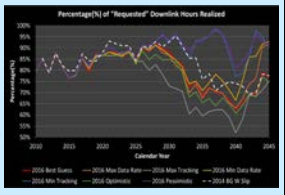
Strategic Optical Link Tool (SOLT)

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

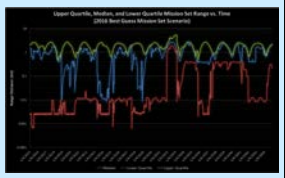


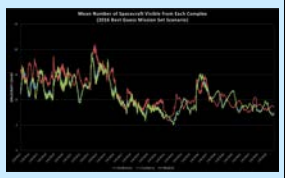
Architecture Loading Analysis Tool (ALAT)

Antenna/Telescope Architecture Loading Simulations



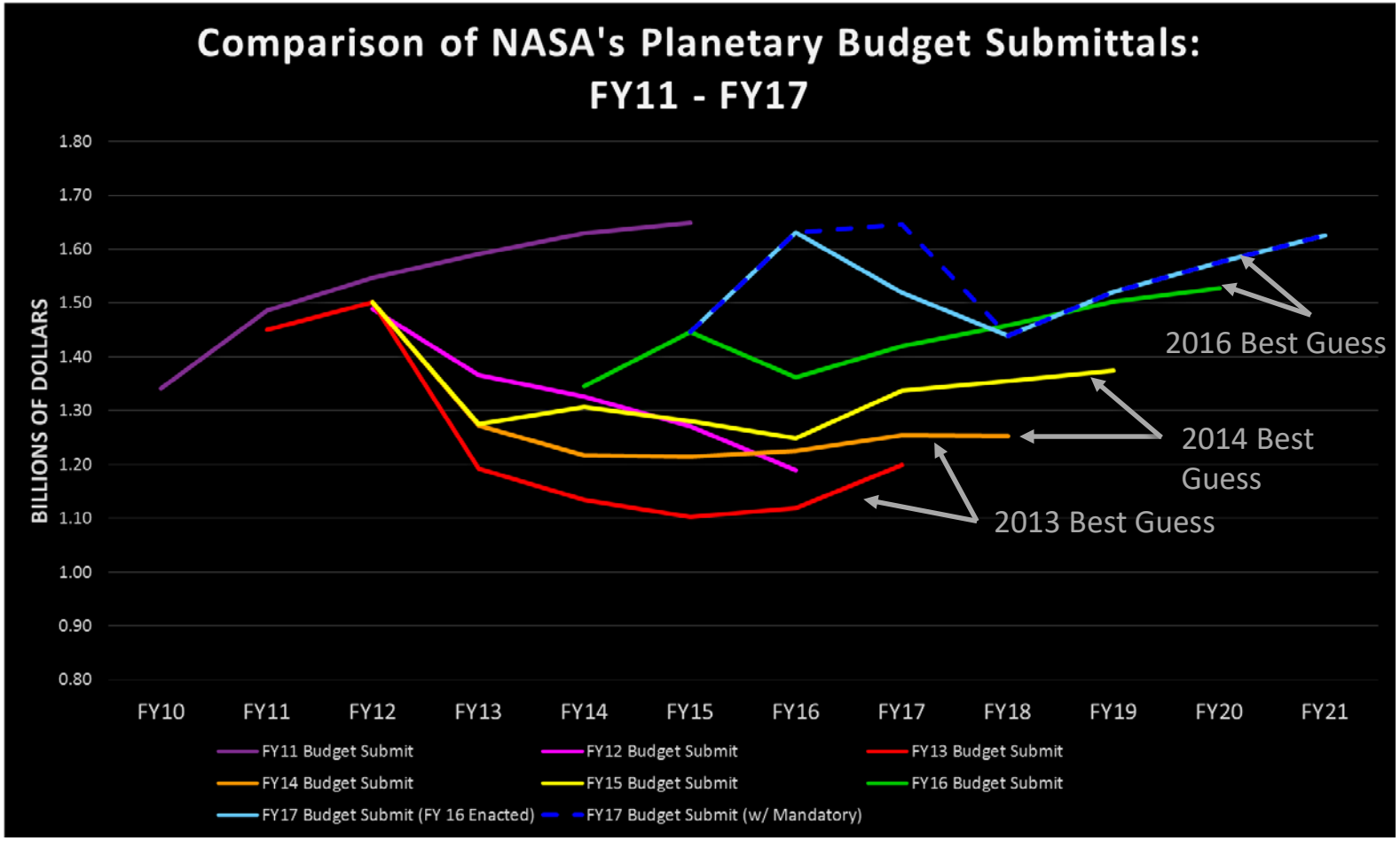
Architecture Loading & Data Traffic Implications





Aggregate & Individual Mission Geometry as a Function of Time

Definition of Mission Set Scenarios (1/7)



The nature of the "Best Guess" mission set scenario for a given year is at least partially correlated to the 5-year budget run out and the sorts of pre-formulation activities that it supports.

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Definition of Mission Set Scenarios (2/7)

Scenario	Description	Key Attributes
2013 Best Guess	Based on best guess in 2013 as to what will actually fly between 2013 and 2040.	Aligns with 4-30-13 AMPM and SCMM. Mission-candidate assumptions based on Decadal Survey priorities, NASA roadmaps, prior competition results, available budget, etc. 2016 ExoMars support, but no support for ESA's 2018 Mars mission. Slow MSR assumed. Includes Mars ESA-L2. EM-1 and EM-2 involve DRO rendezvous missions. ARM occurs with EM-3 involving a rendezvous with the asteroid, and EM-4 & EM-5 involve DSH follow-up missions to the same asteroid. EM-6 goes out to a NEO. Subsequent human Mars missions both involve Mars landings. No cubesat missions included.
2014 Best Guess	Mission set based on best guess in 2014 as to what will actually fly between 2014 and 2040.	Aligns with 6-13-14 AMPM and SCMM. Fewer flagship and New Frontiers opportunities, slightly more Discovery opportunities, and substantially more SMEX and Explorer opportunities. Rather than carrying Europa Clipper as a New Frontiers mission, Europa Clipper is carried as a flagship mission that launches via SLS. EM-2 becomes a test of the interplanetary injection stage for SLS and affords Europa Clipper its SLS launch. Every SLS launch other than EM-2 is assumed to deploy 11 6-U cubesats and every planetary mission launch (including Europa Clipper) is assumed to carry one or more cubesats to its destination or to targets in route. Ditto for Solar Probe Plus. Cubesats also play a role in many of the SMEX and Explorer opportunities. And, Mars-31 provides the ERV for MSR, with ESA-L2 becoming part of IXO. Human Mars missions same as 2013 Best Guess.

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Definition of Mission Set Scenarios (3/7)

Scenario	Description	Key Attributes
2014 Best Guess with Slips	2014 Best Guess mission set with several missions slipped in accordance with new data in the last quarter of the fiscal year.	EM-1 and all of its 11 secondary payloads slip from a 12/17 launch to 11/18. Resource Prospector Mission slips from 6/2019 to 5/2020. Solar Orbiter Collaboration slips from 7/2017 to 9/2018.
2016 Best Guess	Mission set based on this year's best guess as to what will actually fly between now and 2045.	No new AMPM released during FY'15. 2016 Best Guess extrapolates from 6-13-14 AMPM and FY'15 SCMMs. Relative to the 2014 Best Guess, all Discovery launch dates slip one year consistent with Discovery 13's launch date shift and incorporate latest Discovery mission concepts. Europa subsumes the New Frontiers-4 mission and launches on an SLS testing the new Energetic Upper Stage in 2022. Other new Frontiers opportunities incorporate the latest "Outer Planet and Ocean Worlds" concepts. WFIRST SEL2 support still assumed. EM-2 slips to 2023. EM-1 deploys 13 6-U cubesats from its upper stage, of which 9 require DSN support. Cubesat concepts and destinations for subsequent EM-n missions (that carry humans onboard) mirror those for EM-1's, except that 10 cubesats require support. EM-2 takes astronauts to a lunar DRO. EM-3 through EM-5 are involved in progressively longer ARCM missions that also test out the Deep Space Habitat used in subsequent H2M Phobos and Mars missions. (Continued Next Page)

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Definition of Mission Set Scenarios (4/7)

Scenario	Description	Key Attributes
2016 Best Guess (Continued…)	Mission set based on this year's best guess as to what will actually fly between now and 2045.	The human mission sequence after EM-5 mirrors that of the H2M minimal architecture. Dedicated Mars Areostationary Relays are also assumed for the early 2030s, with their launches each supporting 11 Mars-bound smallsats – including Mars/Phobos/Deimos flybys, orbiters, and hedgehog & micro-drop landers. Other H2M SLS launches that carry crew also entail cubesats with similar mission/destination assumptions. The Uncrewed Mars EDL Test in 2028 is assumed to have a smallsat launch with it. SLS cargo launches are assumed to be too mass-constrained to support cubesat deployments. Other Mars robotic mission changes from 2014 Best Guess with Slips include: InSight and MarCO's slip to a 2018 launch (in the Best Guess), a Mars 2022 Science Orbiter that also provides relay coverage, an SLS-enabled Mars Sample Return Mission that would get back to Earth in 2027, a JAXA Mars Phobos-Deimos Sample Return mission, a Mars Deep Drill mission, a second ISRO Mars Orbiter Mission (MOM-2), and an Emirates Mars Mission. ESA's 2018 ExoMars Rover is also included, but assumed to slip to a 2020 launch. One smallsat is assumed to launch with the Mars 2020 Rover and with the potential Mars Sample Return mission. (Continued Next Page)

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Definition of Mission Set Scenarios (5/7)

Scenario	Description	Key Attributes
2016 Best Guess (Continued…)	Mission set based on this year's best guess as to what will actually fly between now and 2045.	Other robotic mission changes include slipping KARI's KPLO to 2019 and eliminating any cubesats on it, adding JAXA's Smart Lander for Investigating Moon (SLIM) mission, ensuring that all Venus-bound missions carry a cubesat, adding ESA's AIM and NASA's DART missions, and adding a "low-cost" robotic interstellar mission in the late 2030s (called out as a priority in NASA's HS&T roadmap).
2016 Optimistic	2016 Best Guess mission set plus numerous additional missions and more ambitious schedules.	Includes almost all 2016 Best Guess missions plus DSN support for all upcoming Astro SMEX and HELIO SMEX mission opportunities appearing in the AMPM. EM-2's launch occurs in 2021 rather than 2023, enabling EM-3 to occur in 2024, EM-4 in 2025, EM-5 in 2027, and an additional EM-6 out to an asteroid to occur in 2029. All of these EM-n missions beyond EM-1 deploy 11 cubesats requiring DSN support with assumed destinations similar to those of EM-1's. Meanwhile, the H2M minimal architecture unfolds as it did in the 2016 Best Guess mission set scenario, with identical cubesat/smallsat assumptions. A Google Lunar X-Prize mission requires support in 2017. After the Resource Prospector Mission in 2020, starting in 2026, commercial lunar resource recovery efforts begin with a Lunar Prospector orbiter/relay and a Resource Recovery lander/rover mission occurring every 4 years through 2042. Rather than a "low cost" interstellar mission, a more capable and ambitious robotic interstellar mission occurs around 2037.

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Definition of Mission Set Scenarios (6/7)

Scenario	Description	Key Attributes
2016 Pessimistic	2016 Best Guess mission set minus numerous missions. Also, less ambitious human exploration mission schedule.	Relative to the 2016 Best Guess, only ~50% of the astrophysics flagship missions come to fruition or require DSN support. Only ~25% of the astrophysics Explorer and ~66% of the heliophysics Explorer missions need DSN support. Only ~66% of the astrophysics and ~50% of the heliophysics SMEX missions need DSN support. No ARRM. The EM-n missions occur as shown in the 2016 Best Guess, but don't involve any study of a returned asteroid boulder. Subsequent Human Mars missions forgo pre-placement of Areostationary Relays. The Uncrewed Mars EDL Test in 2028 is eliminated. The crewed Mars Lander Lunar Test in 2035 is eliminated. A Mars Landing Rehersal Mission is added circa 2039. The Mars Short Stay Mission is deferred to 2045. The Mars Long Stay Mission is deferred beyond the study's 2045 time horizon. DSN-supported cubesat secondary payloads accompanying the crewed SLS launches are significantly reduced (7 vs. 10 on the EM-n's). All foreign mission supports beyond Mars 2016 ExoMars/TGO are eliminated. All cubesats accompanying Venus-bound missions (with the exception of a mission in 2042) are eliminated.
2016 Max. Data Rate	2016 Best Guess mission set with candidates for competitively-bid missions changed to ones that maximize downlink rates.	Candidates for Explorer, Discovery, and New Frontiers mission opportunities changed to ones that maximize downlink rates. Similarly, candidates for unassigned astrophysics flagship missions changed to ones that maximize downlink rates.

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Definition of Mission Set Scenarios (7/7)

Scenario	Description	Key Attributes
2016 Min. Data Rate	2016 Best Guess mission set with candidates for competitively-bid missions changed to ones that minimize downlink rates.	Candidates for Explorer, Discovery, and New Frontiers mission opportunities changed to ones that minimize downlink rates. Similarly, candidates for unassigned astrophysics flagship missions changed to ones that minimize downlink rates.
2016 Max. Tracking	2016 Optimistic mission set with candidates for competitively-bid missions changed to ones that maximize downlink tracking-hour requirements.	Candidates for Explorer, Discovery, and New Frontiers mission opportunities changed to ones that maximize downlink tracking-hour requirements. Similarly, candidates for unassigned astrophysics flagship missions changed to ones that maximize tracking-hour requirements.
2016 Min. Tracking	2016 Pessimistic mission set with candidates for competitively-bid missions changed to ones that minimize downlink tracking-hour requirements.	Candidates for Explorer, Discovery, and New Frontiers mission opportunities changed to ones that minimize downlink tracking-hour requirements. Similarly, candidates for unassigned astrophysics flagship missions changed to ones that minimize tracking-hour requirements.

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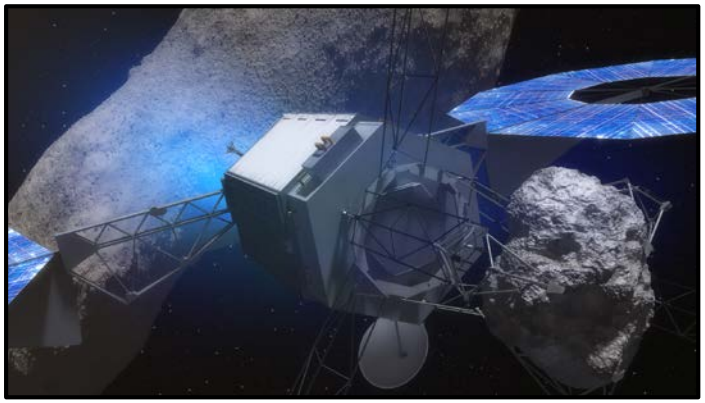
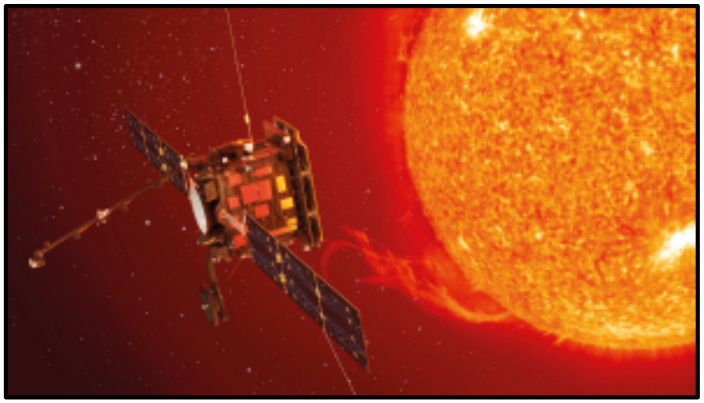
Key Items Not In Scenarios (1/2)

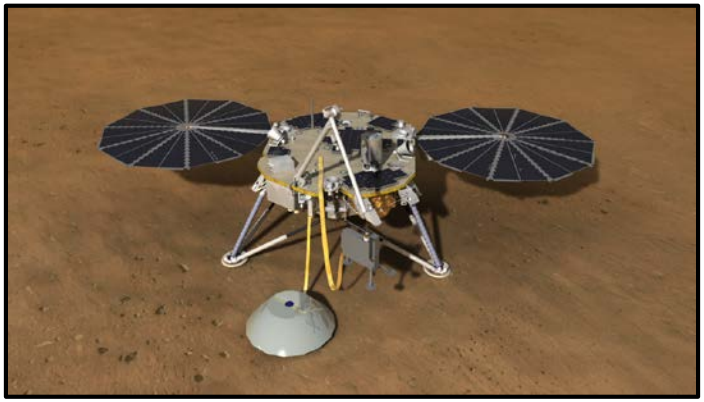


Deferral of ARRM from 2021 to 2022.



Deferral of Solar Orbiter from September to October 2018.

Deferral of ARCM from 2025 to 2026.



Rescheduled InSight and MarCO are only in 2016 Best Guess.

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Key Items Not In Scenarios (2/2)

Space-X Red Dragon Flights

JAXA's UZUME Missions to Lava Tubes

Korean Lunar Exploration Post-KPLO

- Space-X's Red Dragon flights could occur every Mars opportunity starting in 2018.
- UZUME 1 and 2 could occur at the Moon in 2020 & 2025 with UZUME 3 occurring at Mars in 2030.
- KARI could undertake orbiter, lander, and rover missions in 2020-2025 that rely on domestic launch vehicles.
  - U.S. support beyond KPLO currently precluded by nuclear non-proliferation constraints.

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Other Key Assumptions (1/3)

- Antenna-hour plots and loading simulations for the 2016 mission set analyses are run with the following assumptions:
  - 4-MSPA capability for Mars missions. (4-MSPA with OMSPA to be subsequently examined as a variation.)
  - DSN 34m HEF closures with DSS-45 closed on November 1, 2016, DSS-15 closed on November 1, 2017, and DSS-65 closed on November 1, 2019.
  - 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 1, 2017.
  - DSS-25's current 350W 34 GHz uplink is upgraded to 1 kW on October 1, 2018.
  - DSS-56 goes up October 1, 2019 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 October 1, 2019.
  - DSS-54 goes down January 1, 2020 and comes back up on January 1, 2022.

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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-55 receives 1 kW 34 GHz uplink capability on October 1, 2020.
- 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, 2022 with 80 kW X-band uplink, X-band downlink, and Ka 32 GHz downlink.
- DSS-23 comes up on October 1, 2024 with 80 kW X-band uplink, X-band downlink, and Ka 32 GHz downlink.
- No new frequency bands are assumed (e.g., 22 GHz up, 40 GHz up, 37-38 GHz down, optical). (Optical Areostationary Relays to be subsequently examined as a variation.)
- All lunar vicinity HSF missions are assumed to use S & Ka 26 GHz after EM-2. All HSF missions to NEAs and Mars are assumed to use Cat B X-band & Ka 32 GHz.

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Other Key Assumptions (3/3)

- 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.

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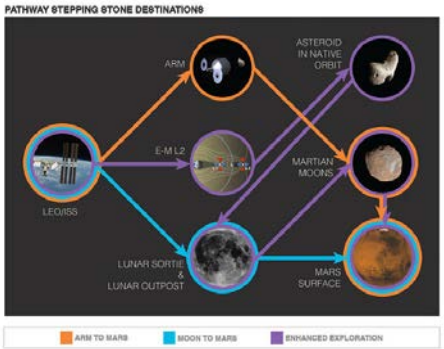
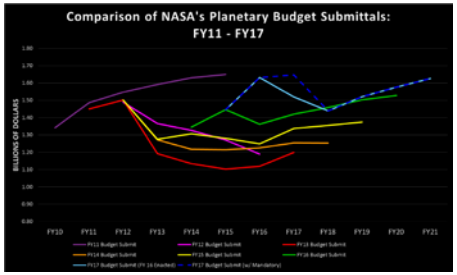
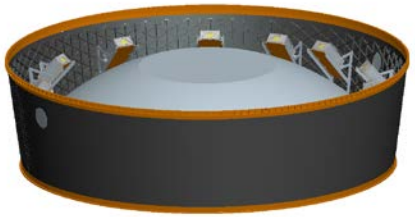
Interpretation of Results

- Perform "sanity" checks.
  - Compare analysis results to historical trends and past projections.
  - Explore impacts of different future scenarios.
  - Perform sensitivity analyses.
- Consider context.
  - Fiscal environment
  - Policy environment
  - Technology issues or developments
  - Other emerging developments
- Make recommendations.







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.

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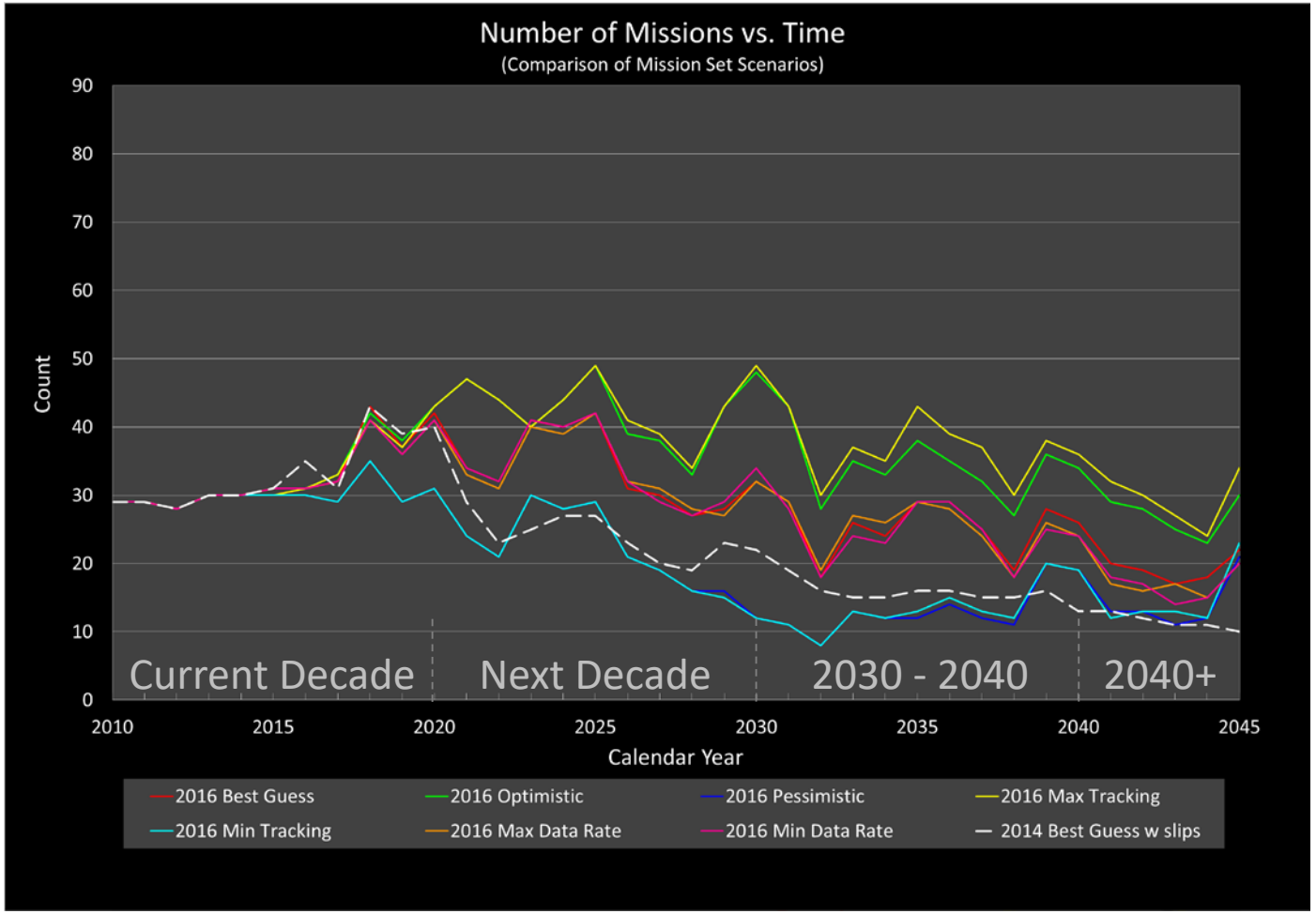
Pre-decisional – for Planning and Discussion Purposes Only

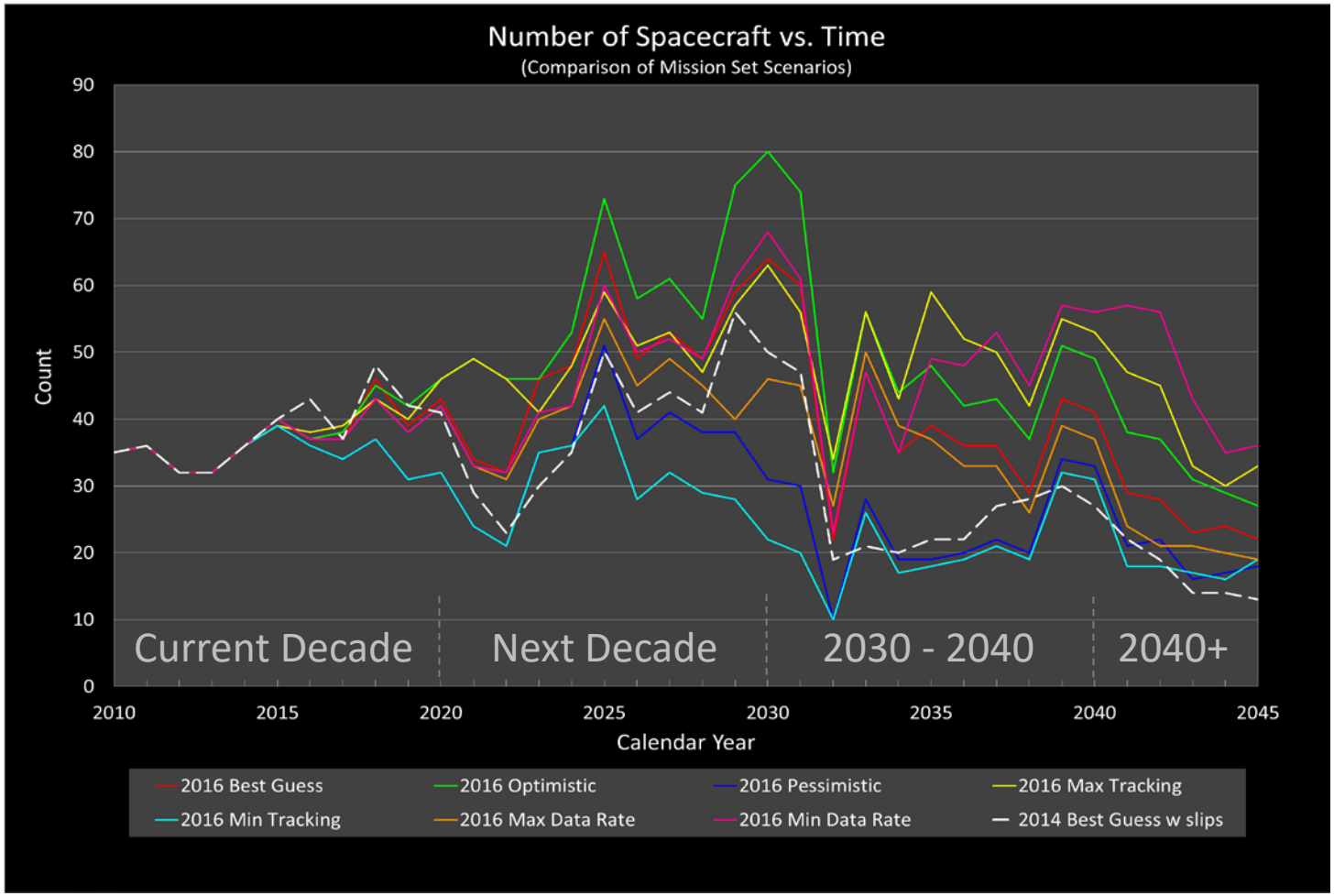
Anticipated Customer Base (1/5)



NASA's pivot toward human Mars exploration and more cubesat secondary payload launch opportunities are contributing to growth in out-year mission numbers relative to the 2014 projection.

Pre-decisional – for Planning and Discussion Purposes Only

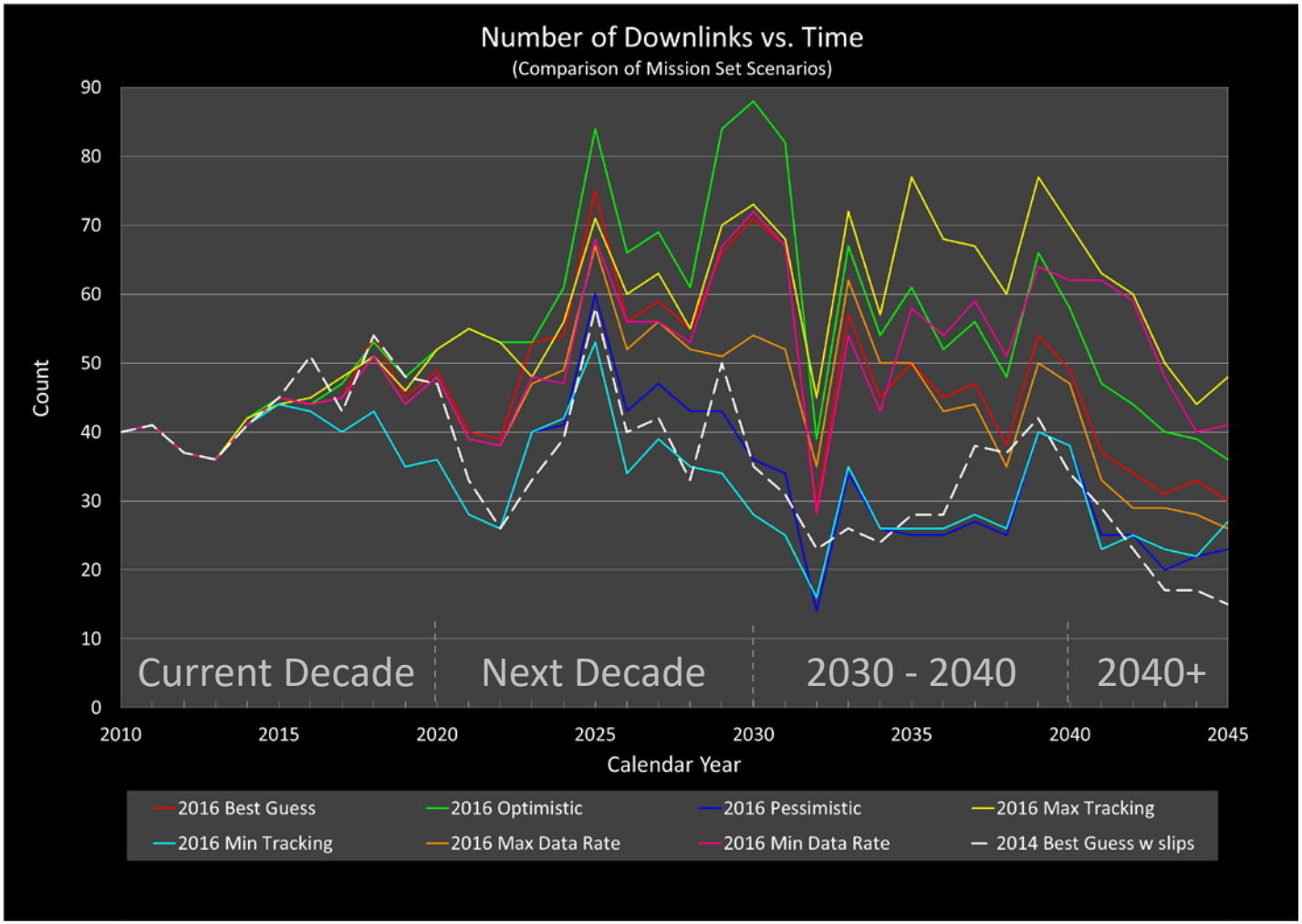
Anticipated Customer Base (2/5)



With mission numbers increasing, and more of them involving multiple spacecraft, spacecraft numbers increase substantially -- ~62% by 2025 in the 2016 "Best Guess" mission set scenario.

Pre-decisional – for Planning and Discussion Purposes Only

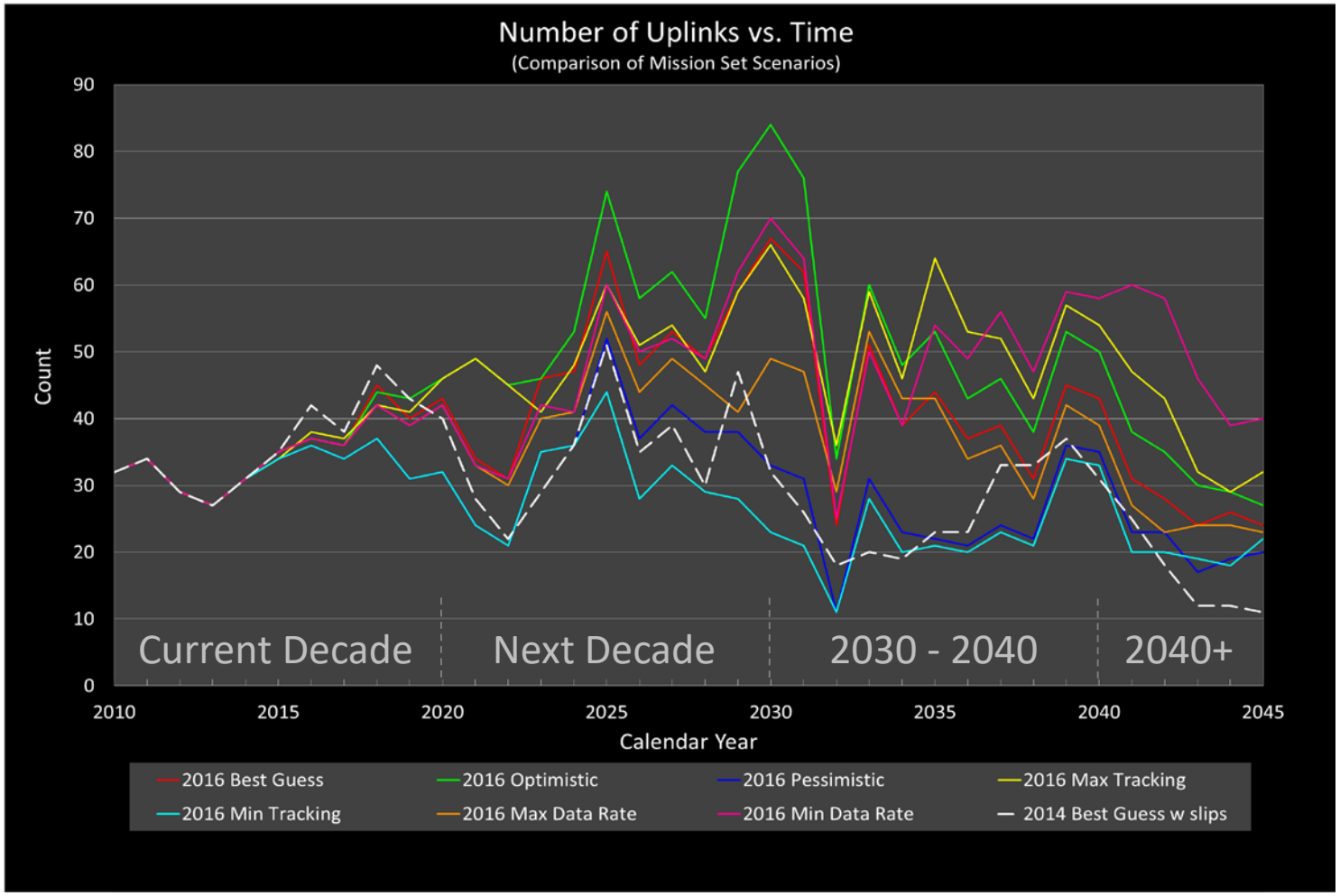
Anticipated Customer Base (3/5)



Since some spacecraft use multiple downlinks, the number of supported downlinks is roughly 15% greater than the number of spacecraft.

Pre-decisional – for Planning and Discussion Purposes Only

Anticipated Customer Base (4/5)



Uplink numbers grow ~75% by 2025 in the 2016 "Best Guess" mission set scenario.

Pre-decisional – for Planning and Discussion Purposes Only

Anticipated Customer Base (5/5)

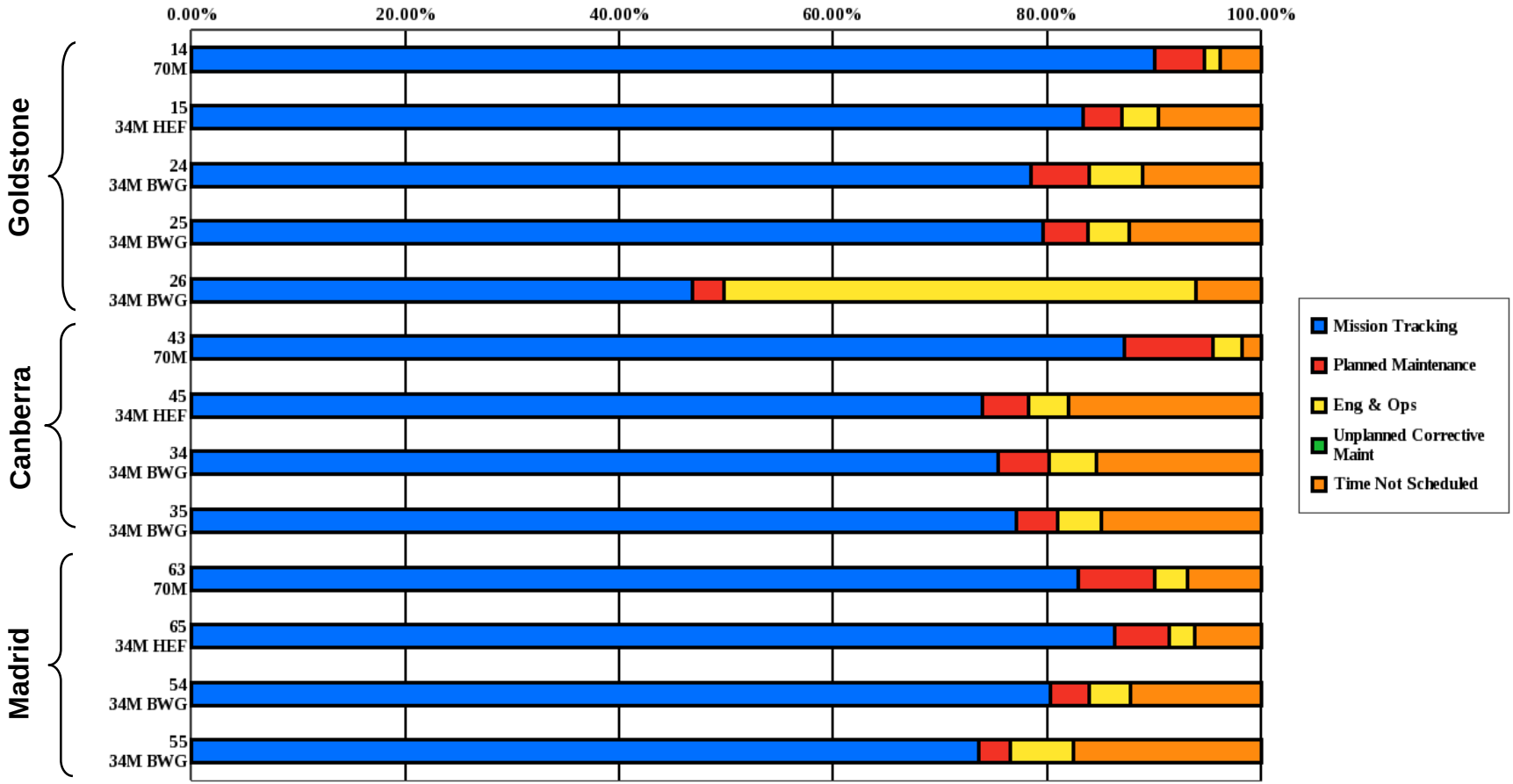
<u>Takeaways</u>:

- *Uplink and downlink demand is projected to increase significantly relative to today's.*
- *Much of this increase will occur within the next 10 years.*

Pre-decisional – for Planning and Discussion Purposes Only

Antenna-Hour Demand (1/X)

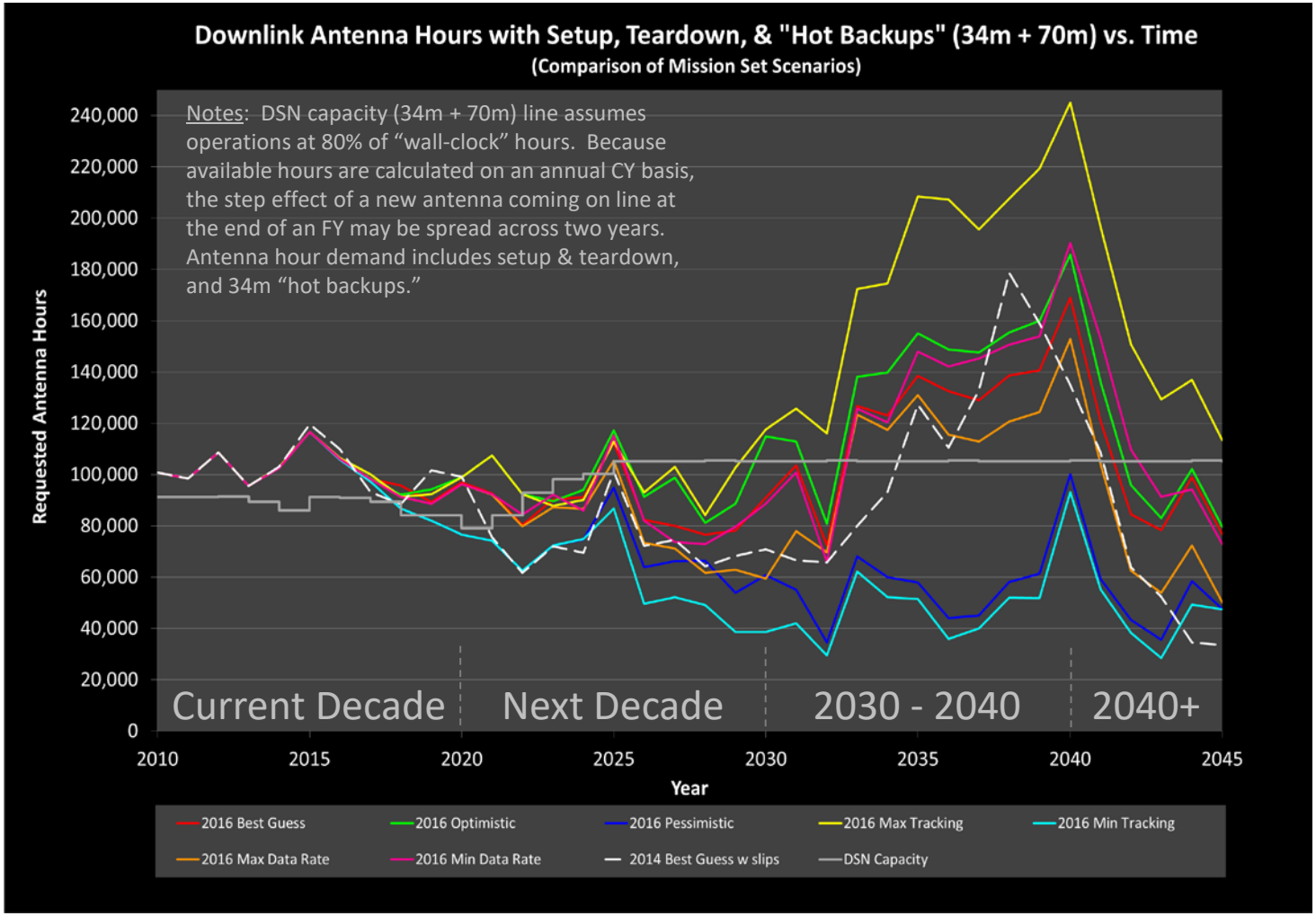
Example: June 2015 Antenna Utilization



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

Pre-decisional – for Planning and Discussion Purposes Only

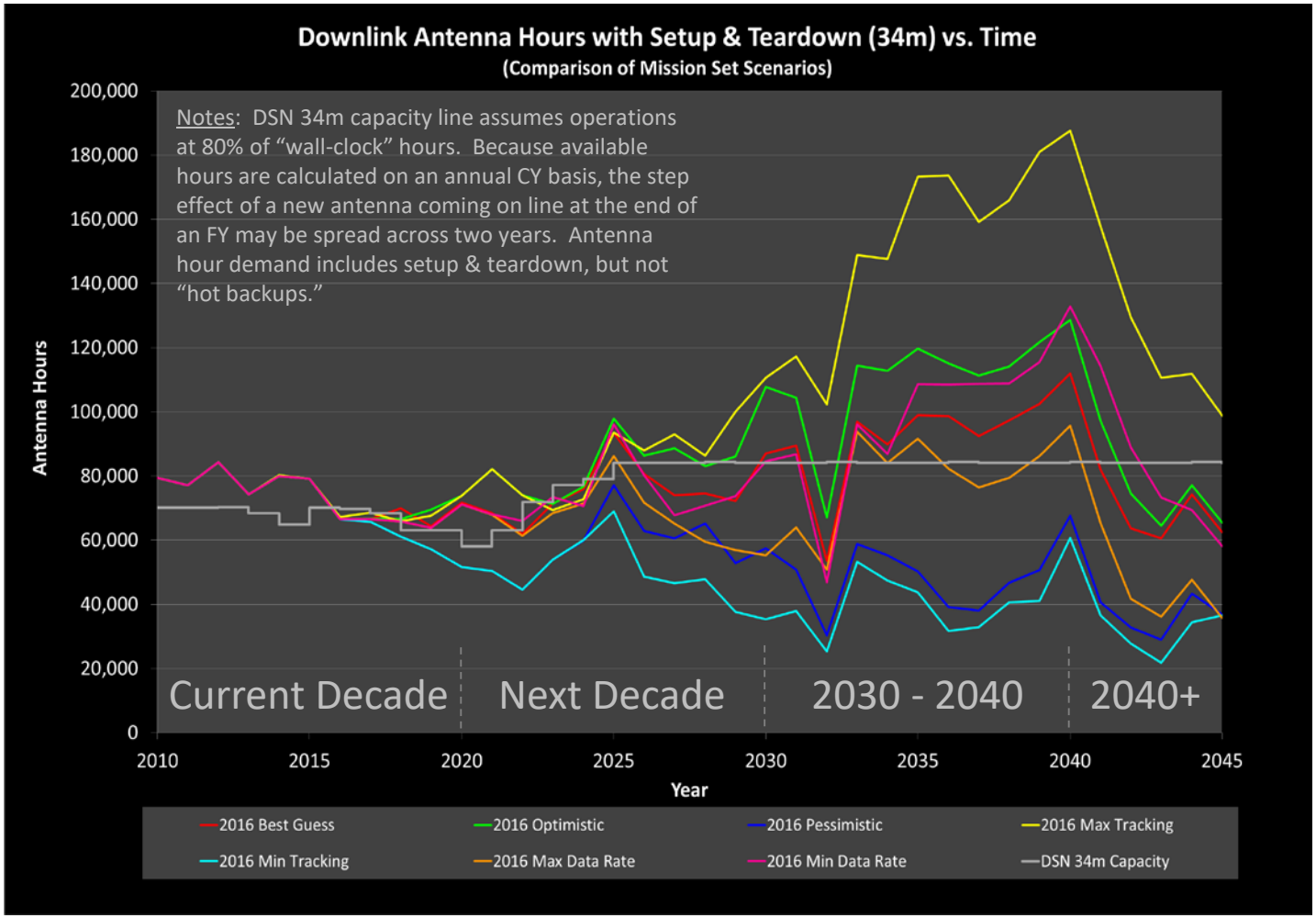
Antenna-Hour Demand (1/7)



The 34m + 70m view obfuscates the fact that the 70m and 34m antennas are not always interchangeable for high G/T and Ka-band requirements.

Pre-decisional – for Planning and Discussion Purposes Only

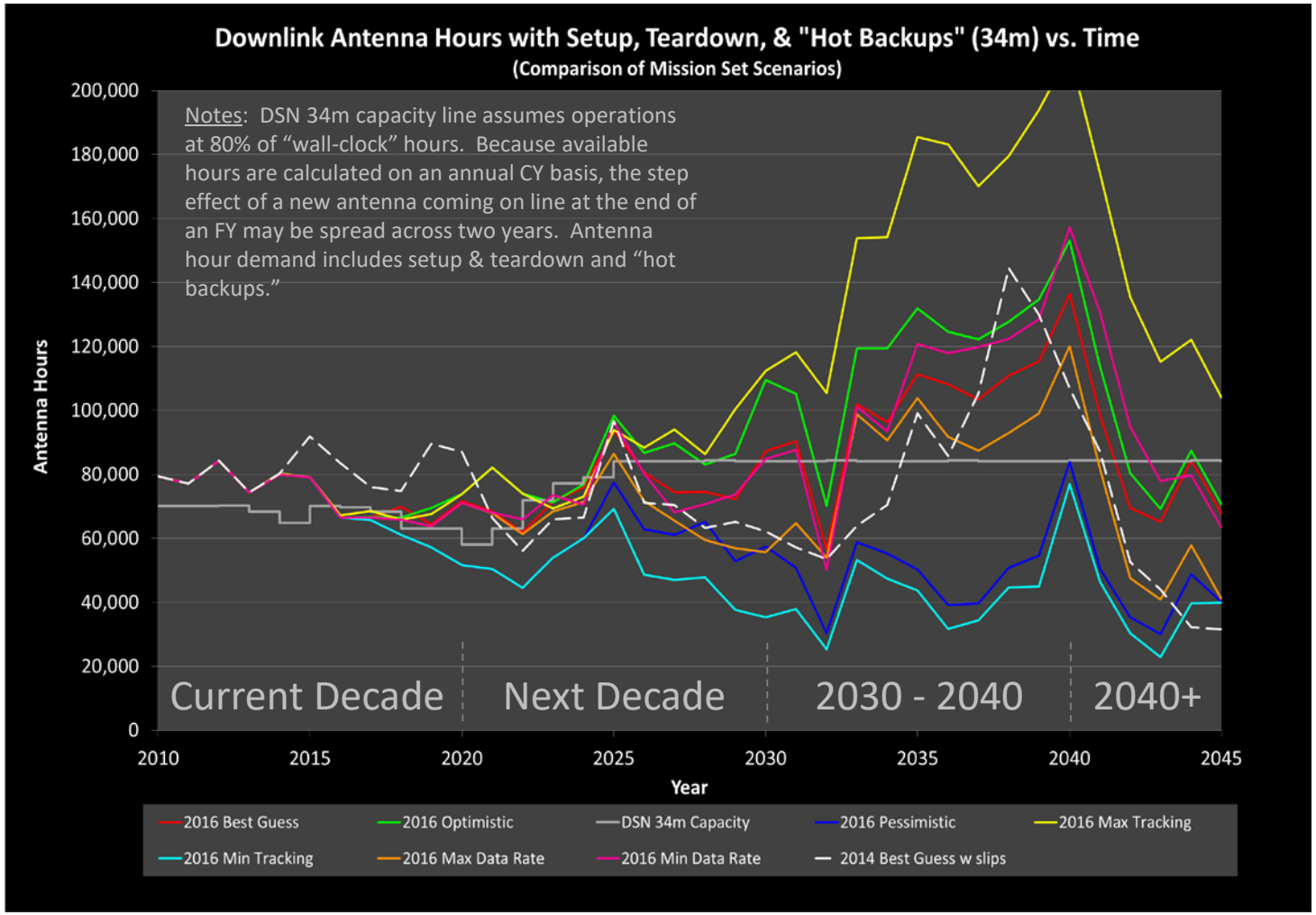
Antenna-Hour Demand (2/7)



Before accounting for "hot backup" requirements, demand already exceeds supply in the near-term and, even with the DAEP buildout, significantly exceeds supply during the human Mars exploration era.

Predecisional – for Planning and Discussion Purposes Only

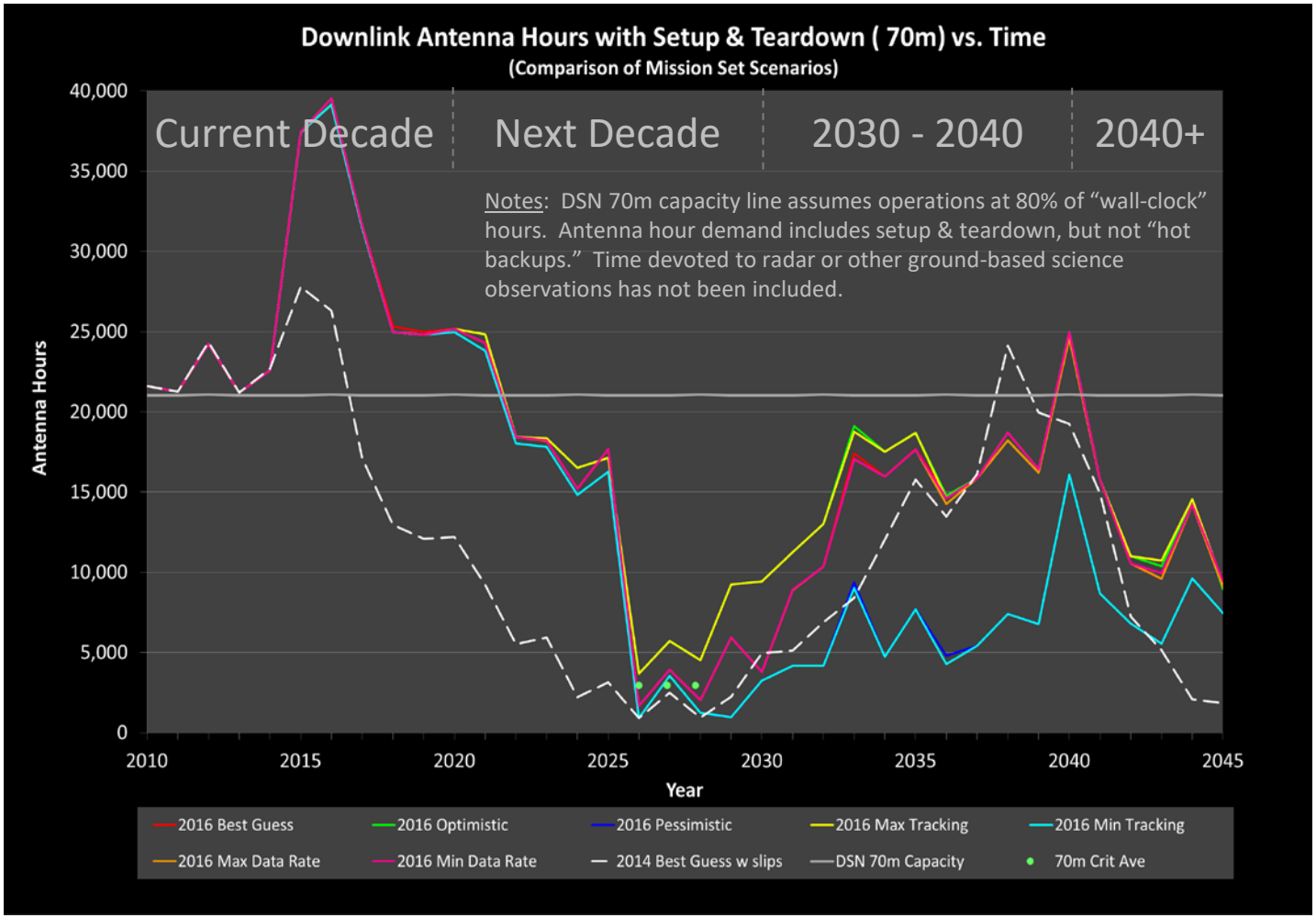
Antenna-Hour Demand (3/7)



Allowing for "hot backups" exacerbates the "human Mars Exploration era" shortfall. The 2014 "Best Guess w/Slips" projection is shown for comparison.

Pre-decisional – for Planning and Discussion Purposes Only

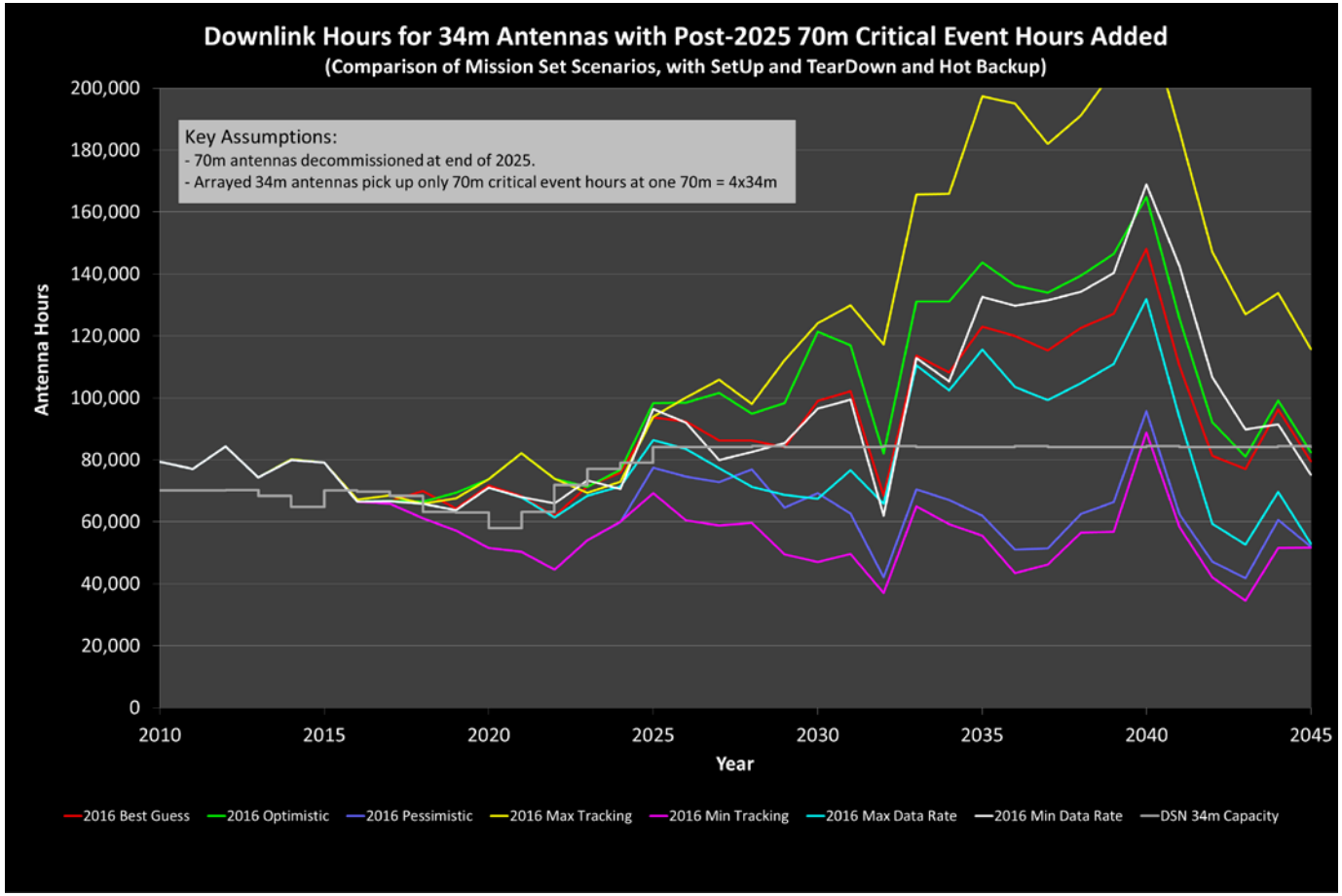
Antenna-Hour Demand (4/7)



A current capacity shortage exists. Surplus capacity is likely next decade due to SMD's "single 34m only for routine support" policy. Mission-critical events drive remaining demand. Full-capacity demand returns in the 2030's due to human Mars exploration.

Pre-decisional – for Planning and Discussion Purposes Only

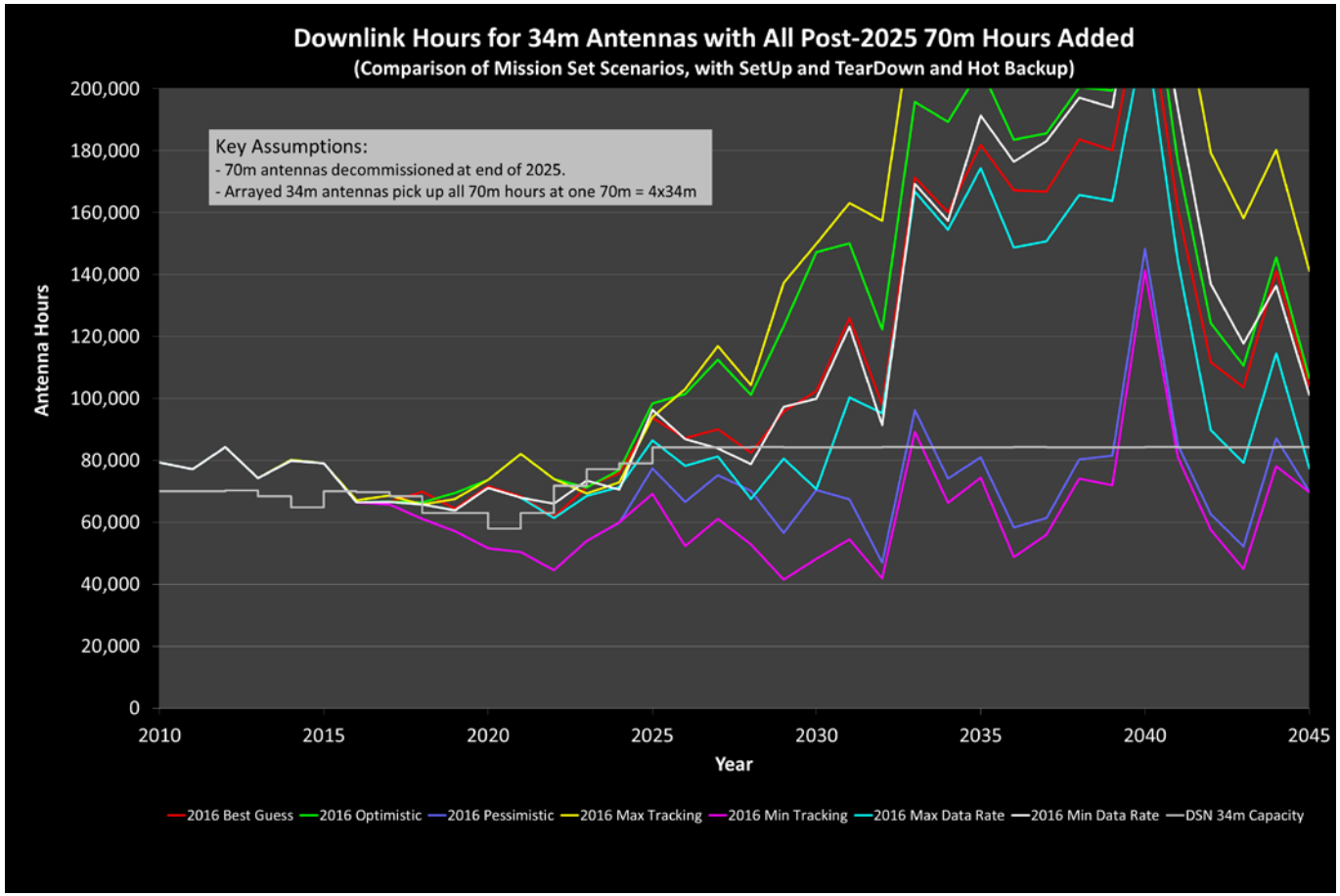
Antenna-Hour Demand (5/7)



Using arrayed 34m antennas to takeover the critical-event load from the 70m antennas on an ongoing basis significantly exacerbates 34m oversubscription in the post-2025 era, despite completion of the DAEP buildout.

Pre-decisional – for Planning and Discussion Purposes Only

Antenna-Hour Demand (6/7)



Using arrayed 34m antennas post-2025 to takeover the entire load from the 70m antennas is largely untenable without additional antennas. Much of the 70m X-band demand in this timeframe is human exploration driven and may be needed whether Ka-band or optical is in use for very high rate data return.

Pre-decisional – for Planning and Discussion Purposes Only

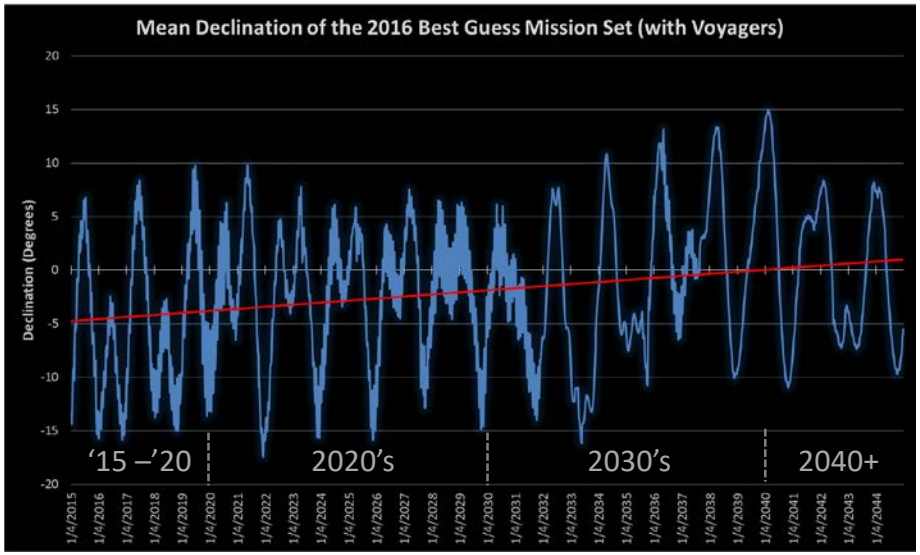
Antenna-Hour Demand (7/7)

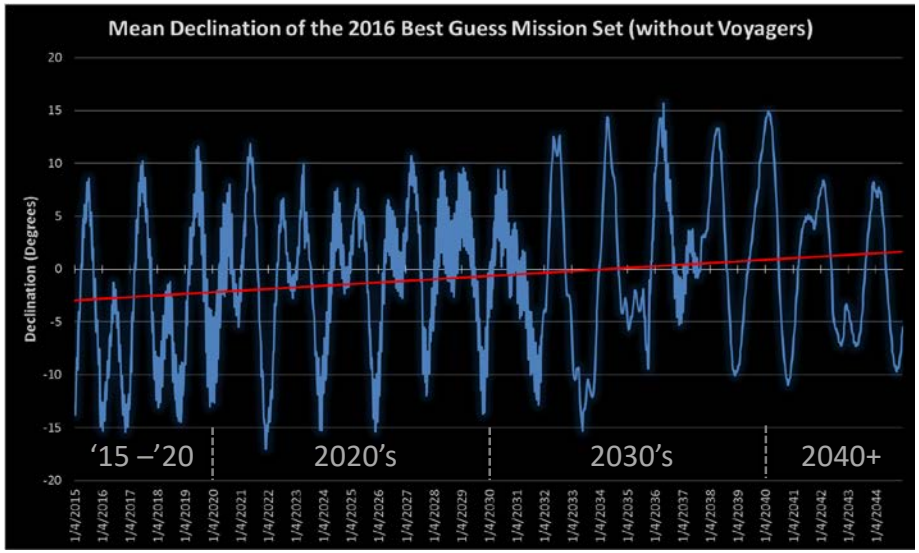
Takeaways:

- *Antenna loading estimates need to account for the actual track time PLUS setup and tear-down time and any requirements for "hot backup" antennas.*
  - *Even then, care must be taken to recognize that the DSN antennas are not all identical. Different antennas have different frequency capabilities which will cause them to load up differently.*
- *The DSN is already operating at capacity and is projected to continue doing so for most of the next decade.*
  - *Mission customer "requirements" are being downsized during the RAP process.*
  - *The DAEP buildout is essential to keep pace with this "downsized" demand.*
- *Post-DAEP DSN assets are insufficient for meeting the demands of the human Mars exploration era.*
  - *Critical event support and human Mars exploration support require 70m-equivalent capability. Attempting to provide such support post-2025 via arrayed 34m antennas severely exacerbates the 34m insufficiency discussed above.*

Pre-decisional – for Planning and Discussion Purposes Only

Antenna Asset Visibilities (1/6)

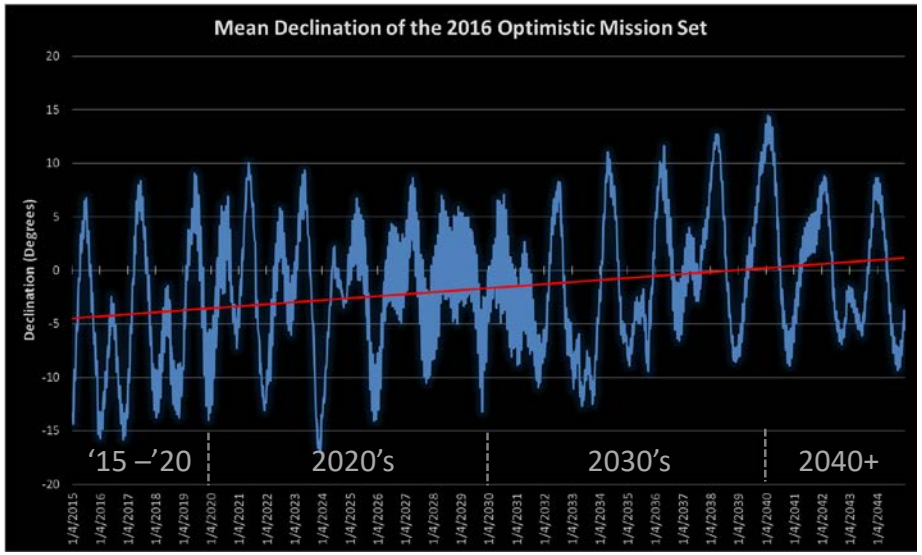


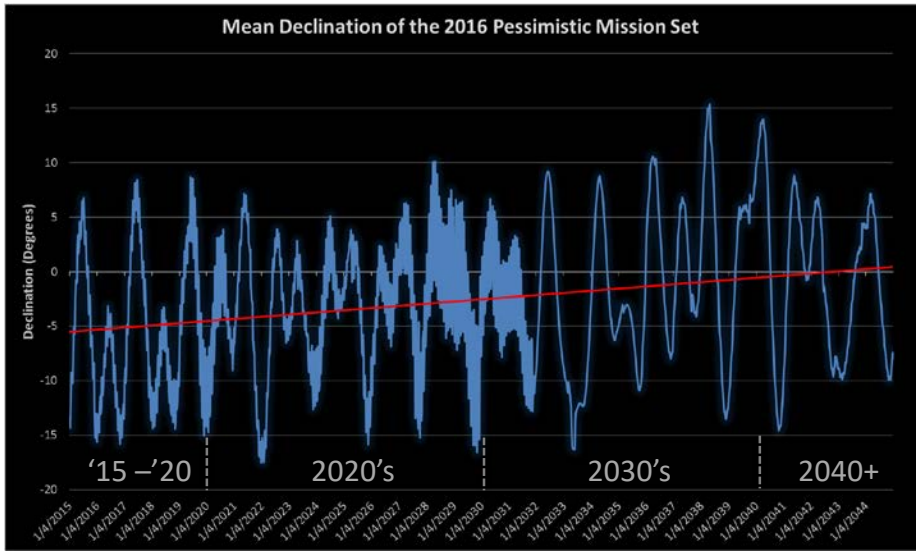


- Antenna visibilities change over time and also impact how efficiently each antenna can be loaded.
- 2016 Best Guess Mission Set exhibits a southern declination bias into the 2030s.
- Even without Voyager 2 (which can only be seen from Canberra), a southern declination bias persists through the next decade.

Pre-decisional – for Planning and Discussion Purposes Only

Antenna Asset Visibilities (2/6)



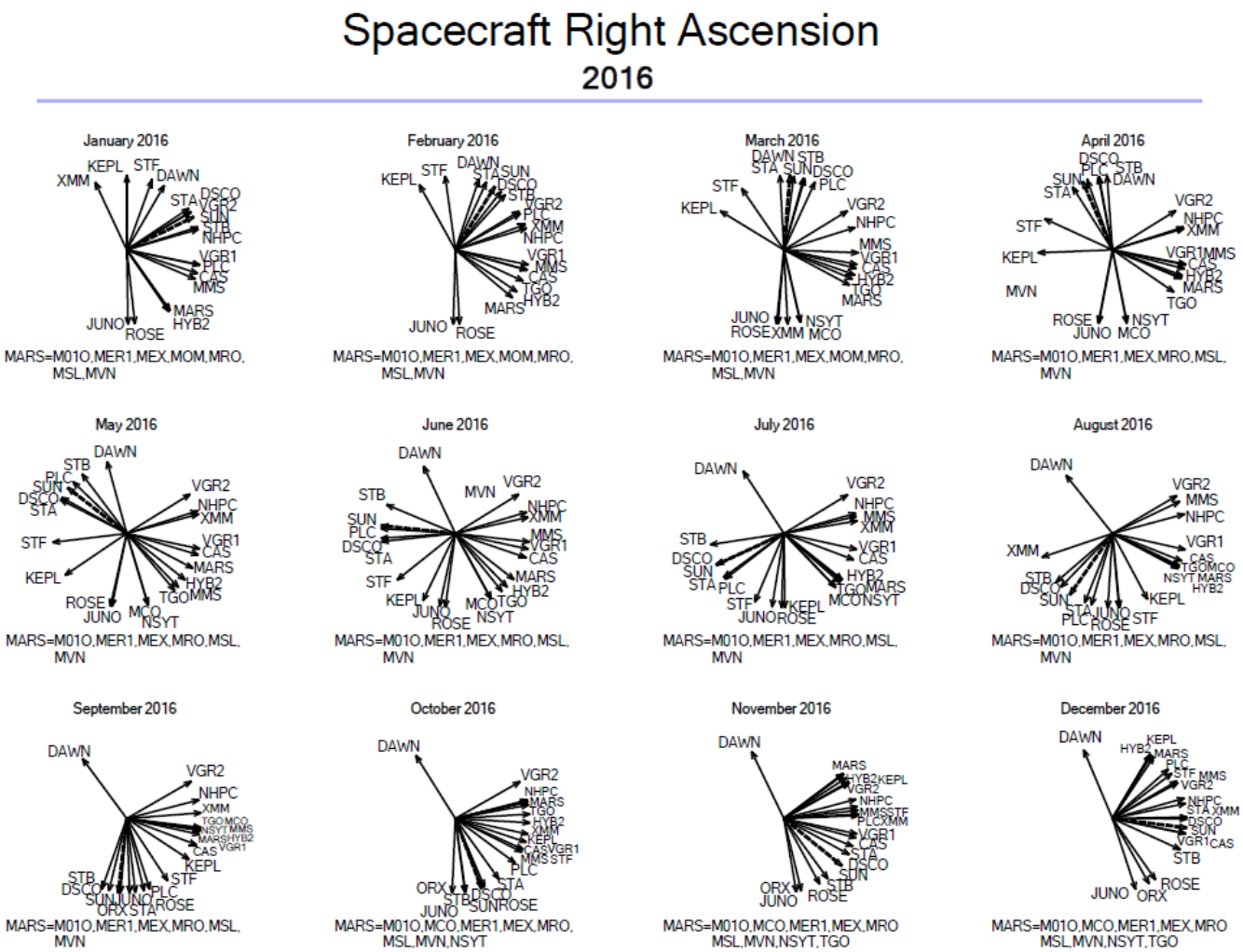


- Both the 2016 Optimistic and Pessimistic Mission Sets exhibit a similar southern declination bias.

- In the 2030's and 2040's, the amplitudes of the southern declination swings are generally less, and those of the northern declinations swings are generally more, than in earlier decades.

Pre-decisional – for Planning and Discussion Purposes Only

Antenna Asset Visibilities (3/6)



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

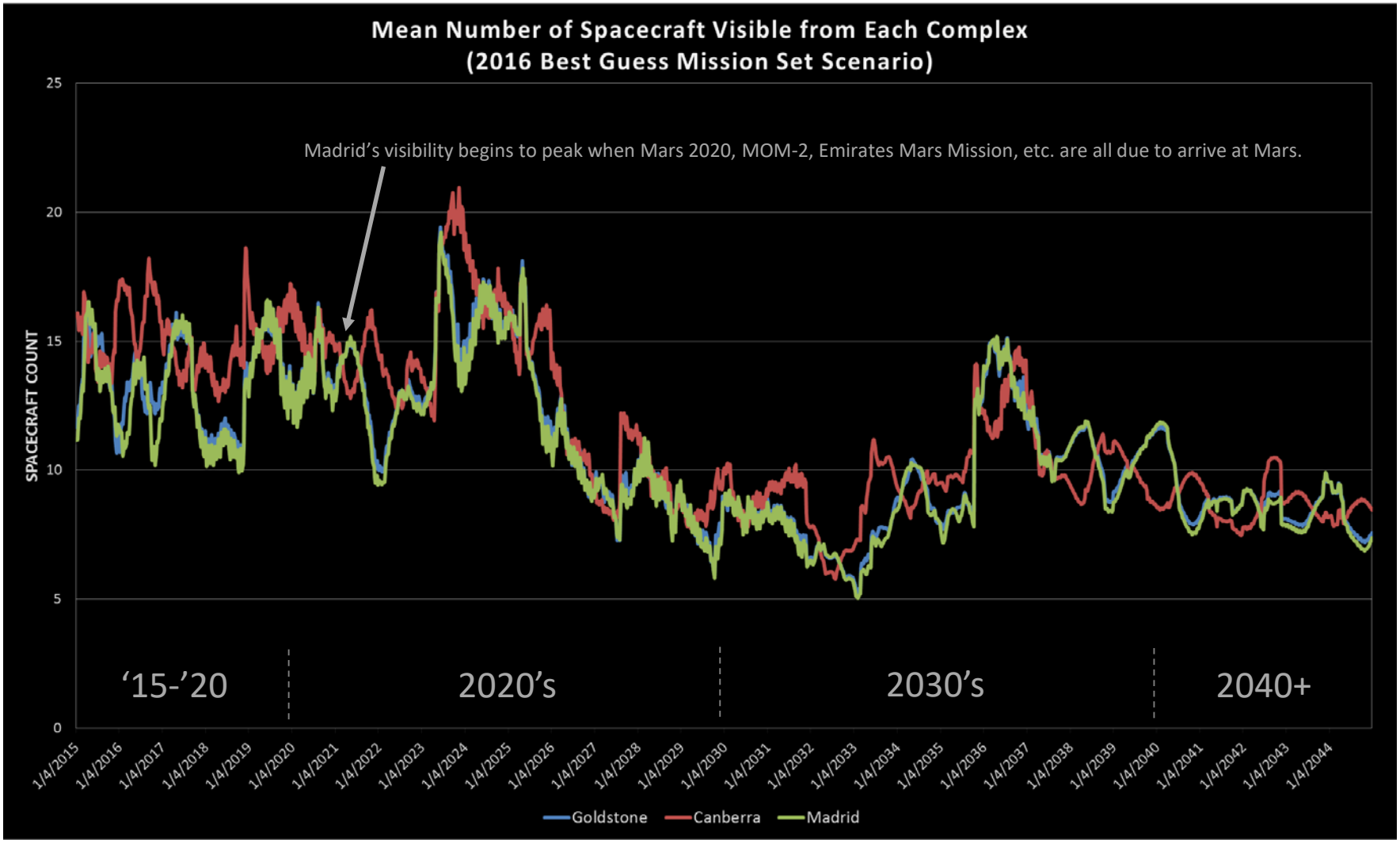
At selected times, the bulk of the missions may be visible from just one or two complexes at a time.

As of June 2015

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.

Pre-decisional – for Planning and Discussion Purposes Only

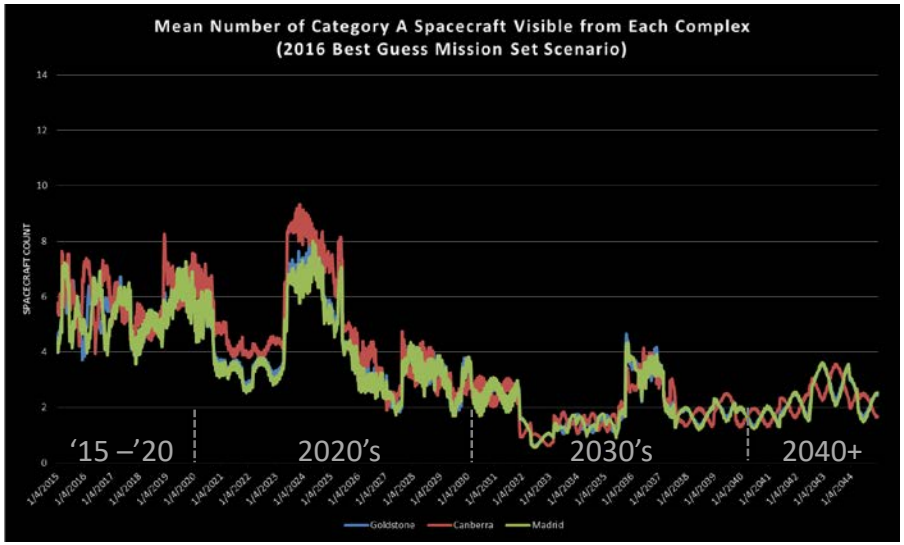
Antenna Asset Visibilities (4/6)

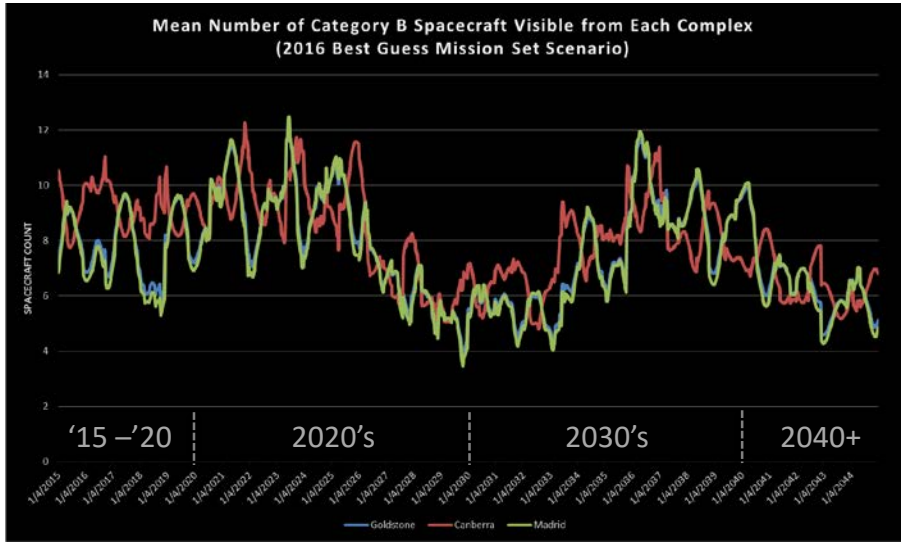


This plot combines declination and right ascension information. Canberra generally sees the largest number of spacecraft well into the 2030's.

Proprietary – For Planning and Discussion Purposes Only

Antenna Asset Visibilities (5/6)





- From ~2019 to 2026, Canberra seems to be able to see the most Category A spacecraft.

- Over the same time period, maximum Category B spacecraft visibility appears to alternate between Canberra and the northern hemisphere Complexes.

Pre-decisional – for Planning and Discussion Purposes Only

Antenna Asset Visibilities (6/6)

<u>Takeaways</u>:

- *Canberra will have more customer spacecraft visibility, on average, than the other two complexes, through at least the end of the next decade.*
- *Category A missions appear to benefit more continuously from this greater visibility.*
- *While Category B missions are also observable more of the time, this greater visibility tends to be periodic.*
  - *Madrid and Goldstone visibility dominance can occur for extended periods (e.g., Mars 2020's MOI in early 2021).*
- *In the human-Mars exploration era, the hemispheric bias to the mean mission set location disappears; but the large seasonal variations remain.*

Pre-decisional – for Planning and Discussion Purposes Only

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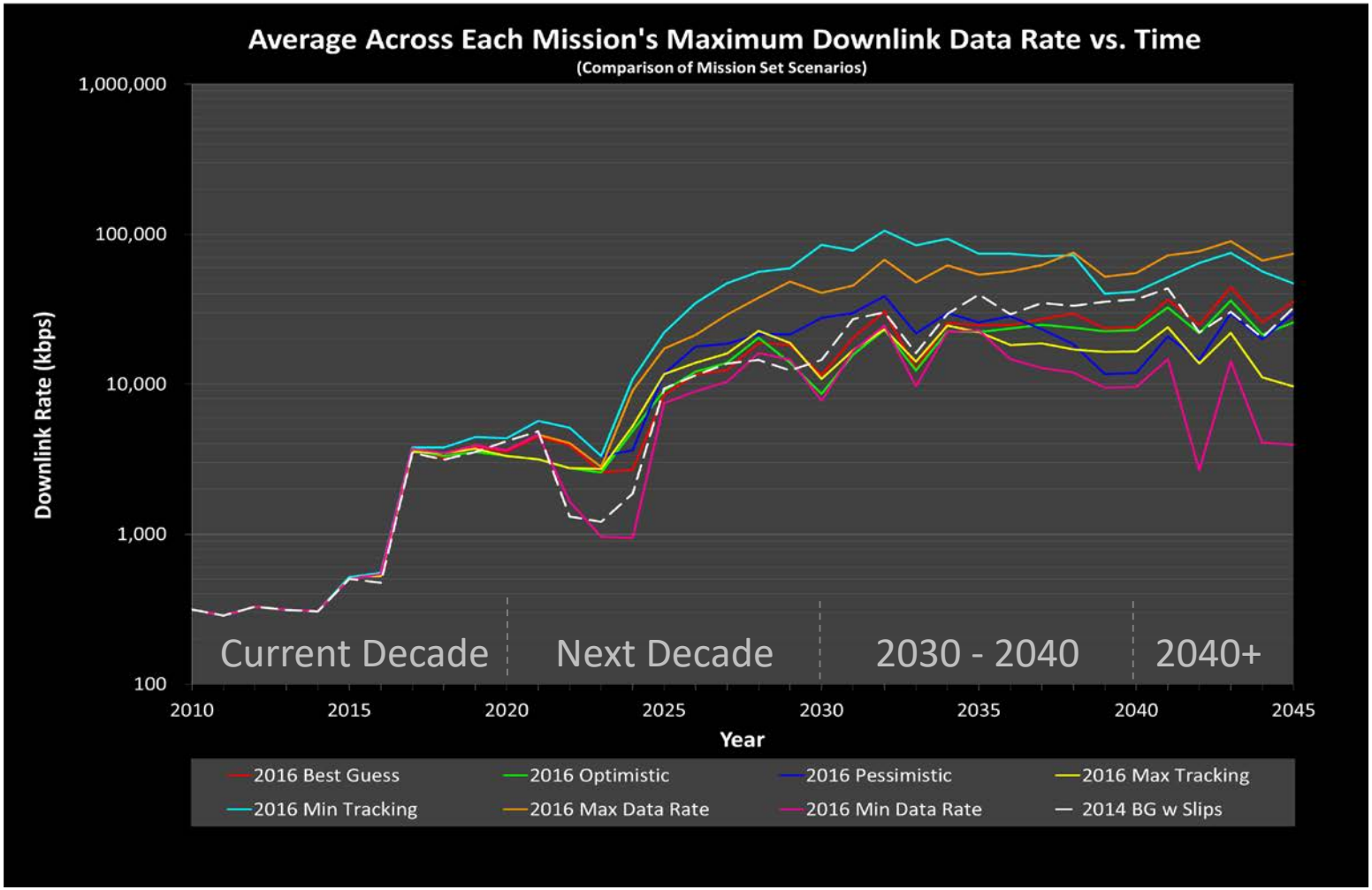
Pre-decisional – for Planning and Discussion Purposes Only

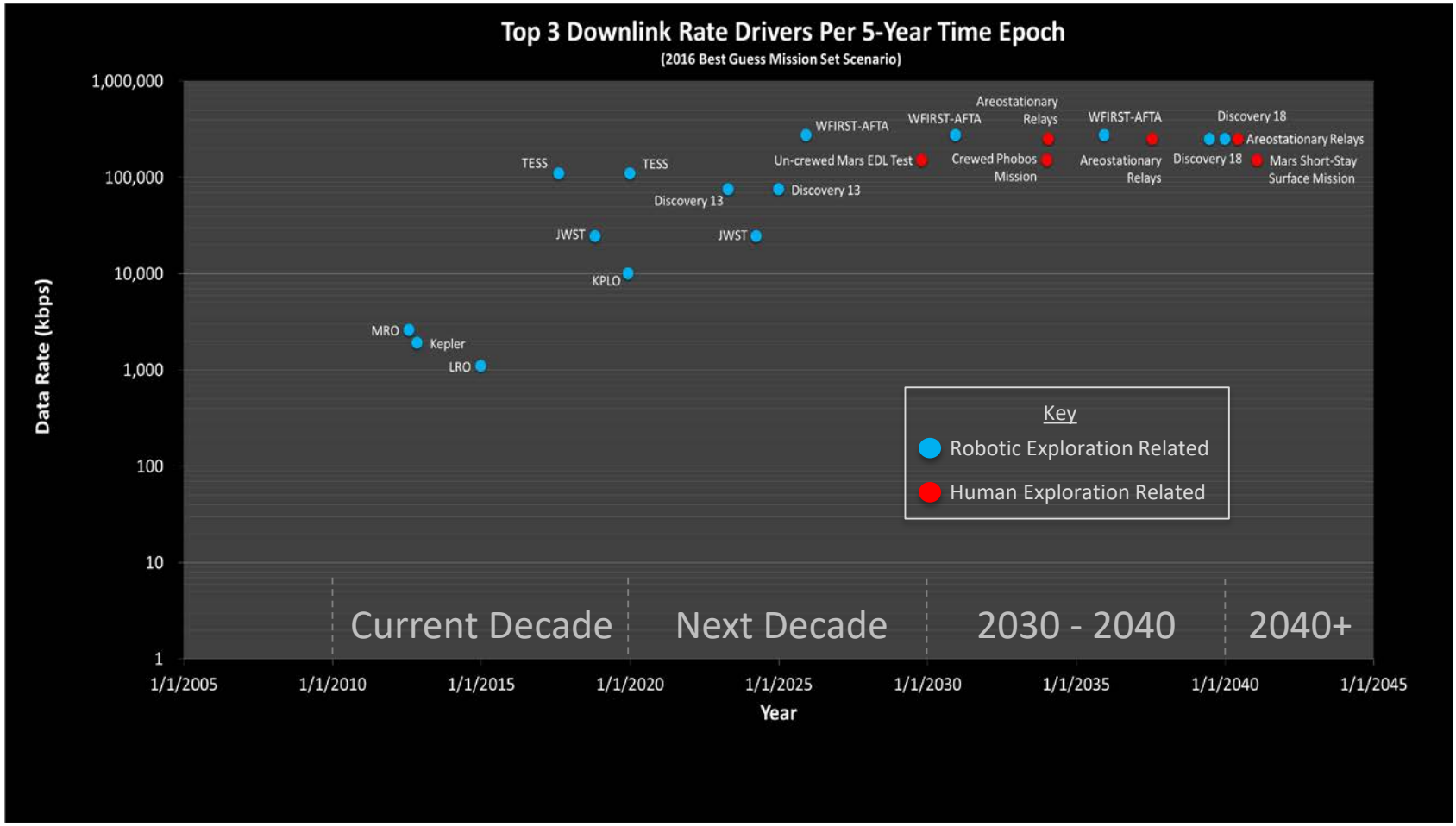
Average Downlink Rates



For most mission set scenarios, average downlink rates increase roughly two orders of magnitude over the next two decades.

Pre-decisional – for Planning and Discussion Purposes Only

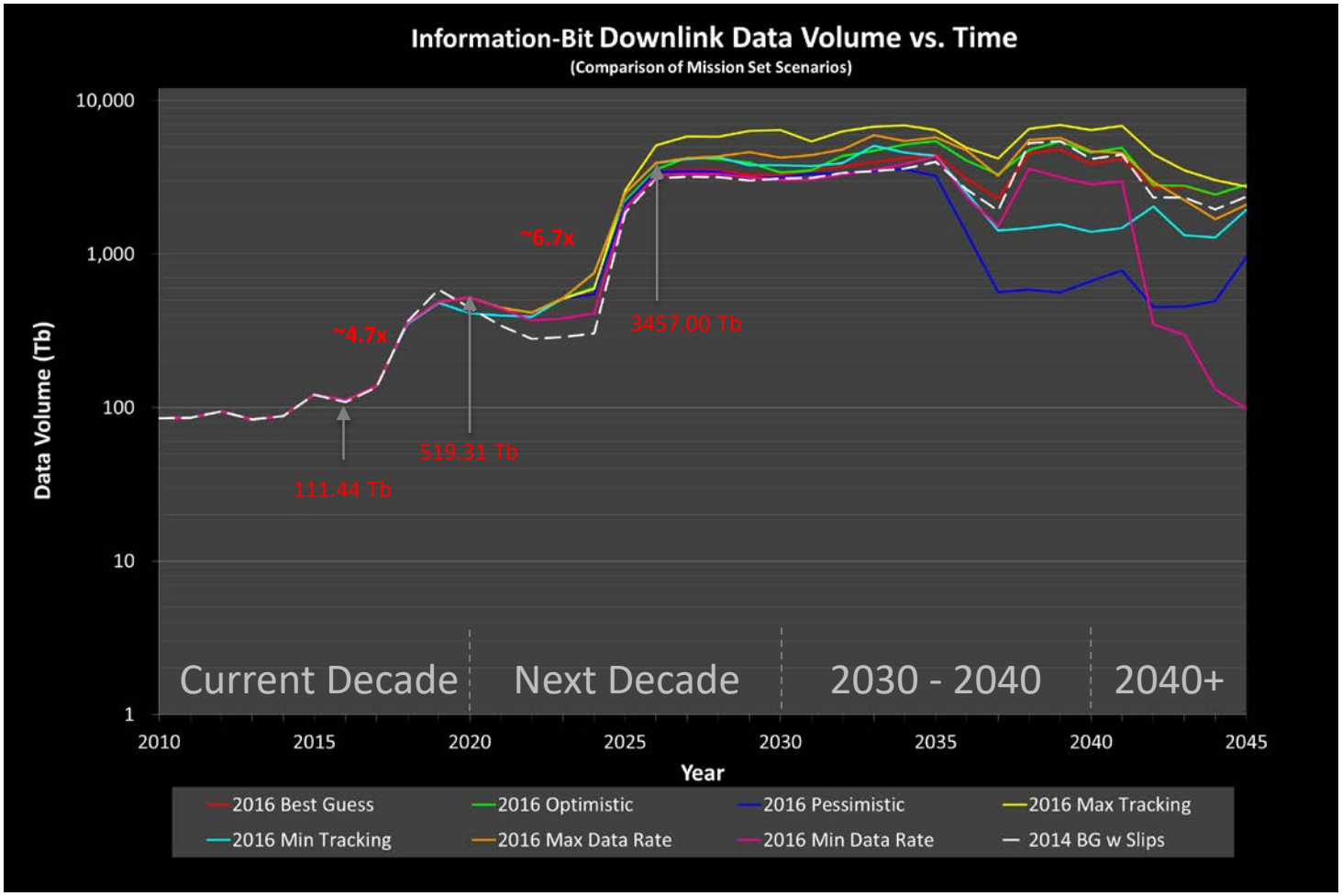
Downlink Data Rate Drivers



Robotic observatory-class missions tend to dominate downlink rates this decade and next. A mix of observatory-class missions and human exploration related missions dominate in the 2030's and beyond.

Pre-decisional – for Planning and Discussion Purposes Only

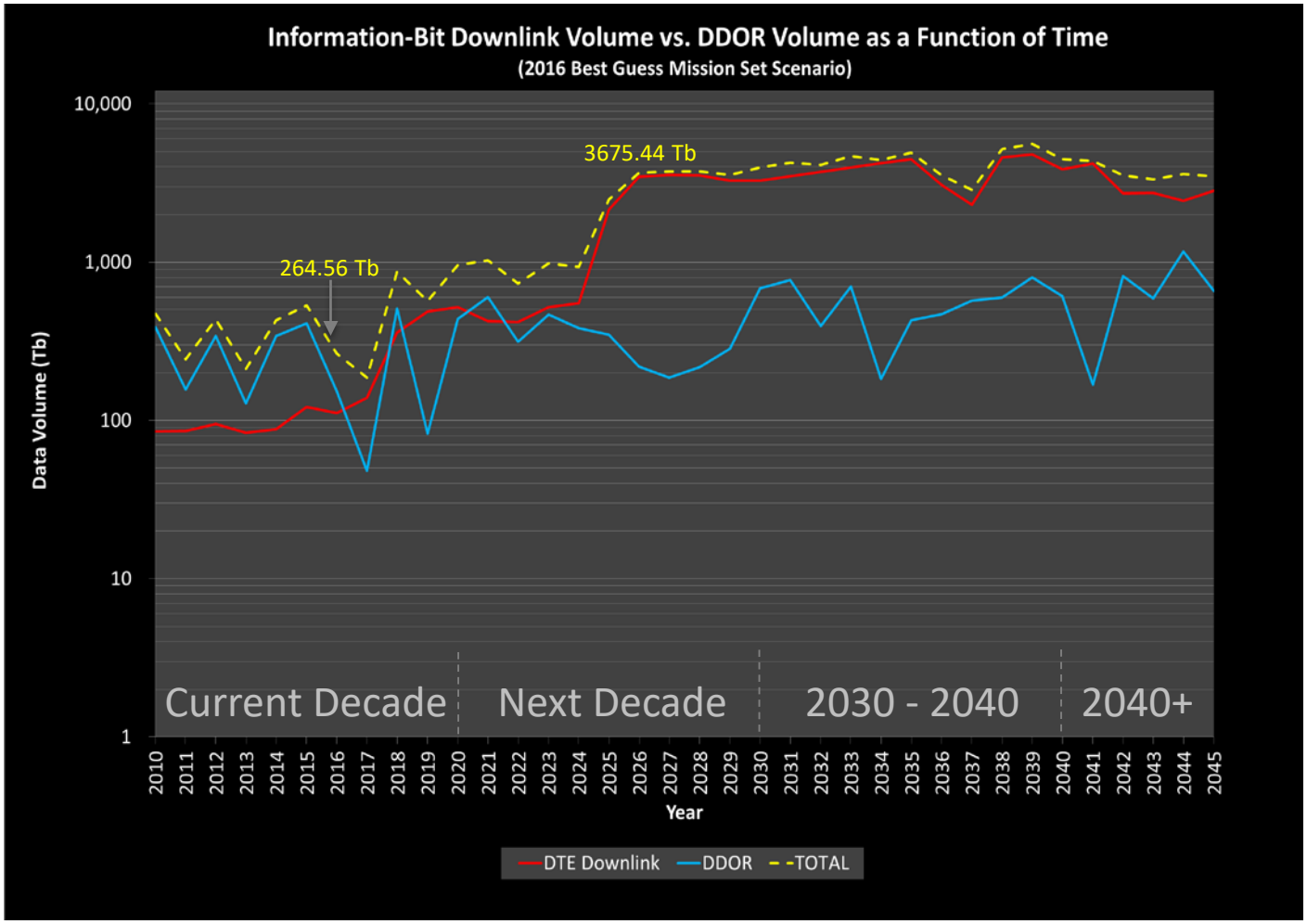
Annual Downlink Data Volume



Between now and 2026, downlink data volume (in terms of information bits) is projected to increase by a factor of ~31.

Pre-decisional – for Planning and Discussion Purposes Only

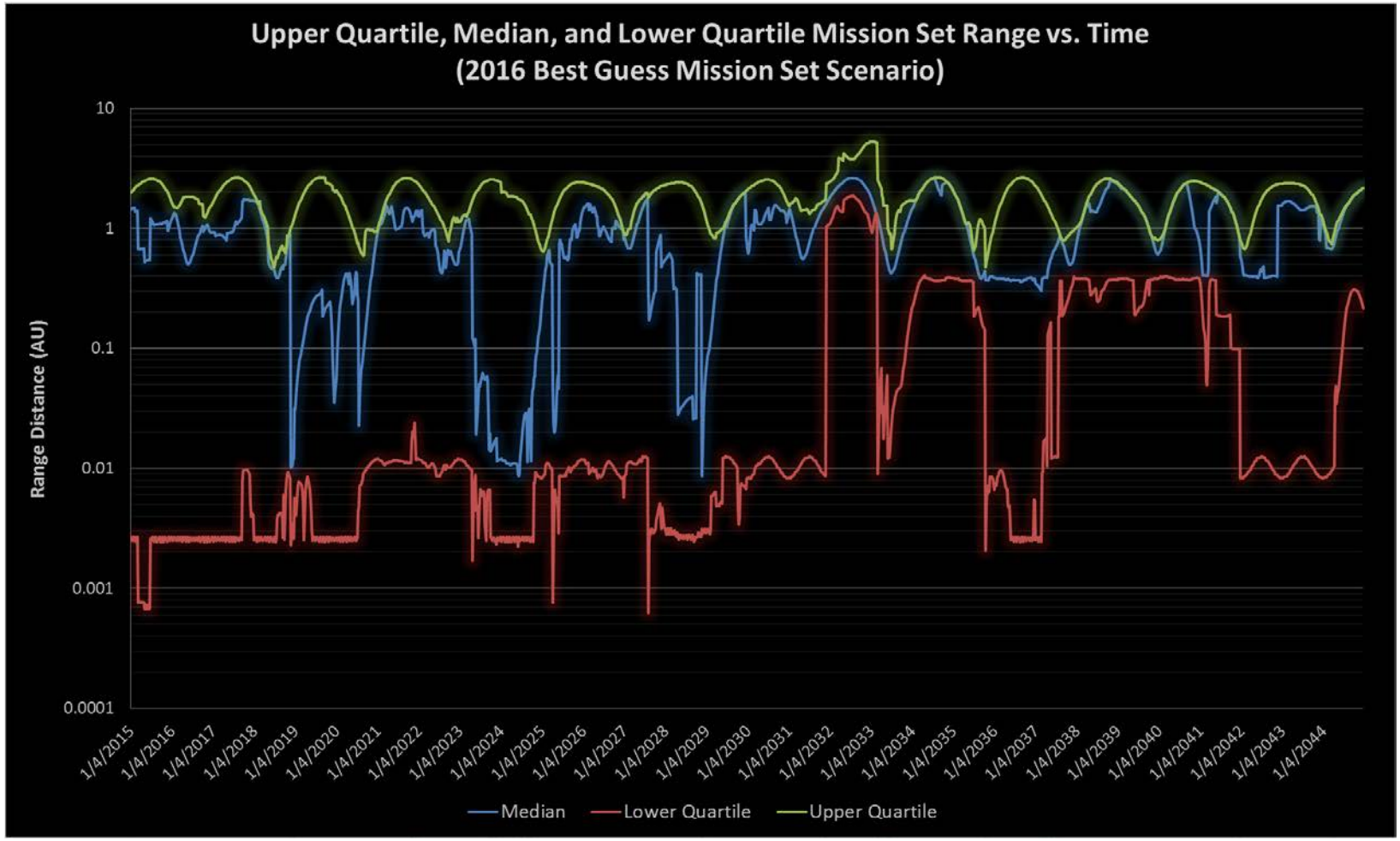
Downlink vs. Delta-DOR Data Volume



In the next 10 years, the combination of downlink and DDOR volume being passed to JPL Central will increase by a factor of ~14.

Pre-decisional – for Planning and Discussion Purposes Only

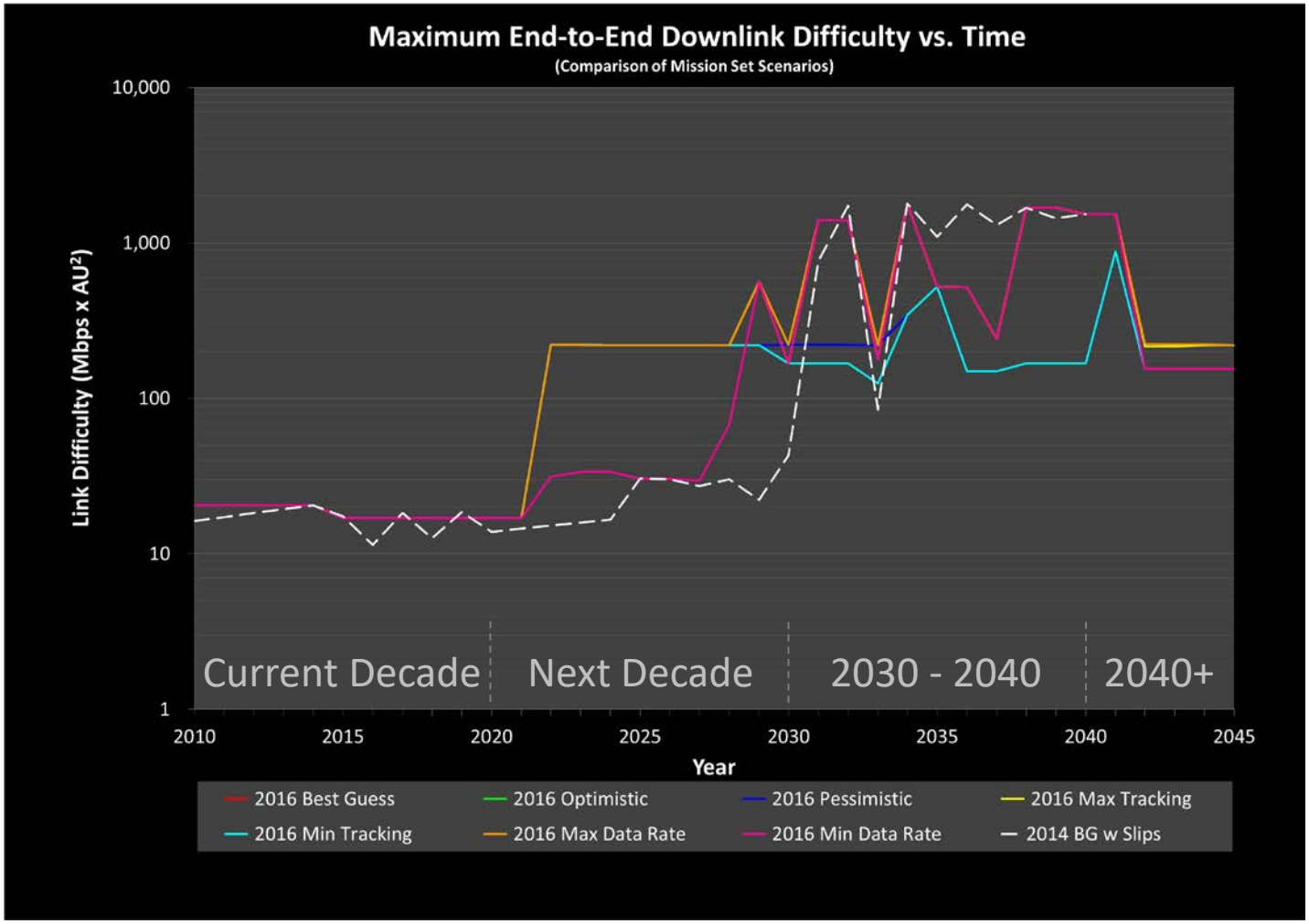
Mission Set Range



For the projected future, ~75% of the mission set will be at Mars distance or less; ~25% will be located at greater than Mars distance. And, through the end of the next decade, ~25% will be located in Category A space.

Pre-decisional – for Planning and Discussion Purposes Only

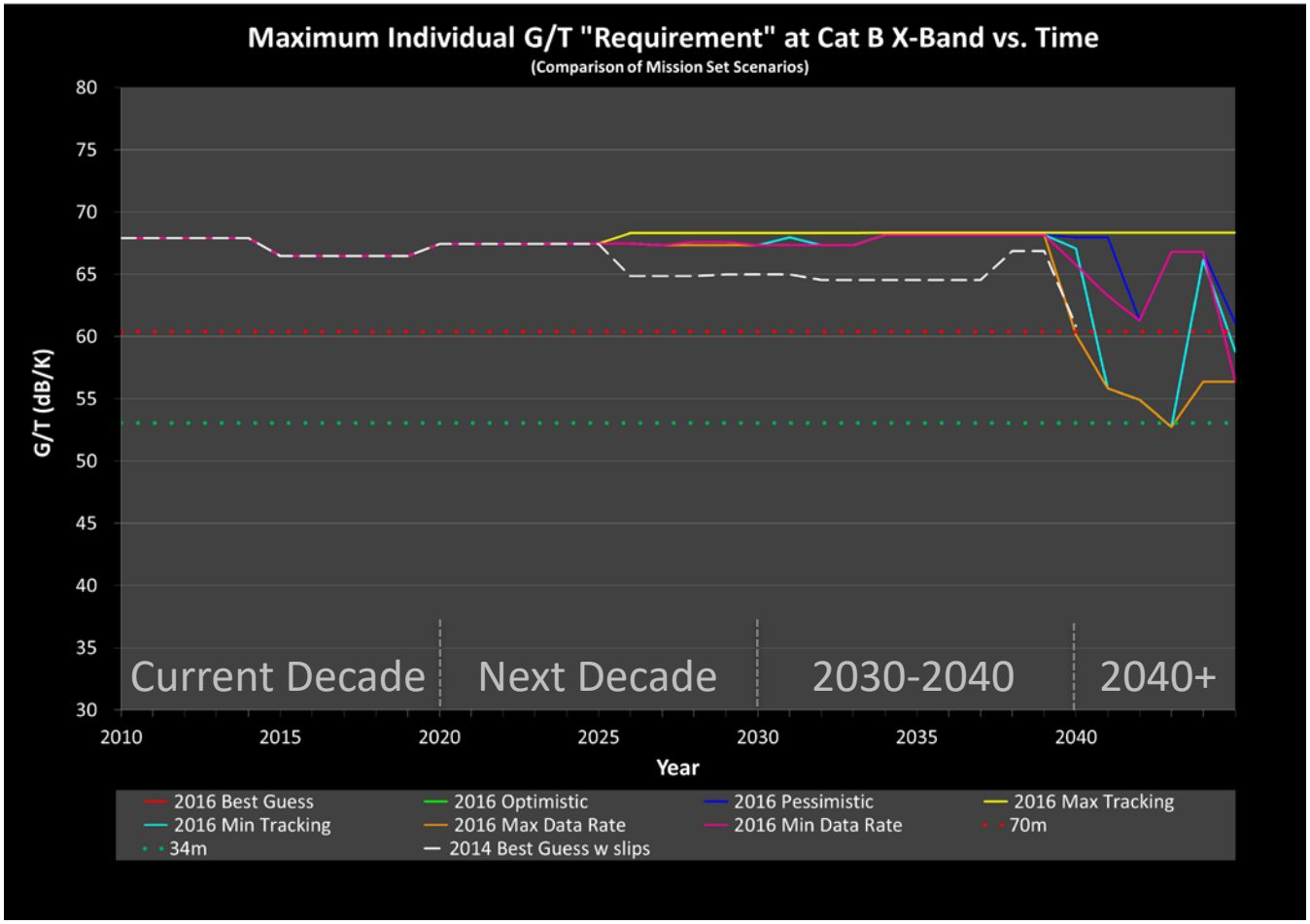
End-to-End Downlink Difficulty



Human Mars exploration's combination of high data rates and relatively long link distances drives up end-to-end link difficulty over 2 orders of magnitude.

Pre-decisional – for Planning and Discussion Purposes Only

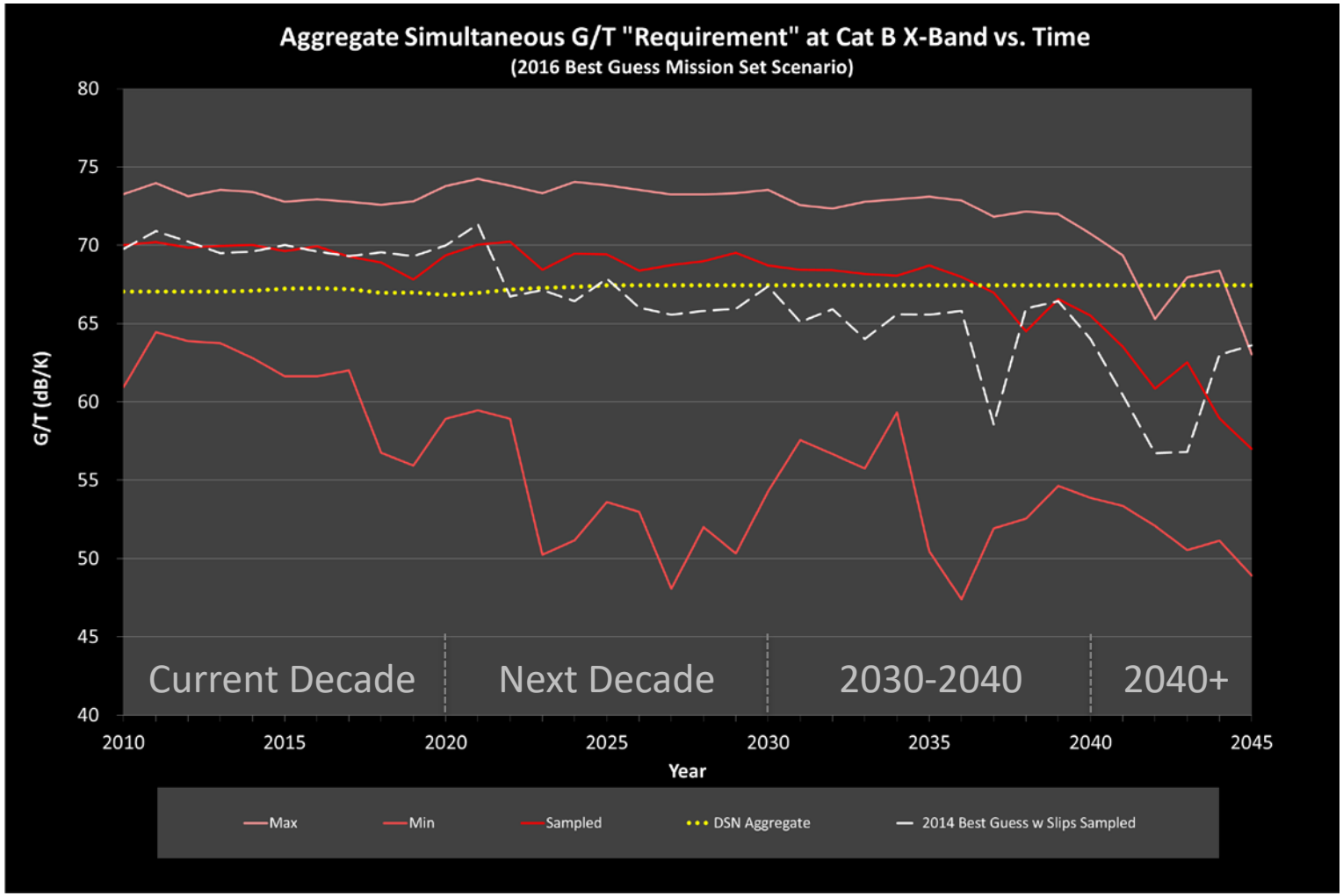
Maximum Individual X-band G/T



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.

Pre-decisional – for Planning and Discussion Purposes Only

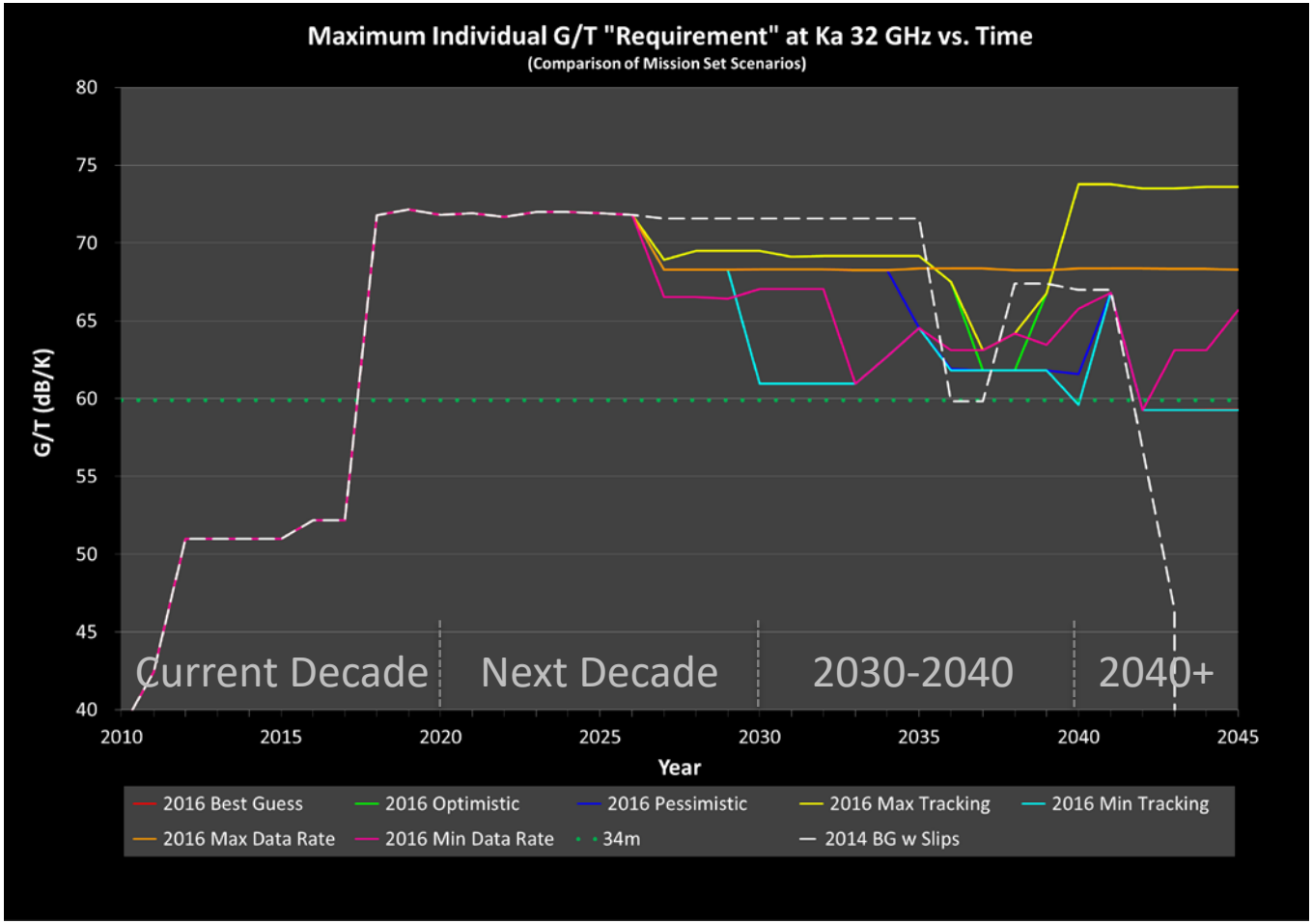
Aggregate X-band G/T



Relative to average demand, aggregate X-band capability may be, at best, marginal over the next 20 years.

Pre-decisional – for Planning and Discussion Purposes Only

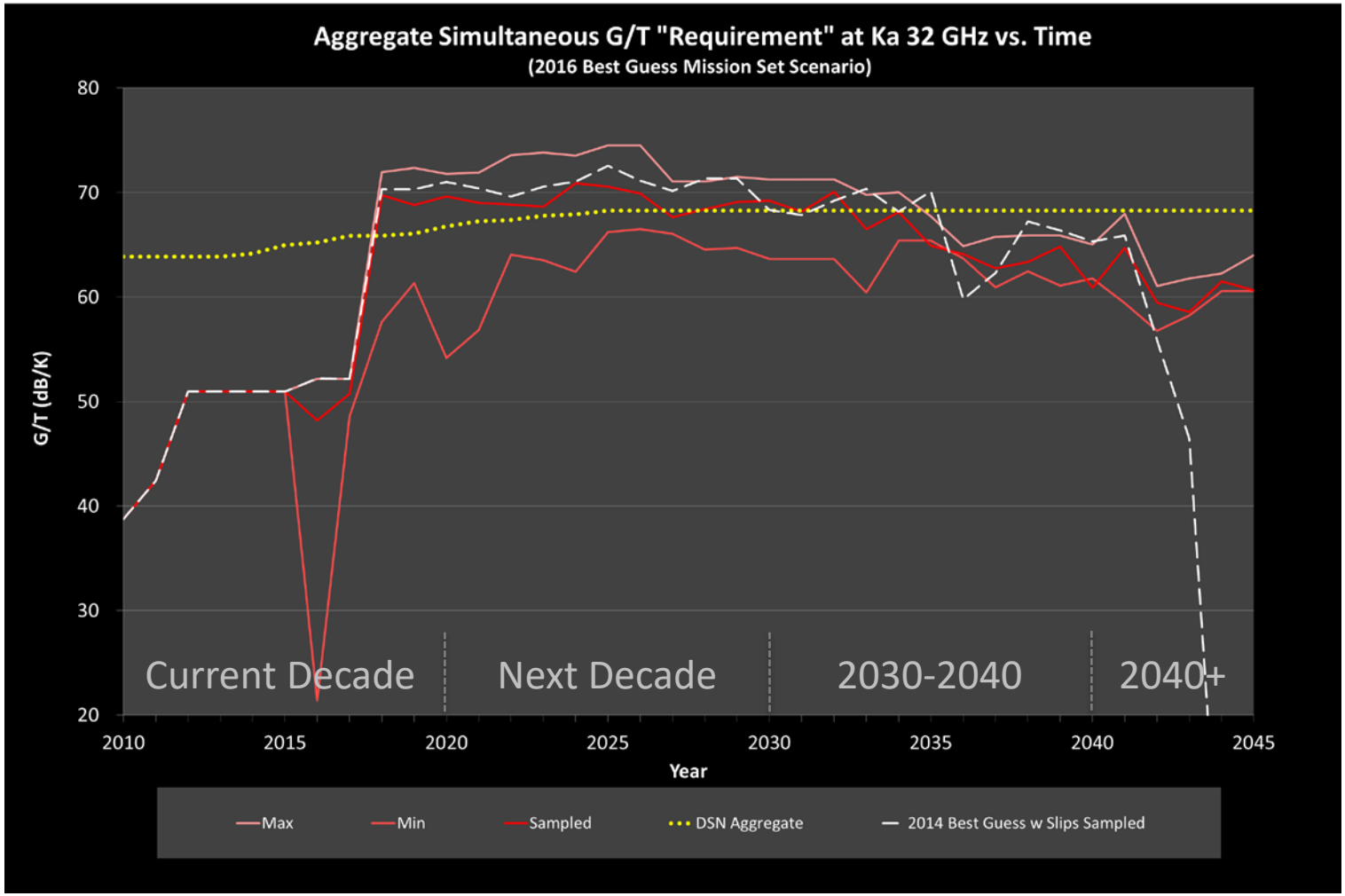
Maximum Individual Ka 32 GHz G/T



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

Pre-decisional – for Planning and Discussion Purposes Only

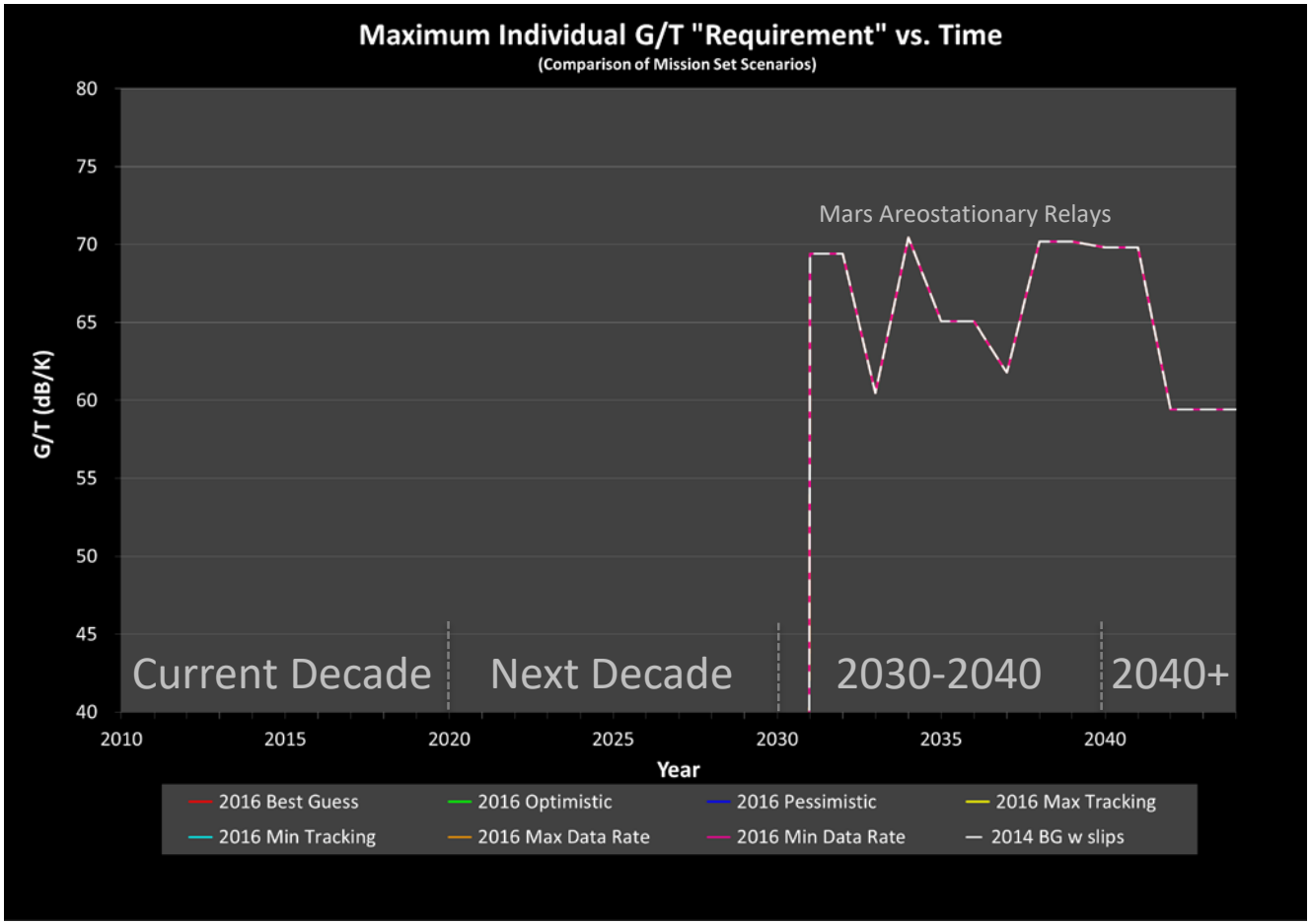
Aggregate Ka 32 GHz G/T



Over the next 20 years, aggregate 32 GHz capability may also be marginal relative to average demand.

Pre-decisional – for Planning and Discussion Purposes Only

Maximum Individual Ka 37 GHz G/T



Mars Areostationary Relays at max. Mars distance drive G/T requirements equivalent to 6 or more arrayed 34m antennas designed for operation at 37 GHz. (At 32 GHz, it would be more.) Optical communications may provide a potential alternative.

Predecisional – for Planning and Discussion Purposes Only

Downlink Capability Demand

Takeaways:

- *Observatory-class missions drive up downlink rates roughly 2 orders of magnitude by 2025.*
- *Increases in downlink data volume, combined with DDOR data, translate into a 10x increase in ground data volume by 2025.*
- *Over the next 20 years, aggregate Cat B X-band and 32 GHz G/T capabilities appear to be, at best, only marginally adequate relative to anticipated simultaneous average demand.*
- *In the human-Mars exploration era, end-to-end link difficulty increases over 2 orders of magnitude, driving possible G/T deficiencies at Cat B X-band and 32 GHz.*
- *The required G/T for Mars Areostationary Relays operating at 37 GHz would amount to at least 6 arrayed 34m antennas.*

Pre-decisional – for Planning and Discussion Purposes Only

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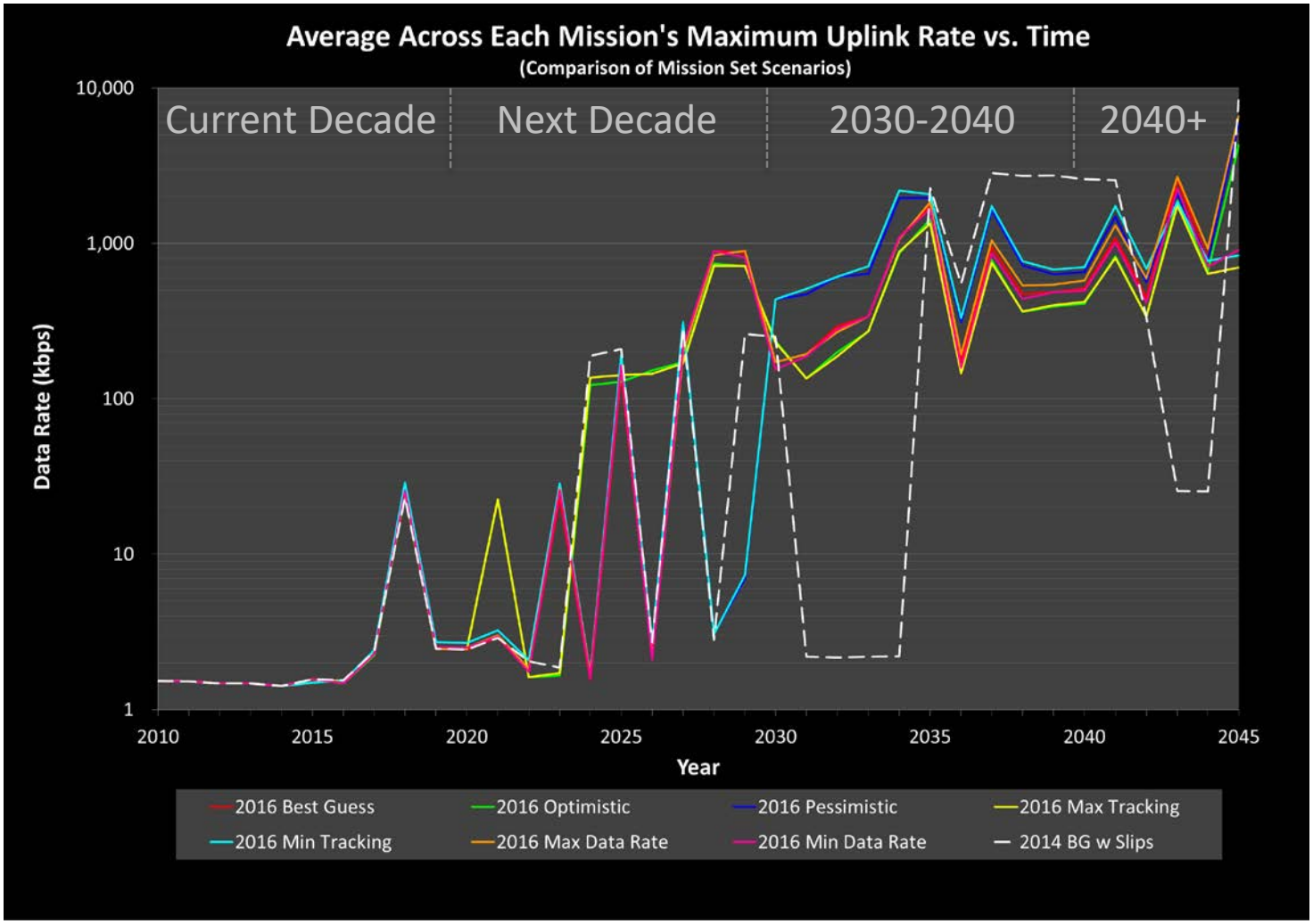
Pre-decisional – for Planning and Discussion Purposes Only

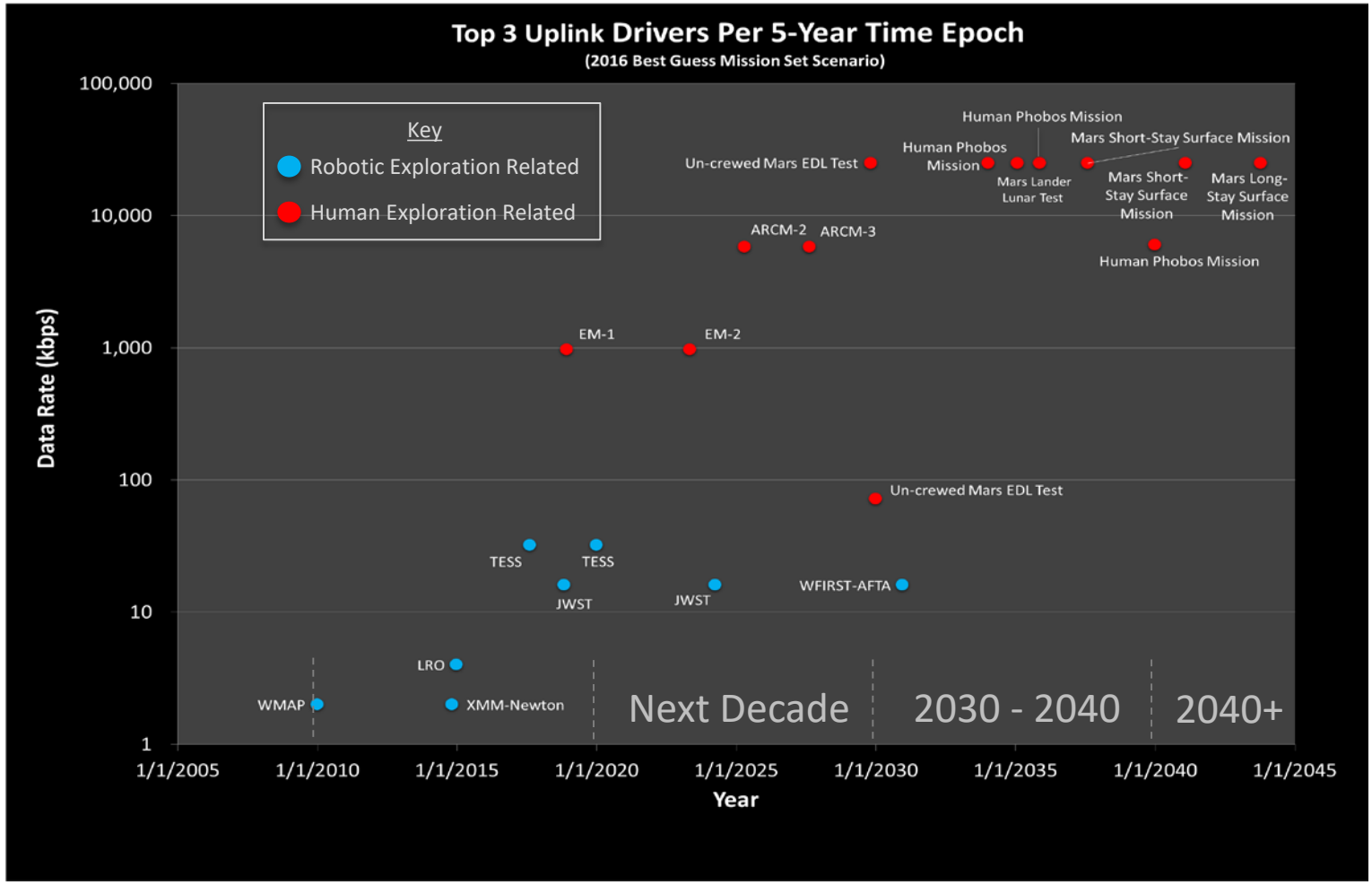
Average Uplink Rates



For most mission set scenarios, average uplink rates increase roughly 3 orders of magnitude over the next 25 years.

Pre-decisional – for Planning and Discussion Purposes Only

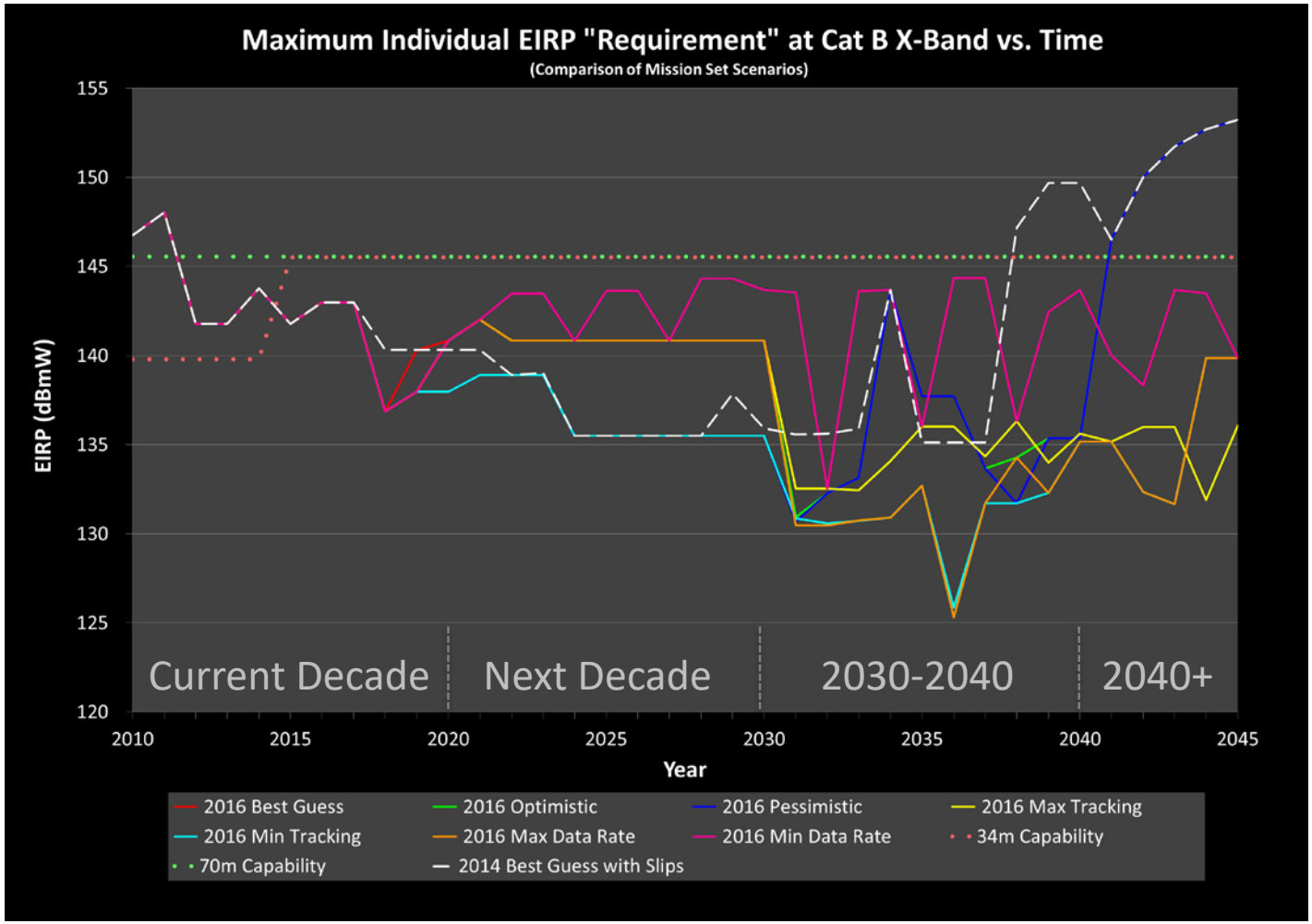
Uplink Data Rate Drivers



Robotic observatory-class missions tend to dominate uplink rates this decade. Next decade, a mix of observatory-class and human-exploration-related missions dominate. In the 2030's and beyond, just the human missions dominate.

Pre-decisional – for Planning and Discussion Purposes Only

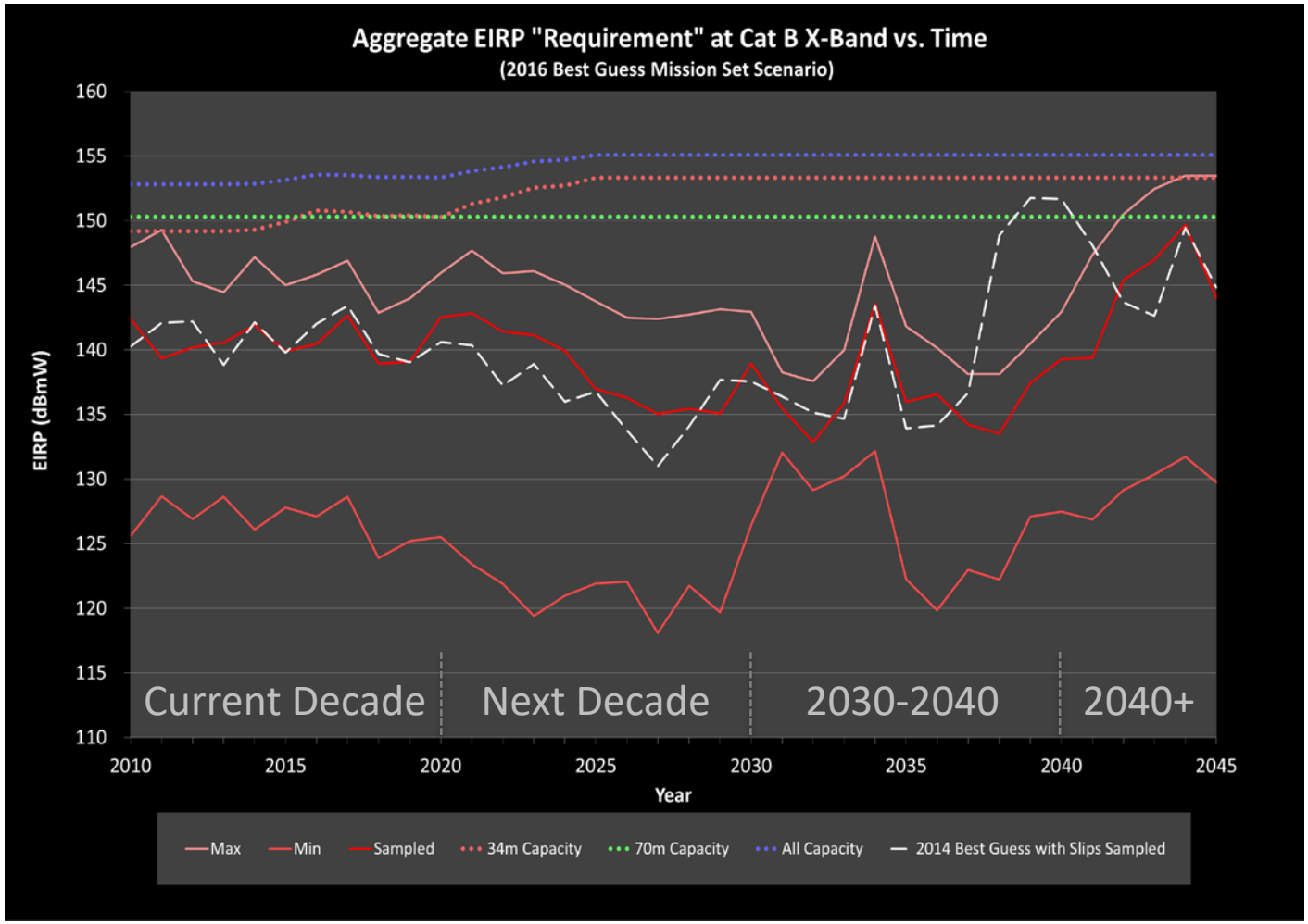
Maximum Individual X-band EIRP



The 70m-20kW and 34m-80 kW capabilities will likely satisfy the non-emergency maximum individual X-band EIRP "requirement" through about 2040.

Pre-decisional – for Planning and Discussion Purposes Only

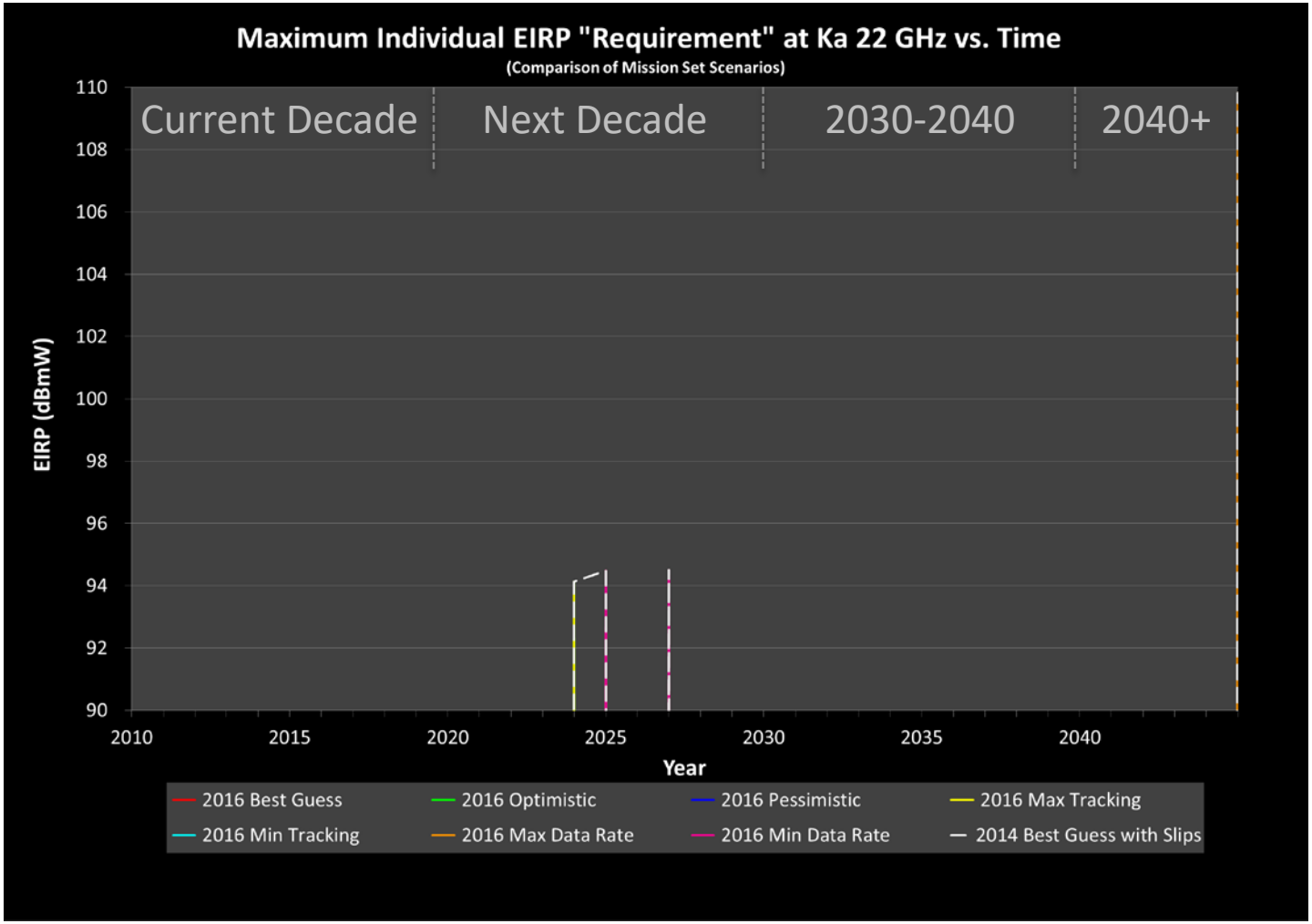
Aggregate X-band EIRP



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.

Pre-decisional – For Planning and Discussion Purposes Only

Maximum Individual Ka 22 GHz EIRP



While there may be a few 22 GHz human exploration users, no such capability is currently planned. Should there be? Or, could 34 GHz be waivered in, instead?

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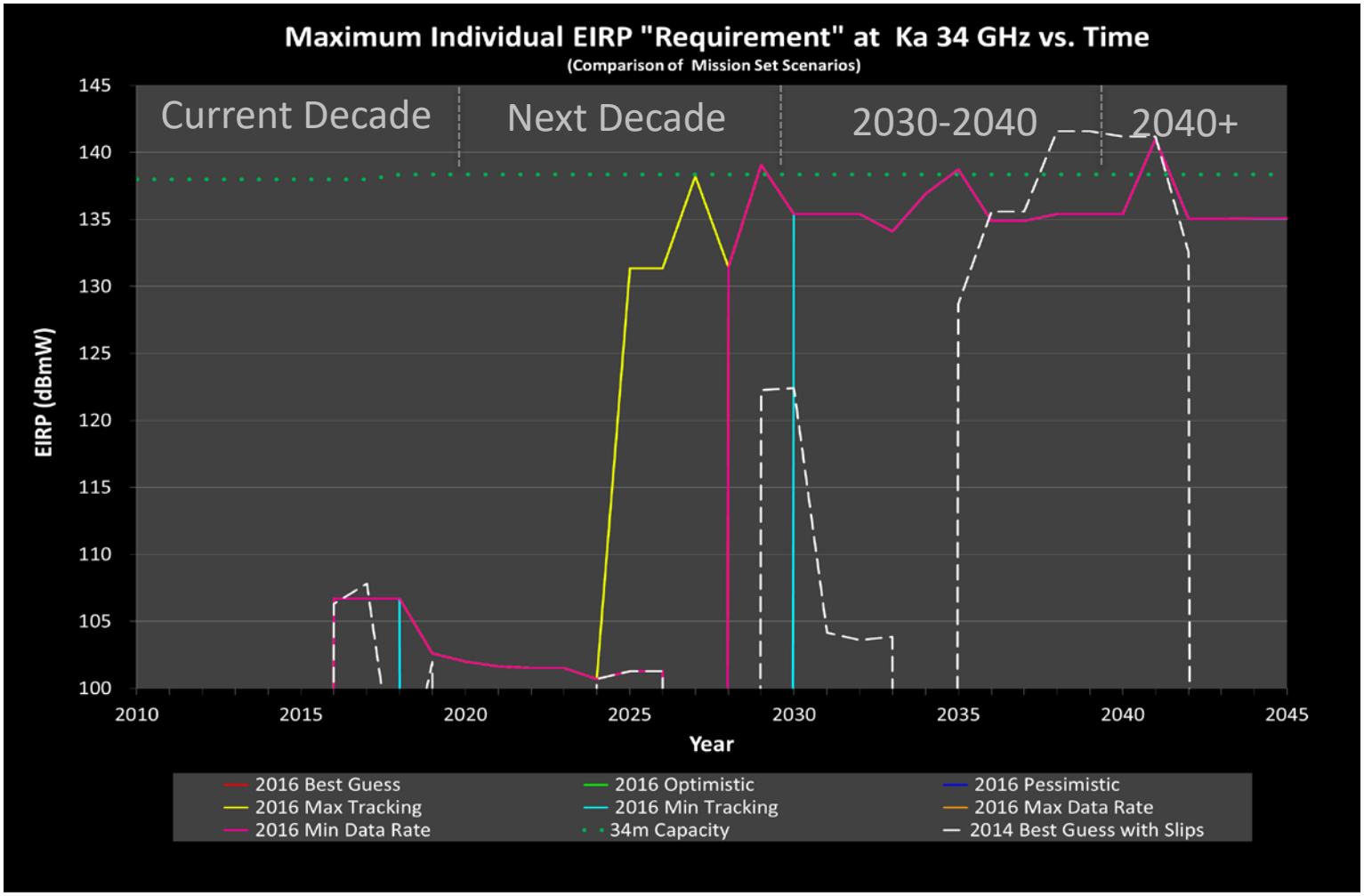
Maximum Individual Ka 34 GHz EIRP



The 3 kW 34 GHz capability planned for later this decade will likely meet the maximum individual EIRP requirement until the early 2040's.

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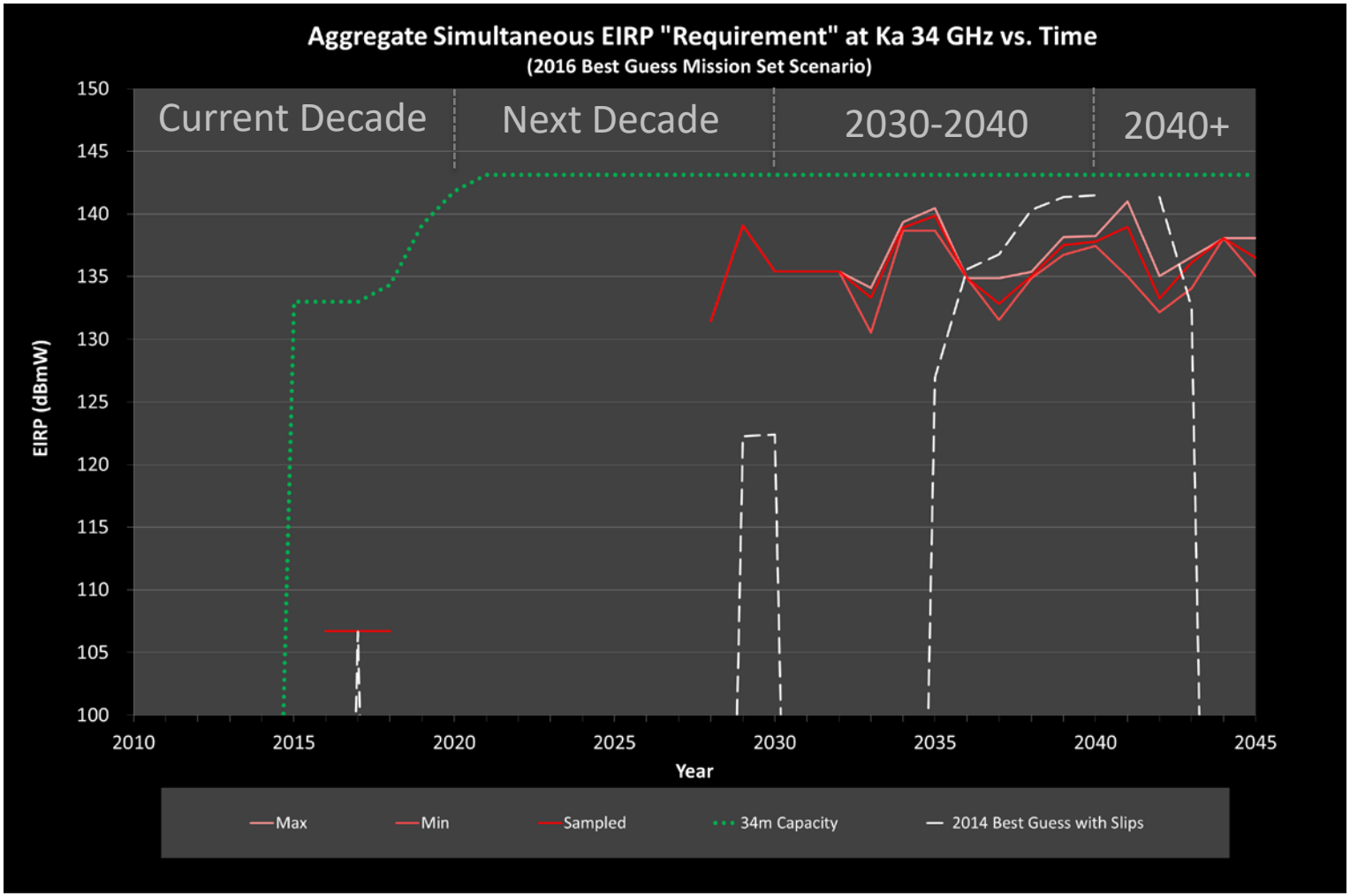
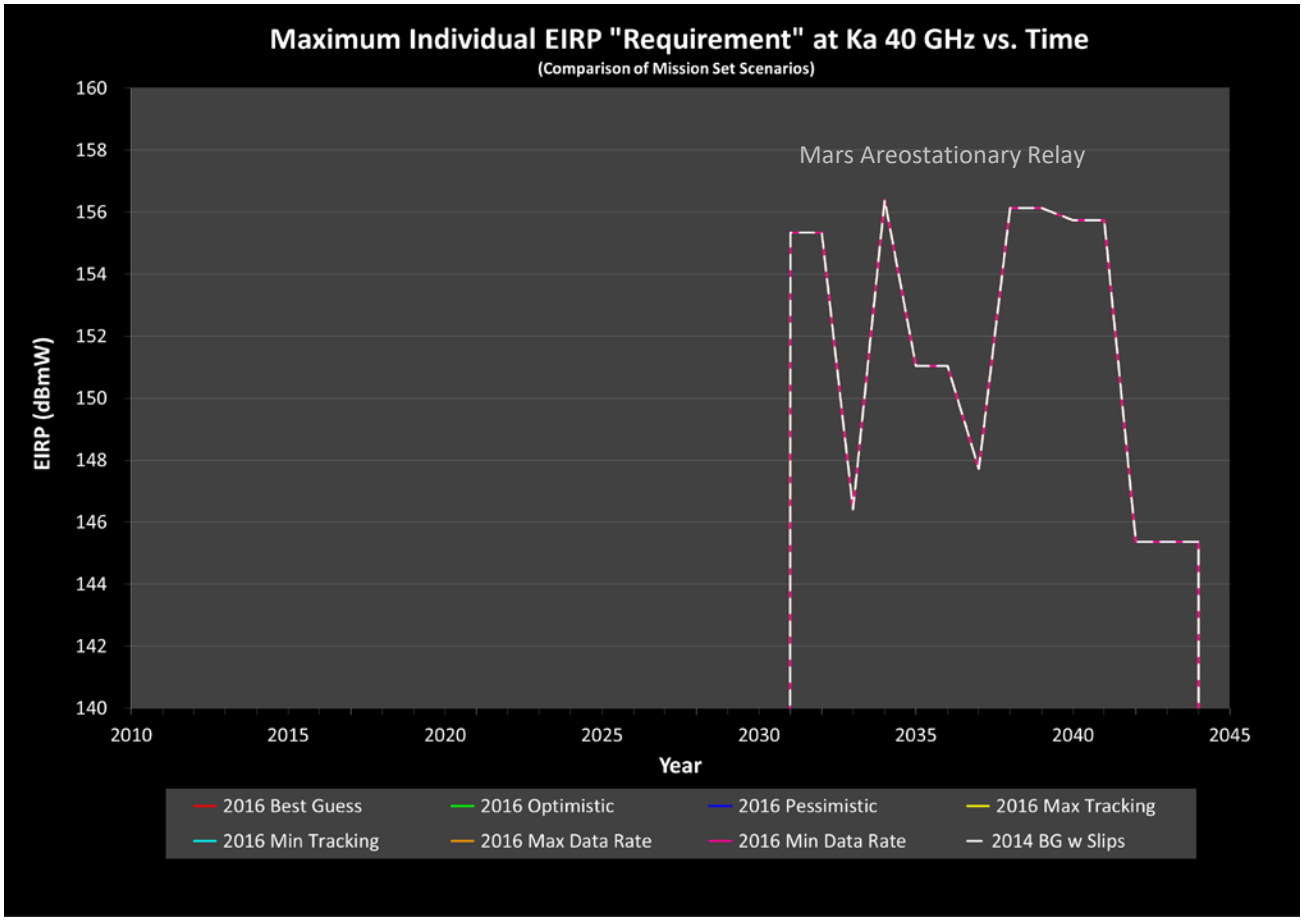
Aggregate Ka 34 GHz EIRP



Planned aggregate 34 GHz EIRP appears to be adequate for projected demand, but does not include any redundant "hot backup" capability at each complex.

Maximum Individual Ka 40 GHz EIRP



To the extent that Mars Areostationary Relays are pursued as part of the human Mars exploration program, their associated uplink rate requirements drive an immense EIRP requirement at Ka 40 GHz.

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Uplink Capability Demand

Takeaways:

- *Human exploration missions drive up uplink rates nearly 3 orders of magnitude over the next 25 years.*
- *The DSN's maximum EIRP capability at X-band and planned capability at Ka 34 GHz should be adequate to ~2040.*
- *The DSN's aggregate EIRP capability at X-band should be adequate through ~2045, assuming continued DAEP buildout and continued availability of the 70m antennas.*
- *Aggregate 34 GHz capability should be adequate over the same timeframe, except that it will lack any margin for "hot backups."*
- *The DSN currently lacks 22 GHz capability for next-decade, lunar-vicinity human exploration missions; and, it lacks 40 GHz capability for Mars Areostationary Relays in the 2030's.*

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Topics

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- **Selected Mission Set Analysis Results**
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  - **Spectrum:** Downlink Count, Downlink Antenna Hours, Uplink Count, and Uplink Antenna Hours
  - **Loading Simulation Results:** "Requested" Downlink Hours Realized and "Requested" Downlink Data Volume Realized
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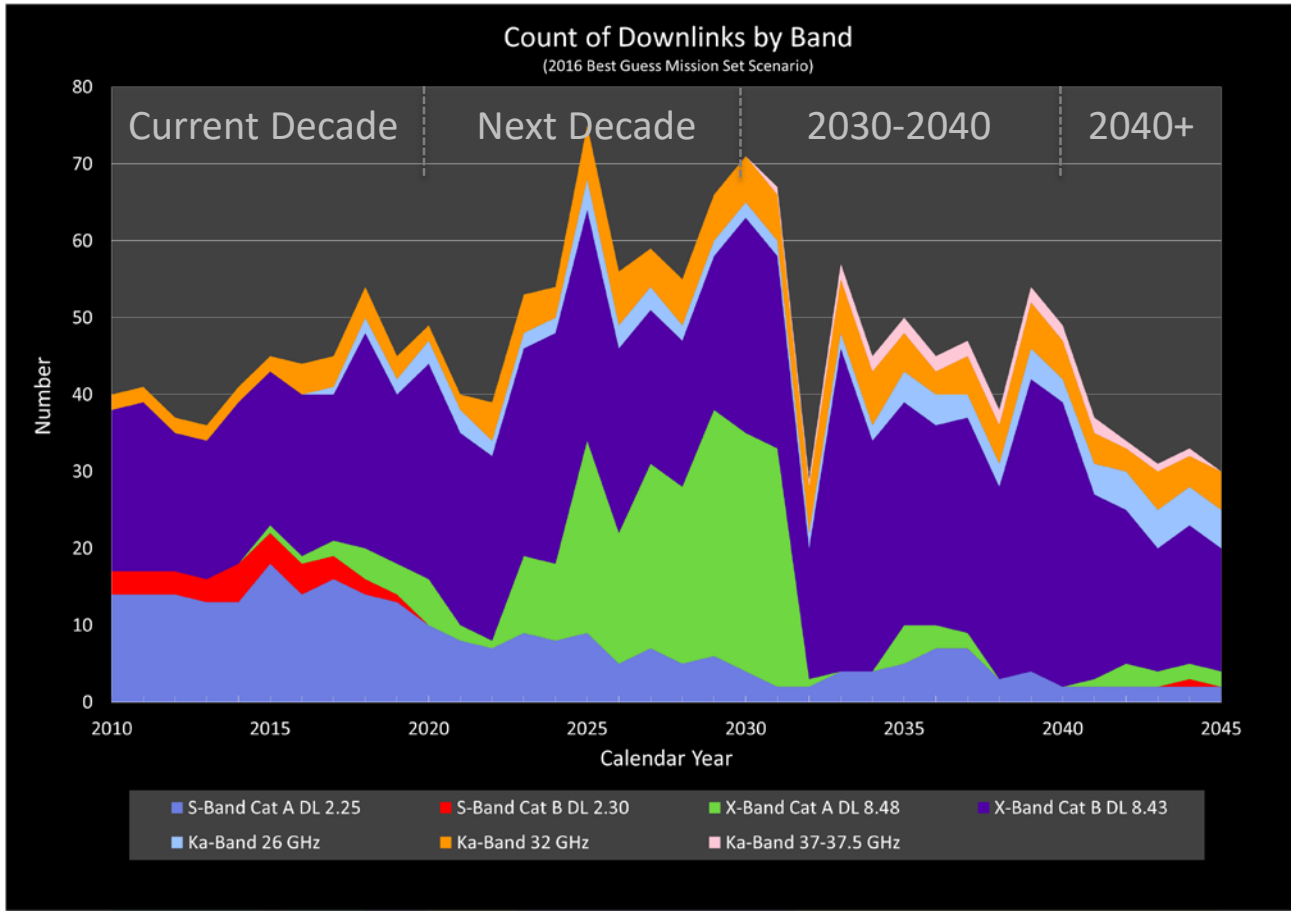
Spectrum Demand by Downlink Count



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 growth:*** *Ka 37 GHz for human Mars relay applications – though, optical might be an alternative.*

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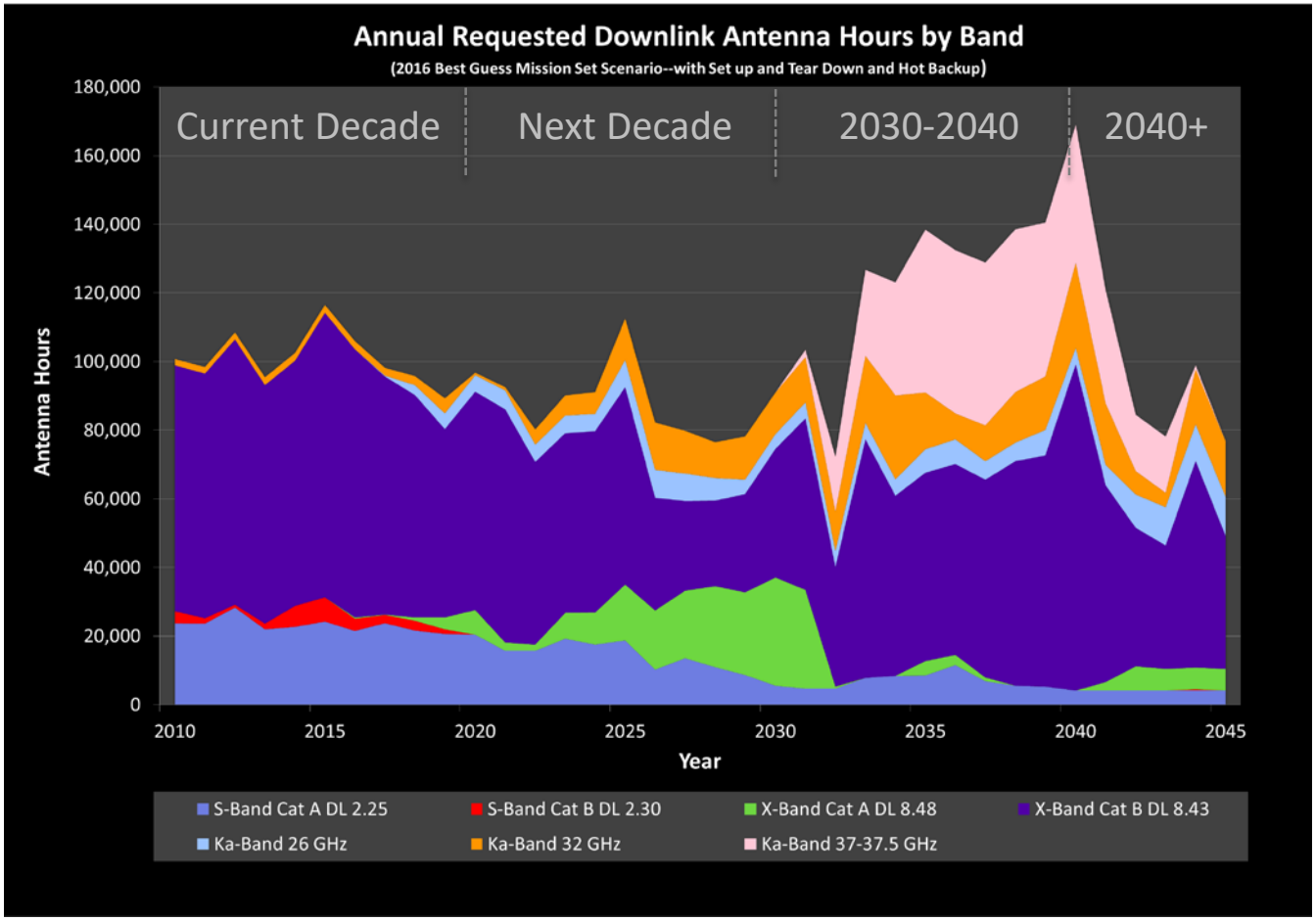
Spectrum Demand by Total Downlink Antenna Hours



From a total antenna hour standpoint, band-use projections are similar to those associated with downlink count until the 2030's, when areostationary relay use of 37 GHz emerges. Optical could reduce or supplant this, however.

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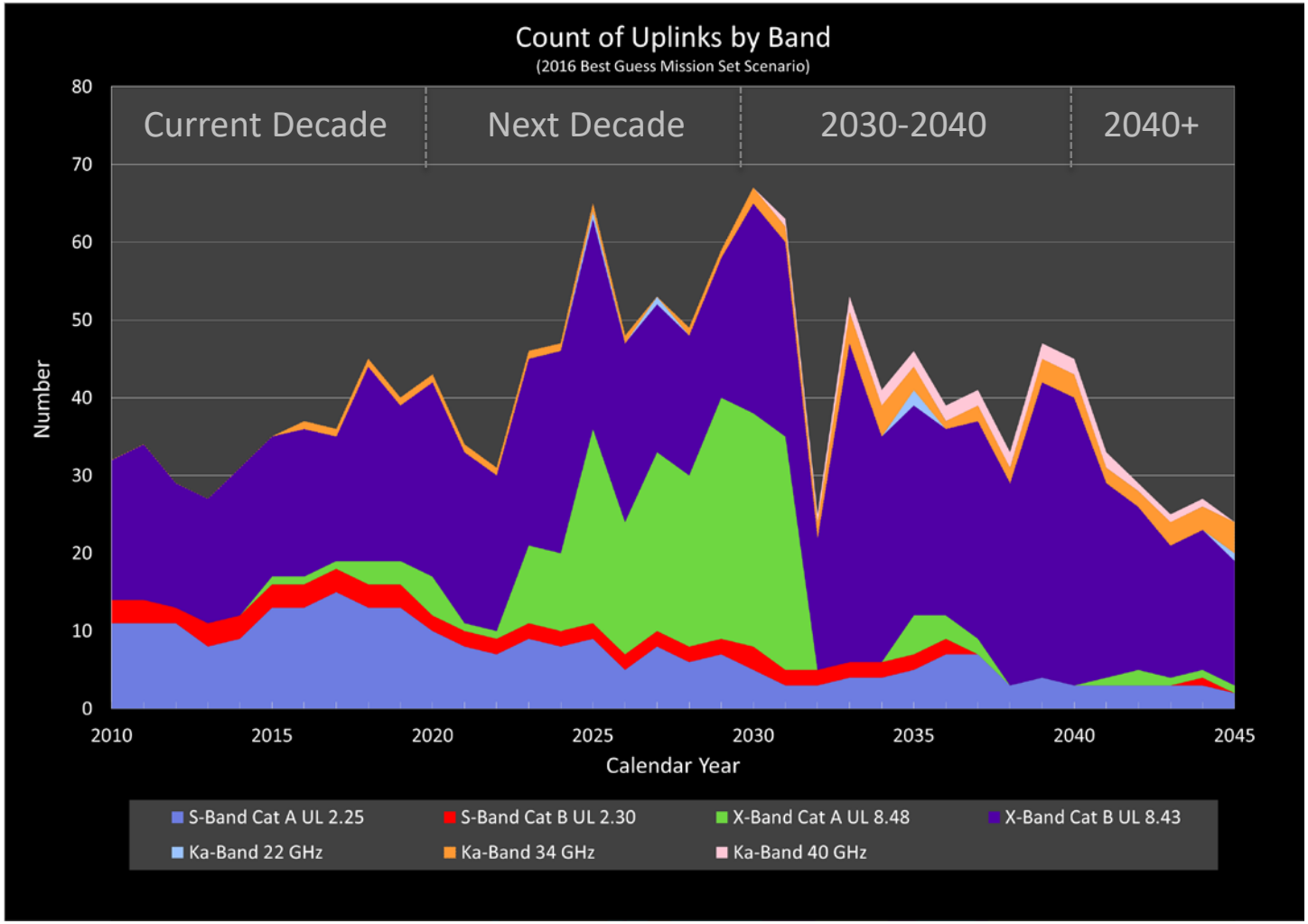
Spectrum Demand by Uplink Count



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.

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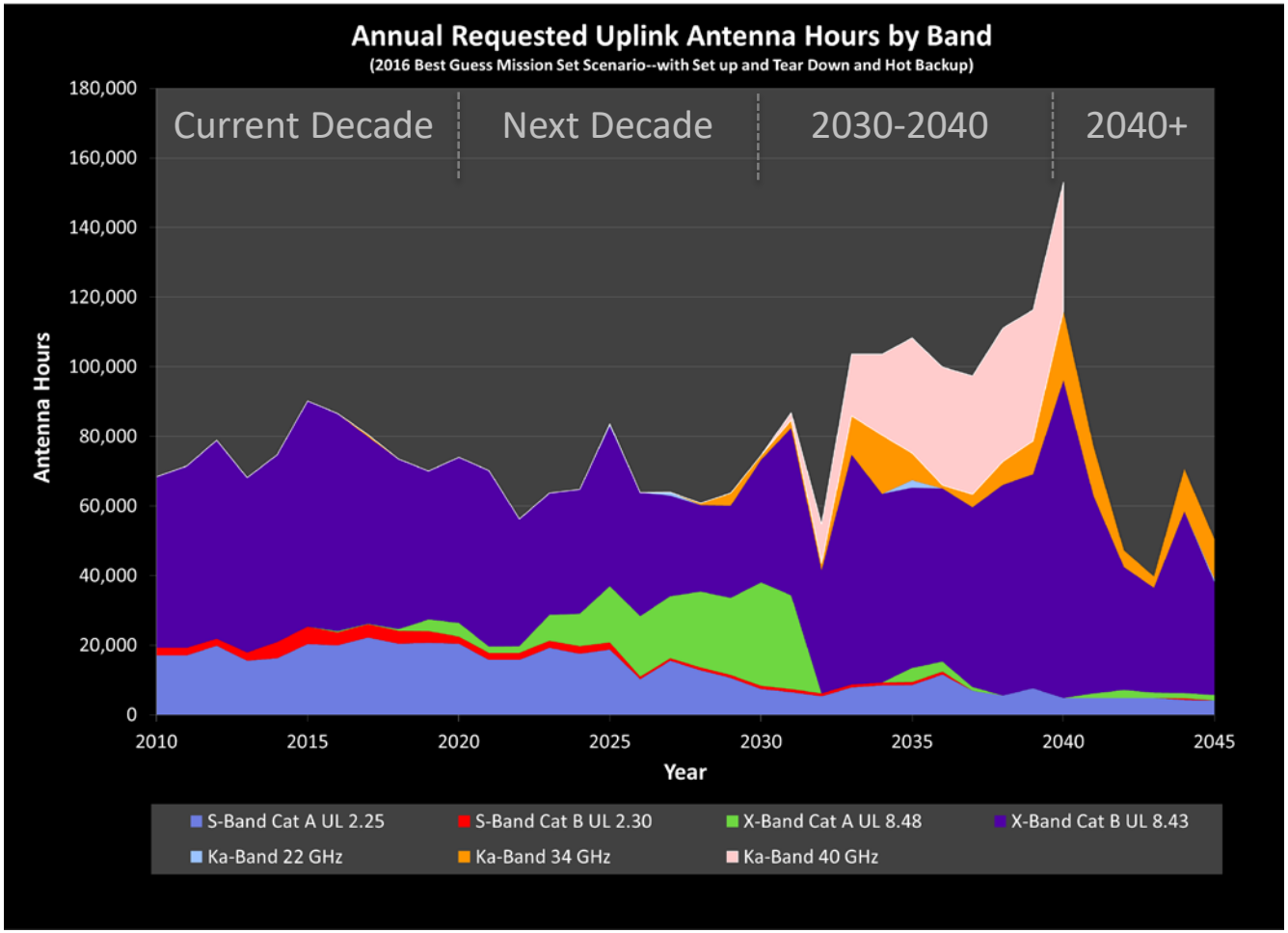
Spectrum Demand by Total Uplink Antenna Hours



Areostationary relay use of 40 GHz leads to substantial antenna hours, even though the number of supported links is relatively small. A high-powered X-band uplink, arrayed 34 GHz uplink, or an optical trunk line might be alternatives.

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Spectrum Summary

Takeaways:

- *The DAEP buildout will address the demand-growth areas.*
  - *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.*
- *The nature of the Mars Areostationary Relays in the human exploration era will drive much of what is needed beyond DAEP.*
  - *37 GHz downlink on multiple antennas that can be arrayed together to meet the required data rates, or optical with 32 GHz arrayed backup, or just optical.*
  - *40 GHz transmitters with possible arraying, or high-power X-band uplink, or arrayed 34 GHz, or optical.*

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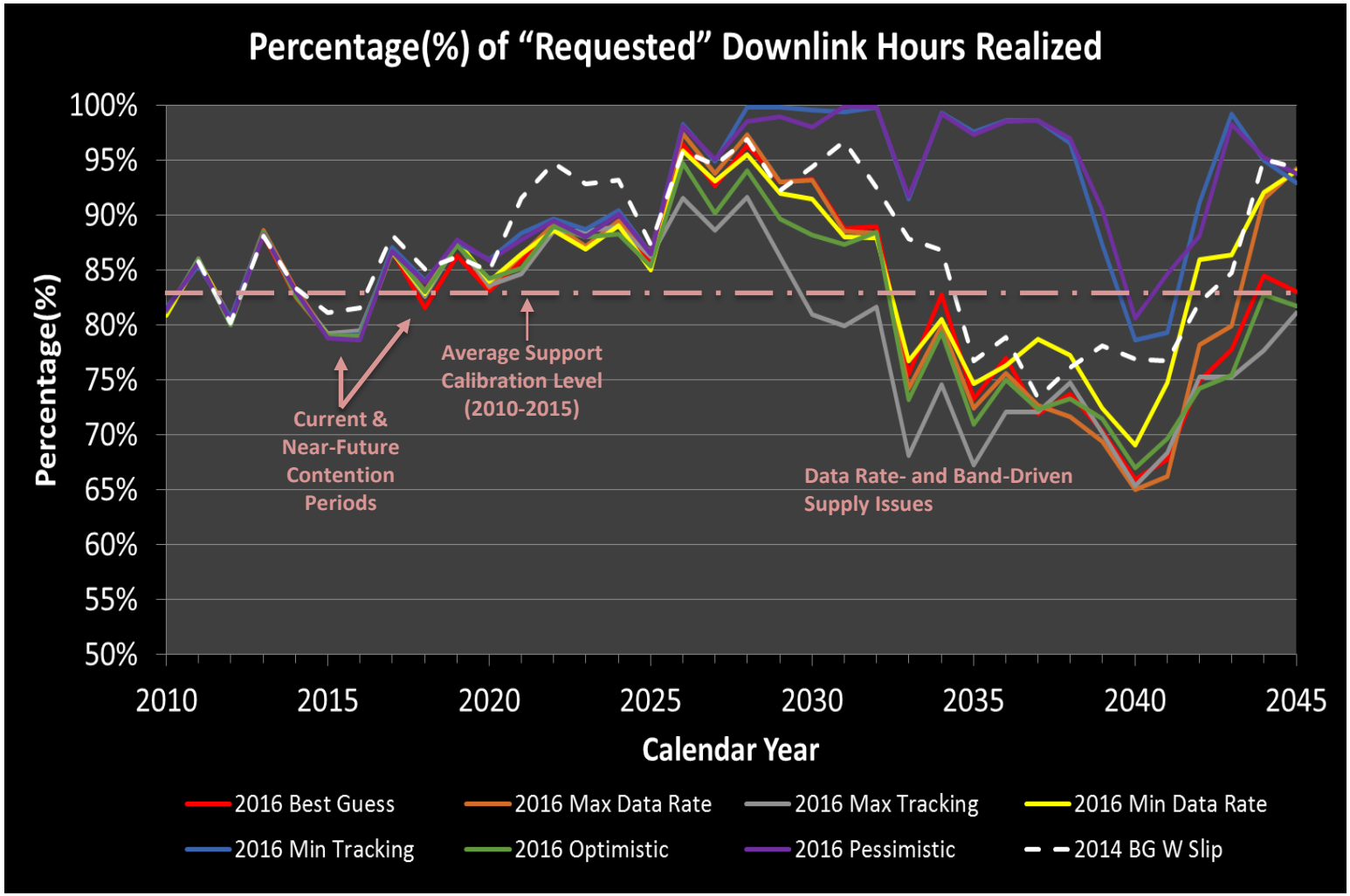
Loading Simulation Results (1/5)



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

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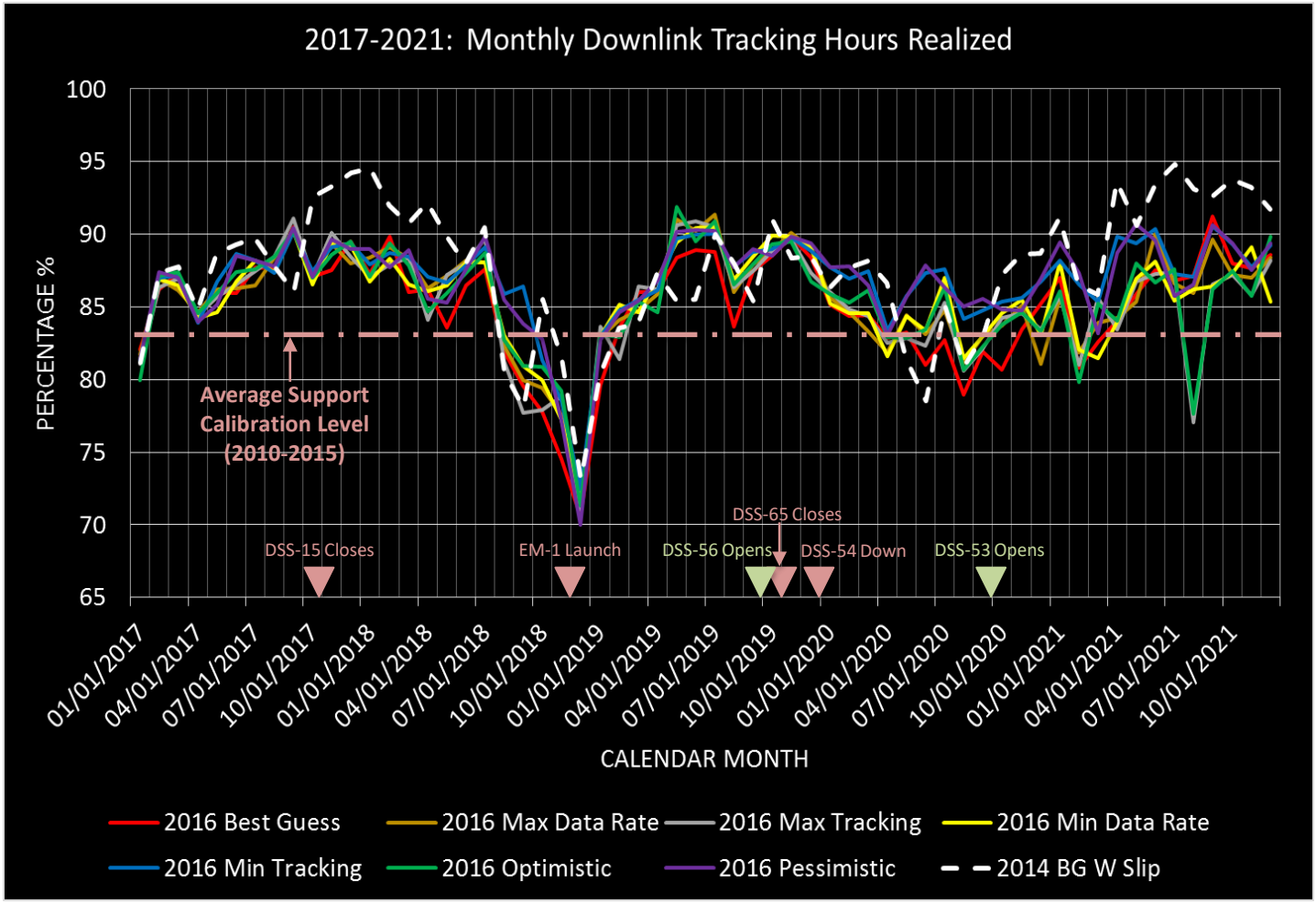
Loading Simulation Results (2/5)



On a monthly basis, peak asset contention starts to become visible – most notably around the EM-1 cubesat secondary payload deployment.

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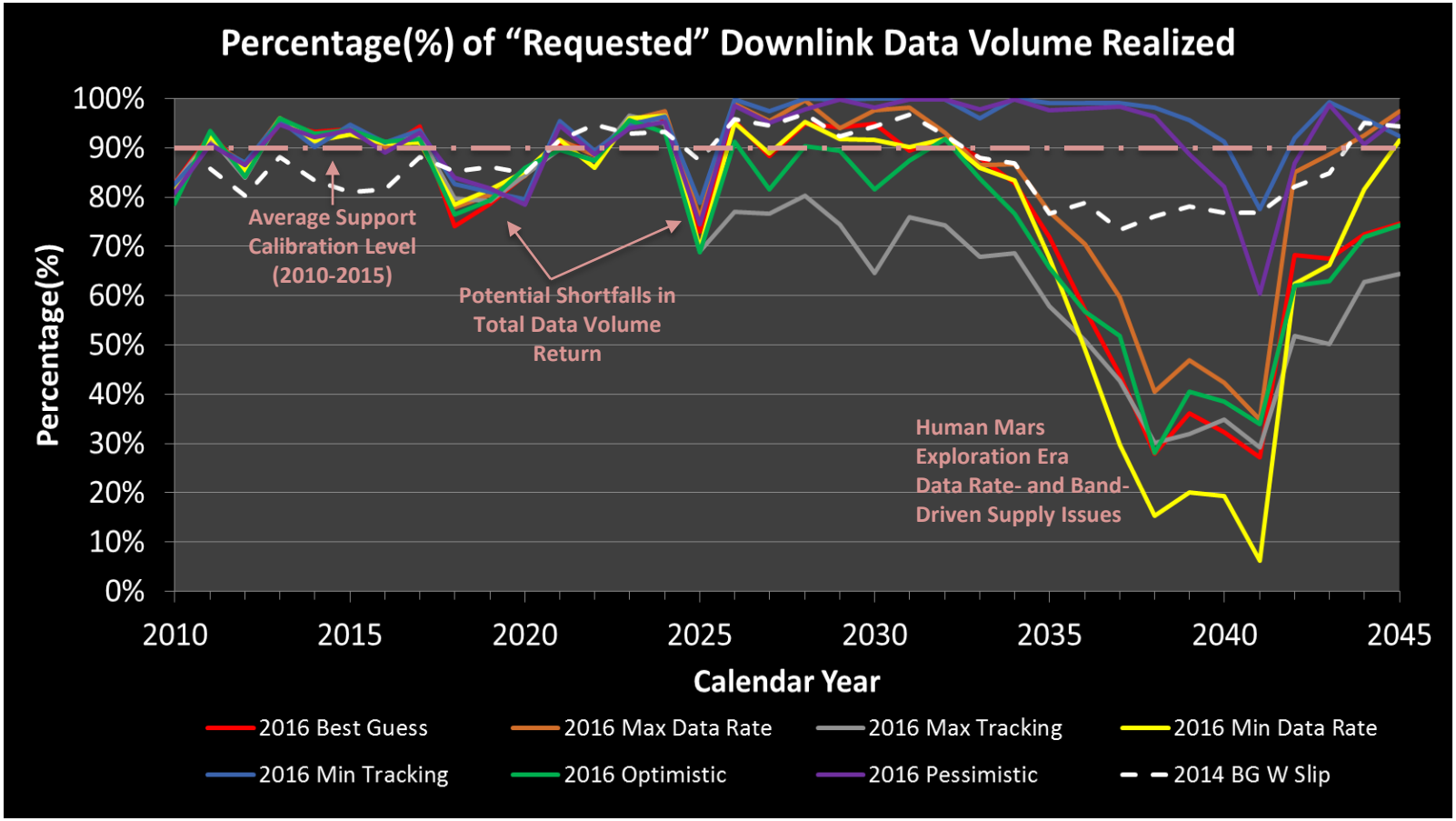
Loading Simulation Results (3/5)



With the emergence of very high data rate missions, even just a couple of unsatisfied tracking passes can have a significant impact on total data volume return. Such conflicts can be actively managed until at least 2035 assuming the DAEP buildout and continued 70m availability.

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Loading Simulation Results (4/5)

Takeaways:

- *Not all antennas share the same downlink frequency band capabilities, nor do they all share the same transmit capabilities. So, simulations may show contention that simple antenna-hour supply vs. demand plots cannot.*
- *Simulations viewed on a monthly basis reveal more peak asset contention than when viewed on an annual basis.*
  - *Peak asset contention appears with respect to EM-1 and its cubesat secondary payload deployments during November-December 2018.*
  - *Capability/capacity shortfalls during the human Mars exploration era are large enough to be readily visible on an annual basis.*

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Loading Simulation Results (5/5)

Takeaways (Continued…):

- *Given the future DSN evolves as assumed in the study, downlink volume simulations suggest that most of the mission set scenarios can be adequately supported during most of the 2020s.*
  - *Total downlink data return in 2018-2019 and 2025 appears to diminish.*
  - *Downlink hours realized, however, does not diminish over the same time periods.*
  - *So, small, low-rate spacecraft appear to be causing large, high-rate spacecraft to miss a small number of "requested" passes – too small to affect realized hours, but large enough to affect total downlink data return. In reality, the scheduling process would actively manage such conflicts.*

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Topics

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Implications (1/6)

- This Decade (and into the Next)
  - Situation: Operating at Capacity
    - Active "down-sizing" of customer requirements during RAP to fit within current capacity.
    - Significant near-term growth in the projected number of supports.
    - "Perfect storm" of launch delays. (E.g., EM-1 and secondary cubesats launching in November 2018. May 2018 launch of InSight and MarCO cubesats has them arriving at Mars in November 2018 during EM-1.)
    - New high-data-rate missions where a few missed passes can result in a substantial reduction in the DSN's total downlink volume return.
  - Challenge: Managing Peak Asset Contention Periods
    - Developing ways to use existing assets more efficiently within available budget.
    - Arranging for alternative assets during peak-load periods.
  - Recommendations:
    - Follow through with assumed future capabilities (4-MSPA, 2nd 26 GHz per Complex, etc.)
    - Consider accelerating introduction of OMSPA and one or more simultaneous multi-spacecraft uplink techniques (e.g., single uplink differentiated by spacecraft ID, with variable turnaround ratios for 2-way Doppler & ranging).
    - Foster alternative asset cross-support capabilities (e.g., MSU, KARI, UAE, Sardinia, etc.).

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Implications (2/6)

- Next Decade
  - Situation: Operating at Capacity & Transitioning to Human Mission Support
    - DAEP buildout marginally keeps pace with projected demand. (Depends, to some extent, on asset-efficient utilization measures developed in prior decade.)
    - Aggregate G/T at X-band and Ka 32 GHz, at best, marginally satisfies average simultaneous demand. Depends on continued 70m availability.
    - With average data rates up 10x to 20x, total data volume return impacts from missed passes become more severe.
    - Data volumes 14 times greater than today move around on the ground.
    - Uplink throughput rates increase to about 4 times today's throughput capability.
    - New 22 GHz uplink users and additional 34 GHz uplink users emerge.
  - Challenge: Upgrading for, and Operating, a Human-Rated System While Meeting Robotic Mission Customer Requirements
    - Safely Operating at capacity while upgrading to the capabilities needed for human exploration.
    - Ensuring return data volume during peak asset contention periods.

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Implications (3/6)

- Next Decade (Continued)
  - Recommendations:
    - Make decisions on which new frequencies to try and support (e.g., 22 GHz, 34 GHz, 37GHz, 40 GHz, etc.). Begin an associated incremental campaign of upgrades.
    - Assess potential throughput "bottlenecks" in ground system as currently planned. For any identified "bottlenecks" to the anticipated data rates and volumes, begin an associated incremental campaign of upgrades.
    - Infuse greater reliance on delay-tolerant networking to help ameliorate contention-driven data volume return problems.
    - Consider augmenting DAEP in the next decade to account for human-mission-driven "hot backup" assets and arraying requirements at Mars distances.

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Implications (4/6)

- The 2030's and Beyond
  - Situation: A Need for Fundamentally New Capability and Capacity
    - Downlink rates from Mars are at least 2 orders of magnitude higher than today's and drive end-to-end link difficulties at least 100 times greater than today's.
    - The number of 34m antennas that have to be arrayed together to satisfy these link requirements exceed the DSN's total capacity, even with the DAEP buildout.
    - Uplink rates to Mars are at least 3 orders of magnitude higher than today's, requiring an EIRP at 40 GHz that is at least 10 times greater than today's X-band capability.
    - The frequency capabilities postulated for the areostationary relay portion of this architecture are not readily available.
      - Antenna surface accuracies suitable for 37-40 GHz
      - Antenna downlink arraying at 37-37.5 GHz
      - High-power 40 GHz transmitters or uplink arraying at 40 GHz
      - Flight-qualified 37/40 GHz spacecraft radios
    - Alternative optical communications infrastructure and flight-qualified spacecraft terminals of the size, power, and modulation types needed are similarly unavailable.

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Implications (5/6)

- The 2030's and Beyond
  - Challenge: Implementing and Operating the Most Cost-Effective Approach for Communicating with Human & Robotic Assets Across the Solar System
    - Determining the most cost-effective combination of RF and optical assets for communicating with Mars system assets.
    - Ensuring that the combination also has cost-effective applicability to communicating with assets across the rest of the solar system.
    - Funding and implementing the necessary new capabilities and capacities next decade while already operating at capacity and transitioning to human mission support.
    - Operating a hybrid RF and optical communications network reliably and efficiently.
  - Recommendations:
    - Begin analysis now. Formulate and conduct technology feasibility studies to assess the cost-effectiveness of particular technical approaches (e.g., high-power X-band uplink, 34 and 40 GHz uplink arraying, high-power optical uplink, space-based optical uplink).

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Implications (6/6)

- The 2030's and Beyond (Continued)
  - Recommendations: (Continued)
    - In parallel with the technology feasibility studies, begin communicating the challenges and associated vision to key decision makers and funding entities.
      - The challenges are complex. Education will take time. One or two briefings to key decision makers will not be sufficient.
    - For the most promising technical approach(es), begin planning flight demonstrations on the next decade's Mars-bound spacecraft.
    - Decide on an approach and begin implementing the necessary infrastructure by 2025, if not before.

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