Carrying On: Iridium NEXT Lithium-Ion Batteries

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IRIDIUM NEXT: 7+ YEARS AND COUNTING

- 66 satellite constellation; 6 planes of 11 satellites each
  - 780 km altitude
  - 86.4 degree inclination
  - 100.48 minute orbital period
  - Beta season ~260 days
  - Dry mass: ~685 kg
- 75 satellites launched between 1/2017 and 1/2019
  - 5 spares launched 5/2023
    - Batteries had been stored for ~6 years

PIONEERS IN THE FIELD

- IRIDIUM NEXT was one of the first fleet-deployed Lithium-Ion batteries for low Earth orbit
- Each battery consists of twenty-eight parallel strings of 9 serially-connected battery cells
- With 80 satellites on orbit, NEXT now has **20,160 battery cells in flight**
- As of April 21, 2024, IRIDIUM NEXT satellites have accumulated:
  - 475 Spacecraft-Years on orbit
  - 2.48 million orbits
  - Over 74 million miles traveled

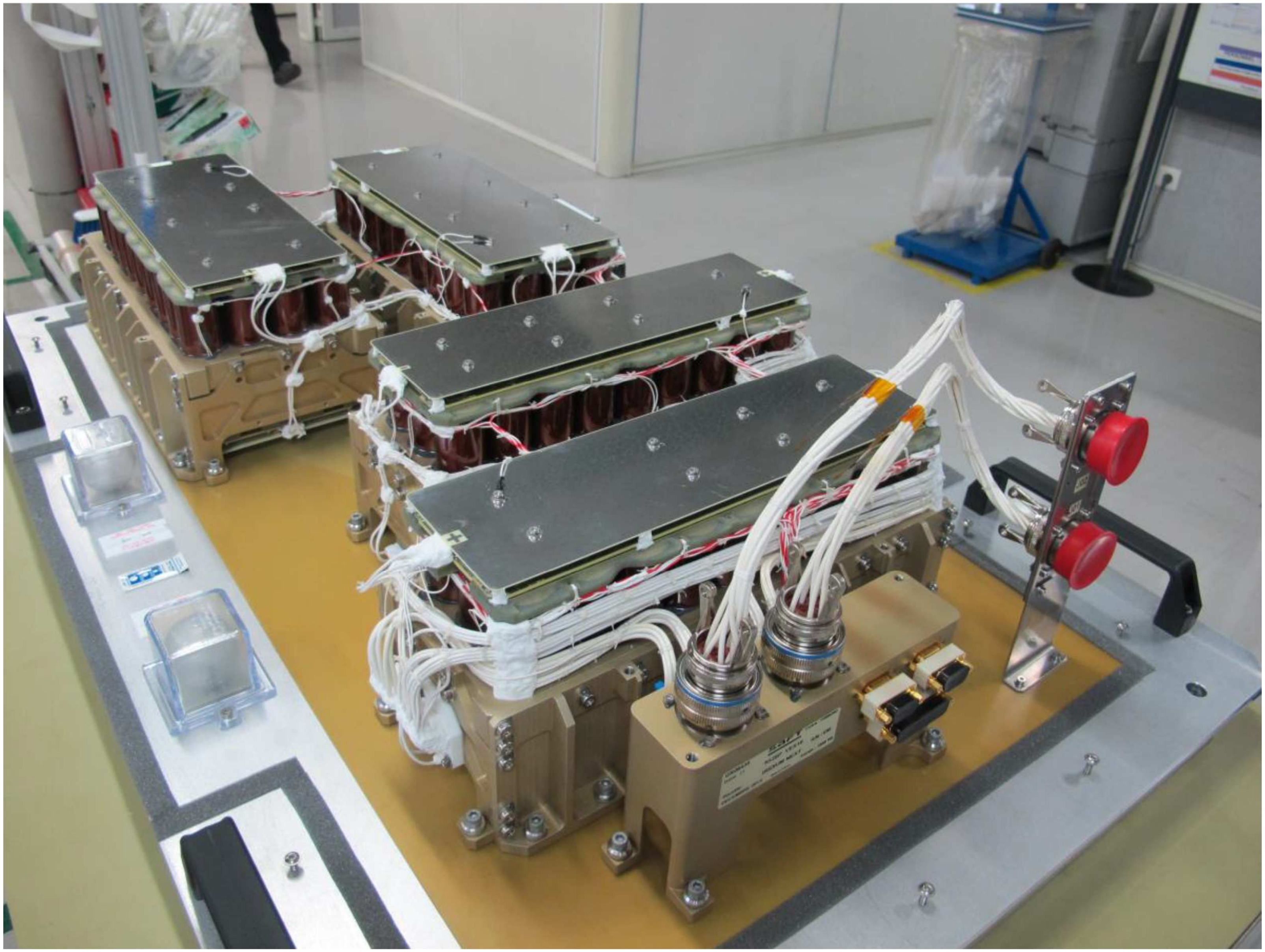
NEXT BATTERIES: 252 "D" CELLS

7.1 MECHANICAL AND ELECTRICAL CHARACTERISTICS

Dimensions (Ø x H)	33 x 60 mm (D-size)
Weight	≤ 115 g
Volume	0.051 dm^3
Voltage range	2.7 V - 4.1 V
Nominal capacity	4.5 Ah @ 4.1V, 20°C
Nominal energy	16 Wh @ 4.1V, 20°C
Specific energy	> 140 Wh/kg (C/3, 20°C)
Internal resistance	≤ 50 mΩ @ 20% DoD
Operating temperature	+10°C / +40°C
Mechanical design margins	EWR & ECSS compliant

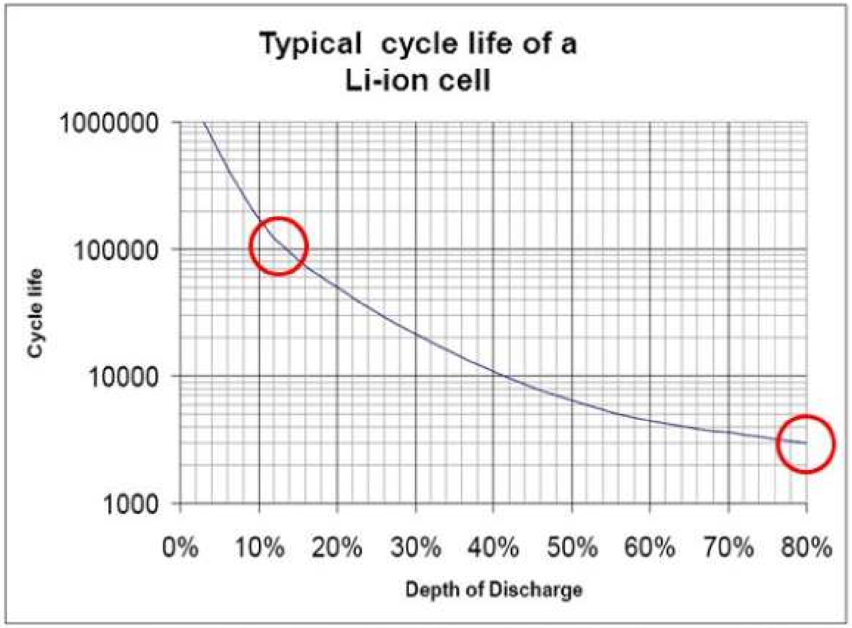
Figure 3: Presentation of a VES16 cell

NEXT BATTERIES: 252 “D” CELLS IN FOUR PACKS



HOW TO MEASURE/ANTICIPATE BATTERY LONGEVITY

1. Account for the number of cycles and the depth-of-discharge (✓)
   - Segregate each range of DOD and assign a weight using a generic Li-Ion curve
   - Assuming wear-out is failure mechanism, sum the weighted cycles vs calendar life and project total life
   - Suggests expected battery life will exceed expected satellite life



Ref: Saft Li-ion LCO/graphite, M. Broussely IMLB12

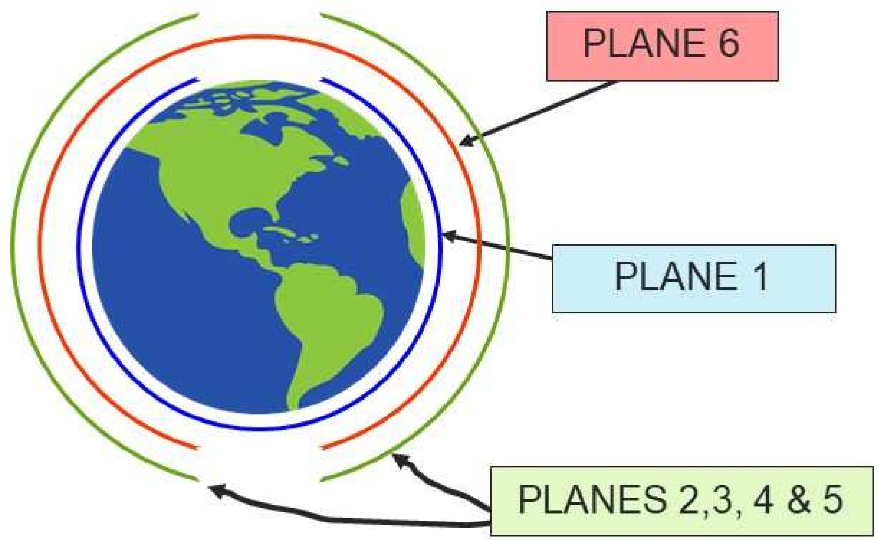
2. Run accelerated life-test (Thales ✓)
   - Shows a maximum of 5% capacity fade after 10 years equivalent cycling

HOW TO MEASURE/ANTICIPATE BATTERY LONGEVITY - 2

3. Trend minimum and/or end-of-discharge voltage (EODV)
   - Problem: Mismatch between TLM sampling rates (multiples of 125 ms) and the Iridium waveform (90 ms), so the various battery voltages manage to sample different parts of the Iridium waveform (Transmit, Receive, Ring/Page) in a round-robin fashion
   - We DO have filtered (2 kHz) voltage telemetry, but generally battery voltages are only sampled every 32 seconds, so an exact EODV is NOT usually captured (filtered or otherwise)
   - Besides, battery current is not sampled concurrent with battery voltage, so it's difficult to correct battery voltage readings for impedance drops
     - Worse, battery currents are combined from two power control units AND are sampled 15ms apart, which means one sample could be from Transmit and the other from Receive, or Ring/Page and Receive, or Transmit and Ring/Page, etc.

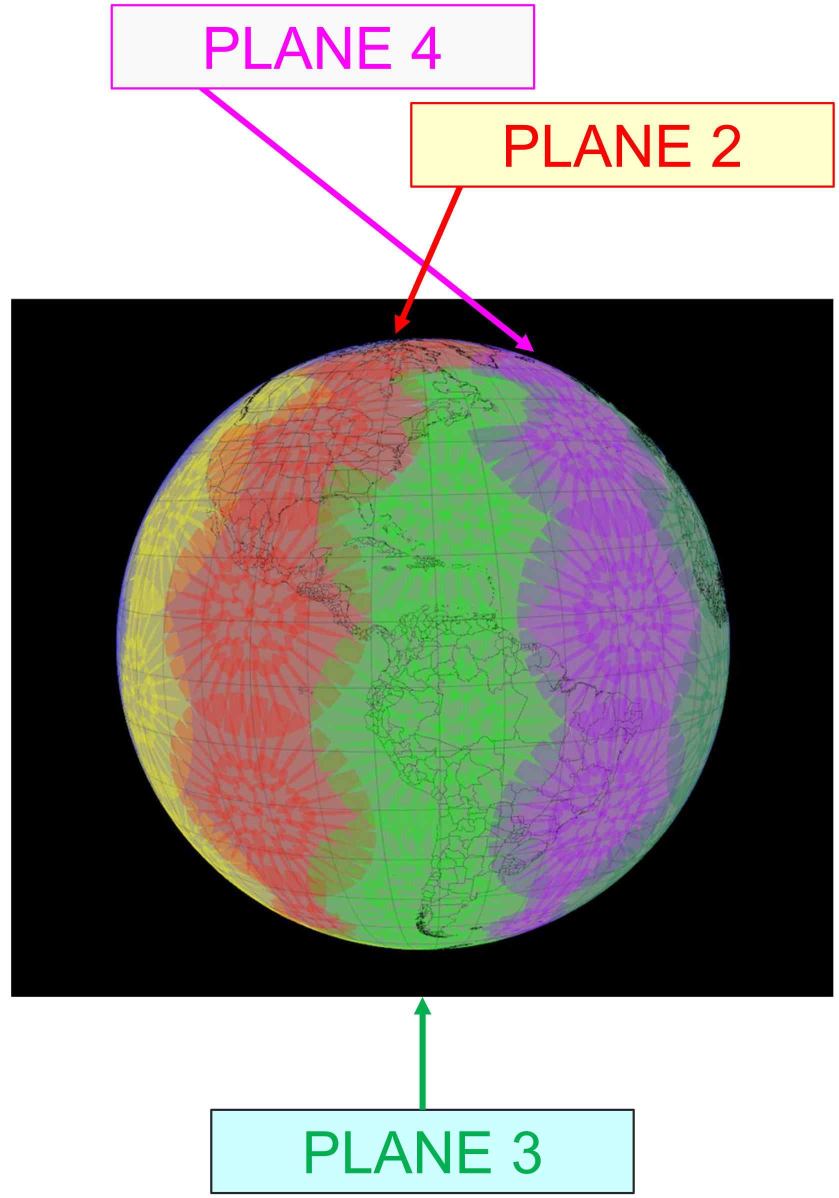
COVER THE EARTH

- Another complication arises from Iridium's service areas being geographically fixed but the Earth's shadow NOT being fixed - moving its center as much as 23.5 degrees north or south of the equator, depending on the time of year
- Iridium covers the entire Earth by specific assignments for each plane of SVs
  - Plane1 is on ~90% of an orbit except over the North Pole
  - Plane6 is on ~90% of an orbit except over the South Pole
  - Planes 2-5 are on ~90% but primarily cover the mid-latitudes
  - Planes 1, 3 and 5 are biased toward the southern hemisphere; 2, 4 & 6 toward the northern hemisphere



A CHALLENGE UNIQUE TO IRIDIUM

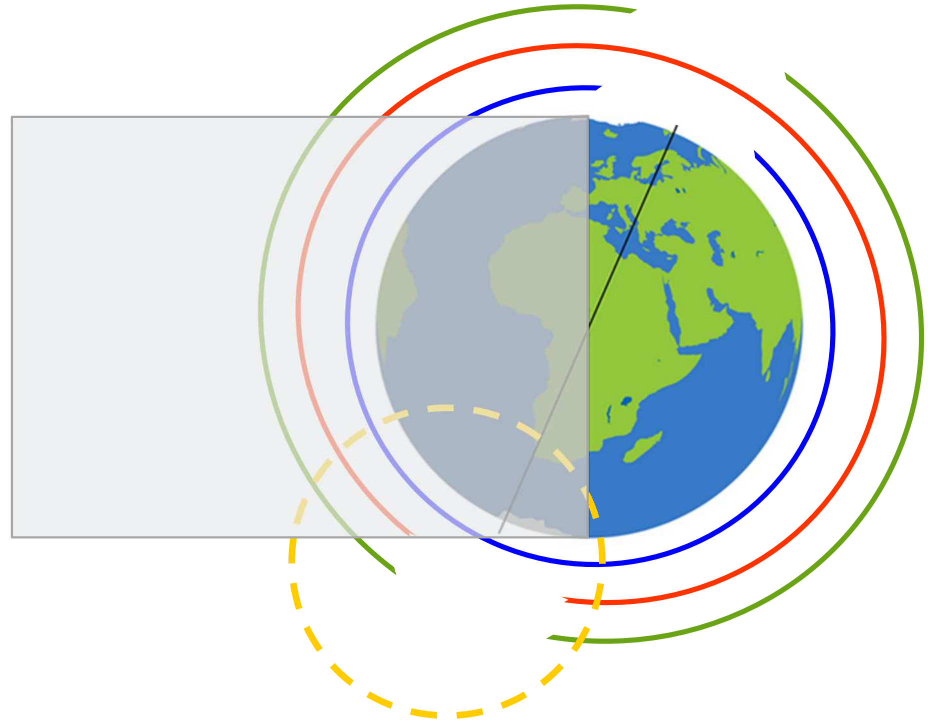
- Given planes cross at the poles, it is necessary to incrementally reduce beam coverage there
  - SV load is ~25% less when beams are Off, which means that battery DOD will be less when beam Off periods overlap with eclipse = less DOD
  - This variable overlap changes as a function of time-of-year
  - In figure at right, Plane3 has reduced beams at the North Pole (before disappearing completely) while planes 2 and 4 do the same at the South Pole

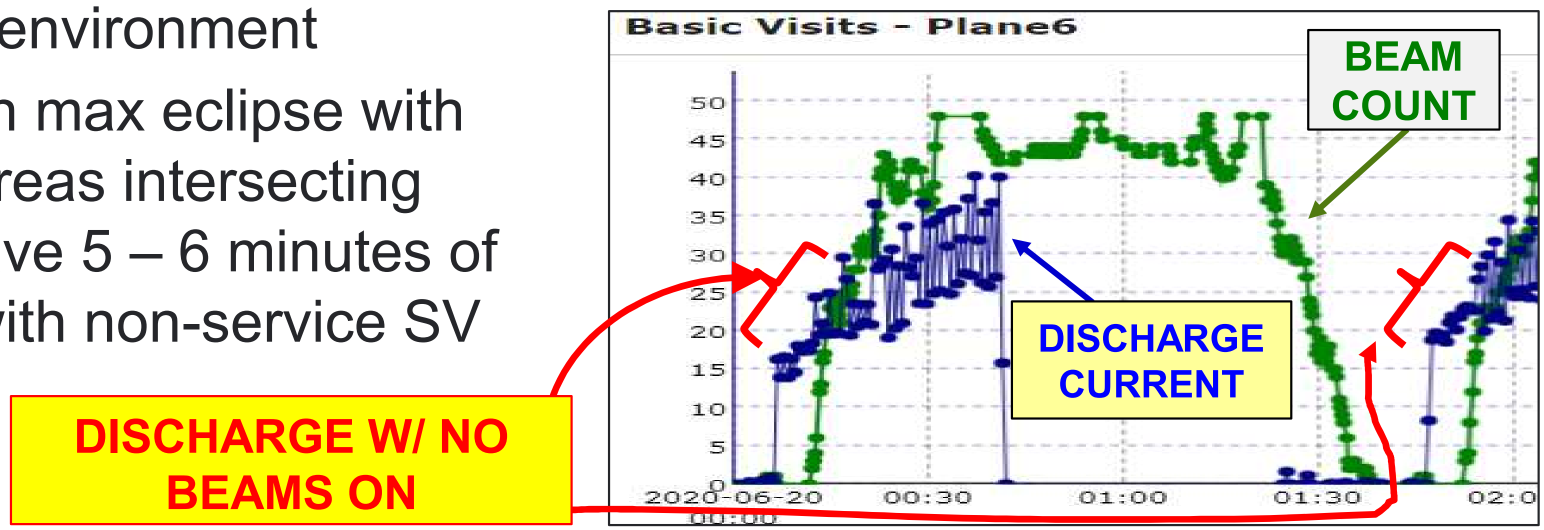


iridium Everywhere

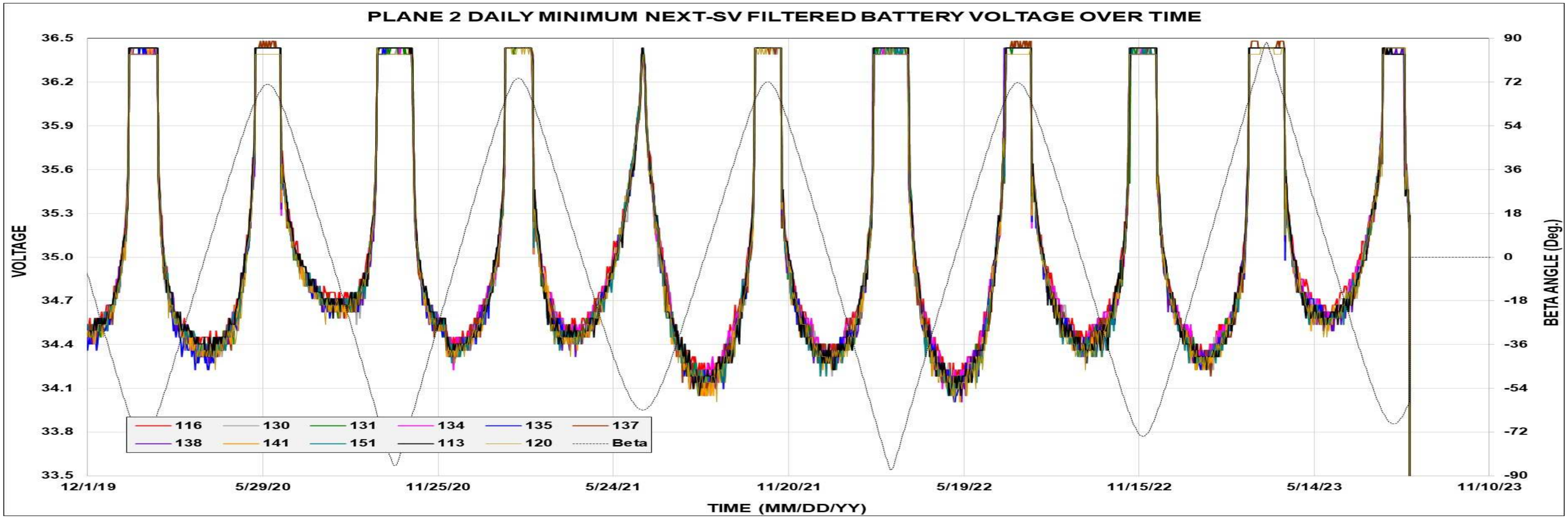
EXAMPLE: NORTHERN HEMISPHERE SUMMER

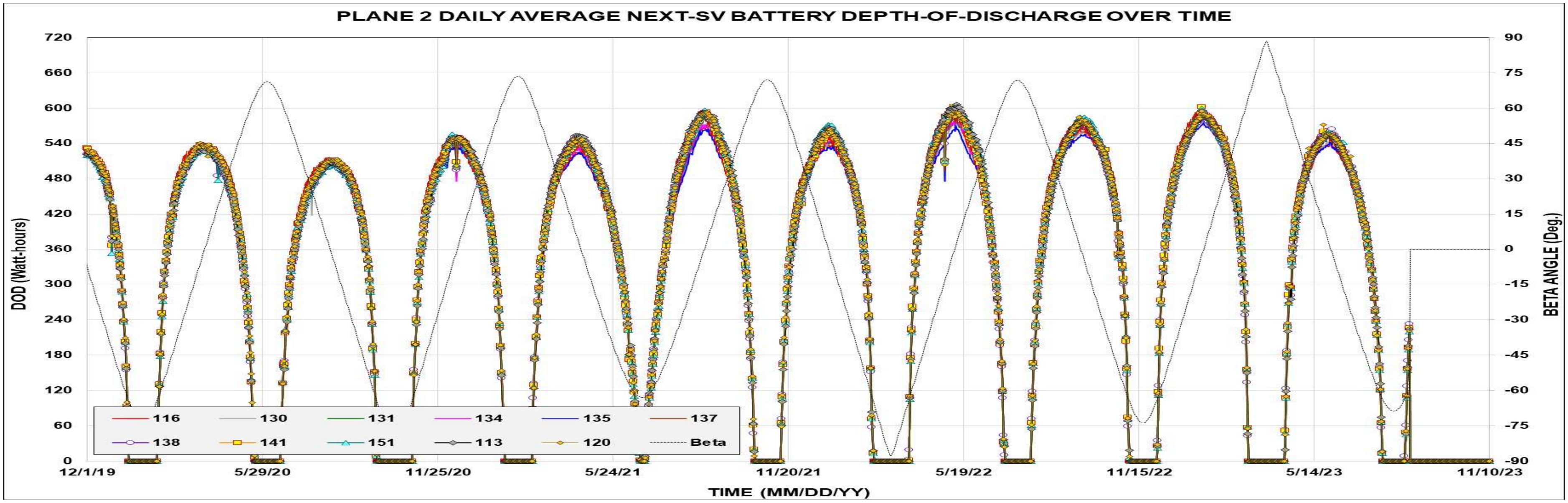
- Except for Plane1, the South Pole non-service areas overlap with the Earth eclipse
  - Lowest average DOD is this time of year
  - Plane6 eclipses partly shifted out of traffic-heavy northern hemisphere
  - Southern hemisphere customers suppressed by time-of-year/weather/environment
  - Any satellite in max eclipse with non-service areas intersecting eclipse will have 5 – 6 minutes of said eclipse with non-service SV loading



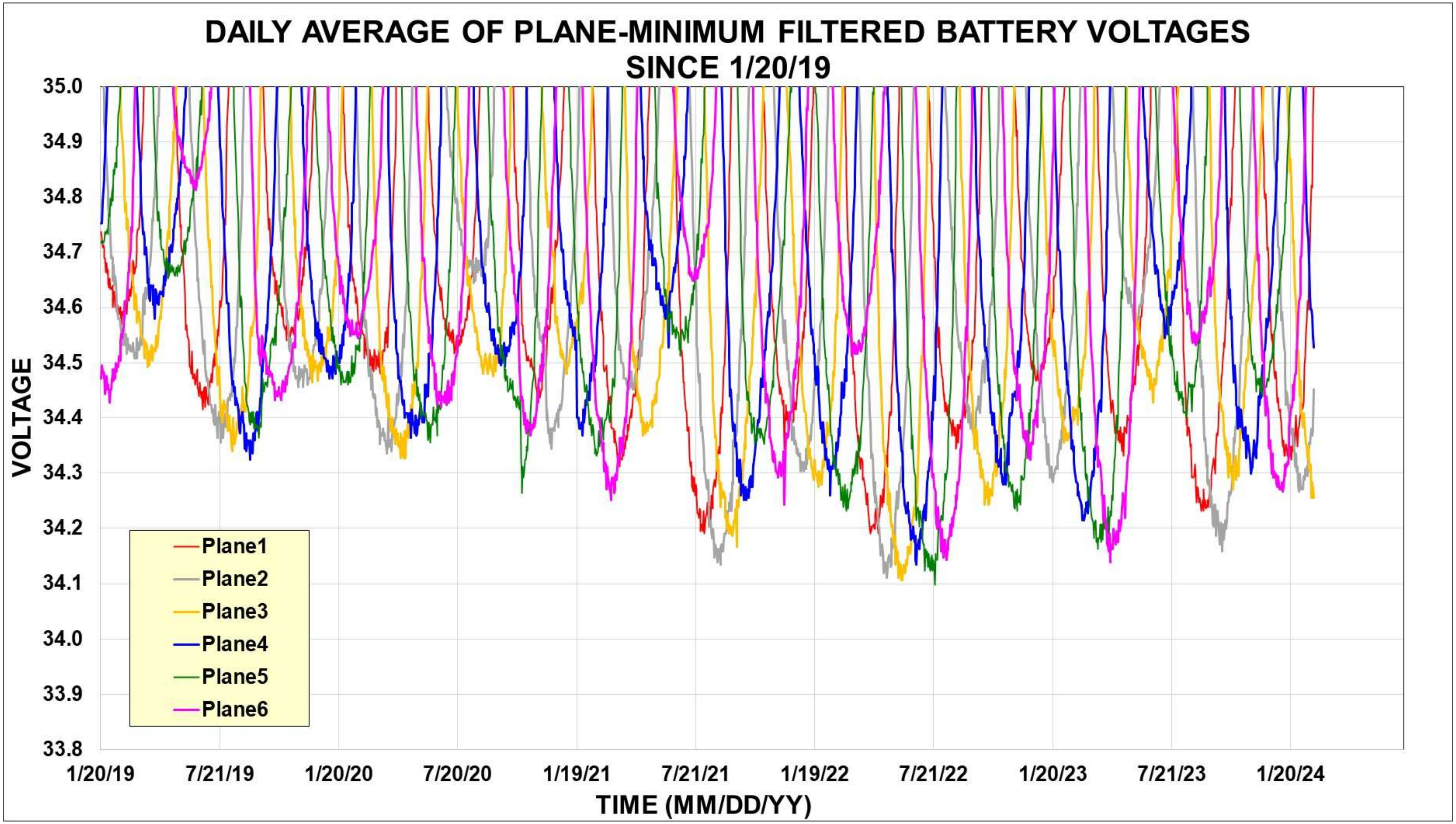


THE UPSHOT: DISJOINTED ECLIPSE SEASONS DIFFICULT TO TREND FOR VOLTAGE

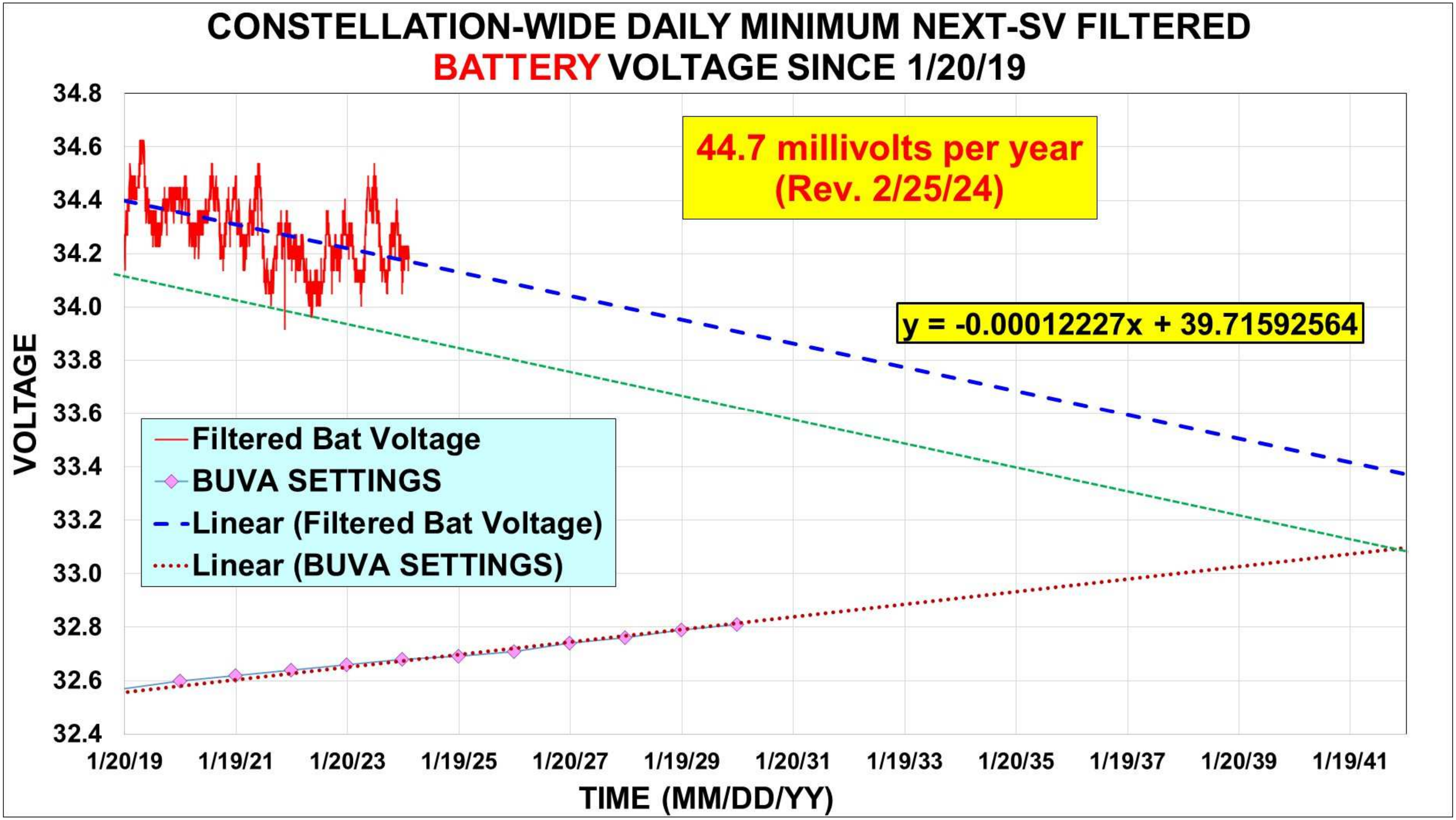




INTERLEAVING ALL 6 PLANES DOESN'T SEEM TO HELP MUCH



APPROACH: TREND THE DAILY MINIMUM VOLTAGE OF THE ENTIRE CONSTELLATION

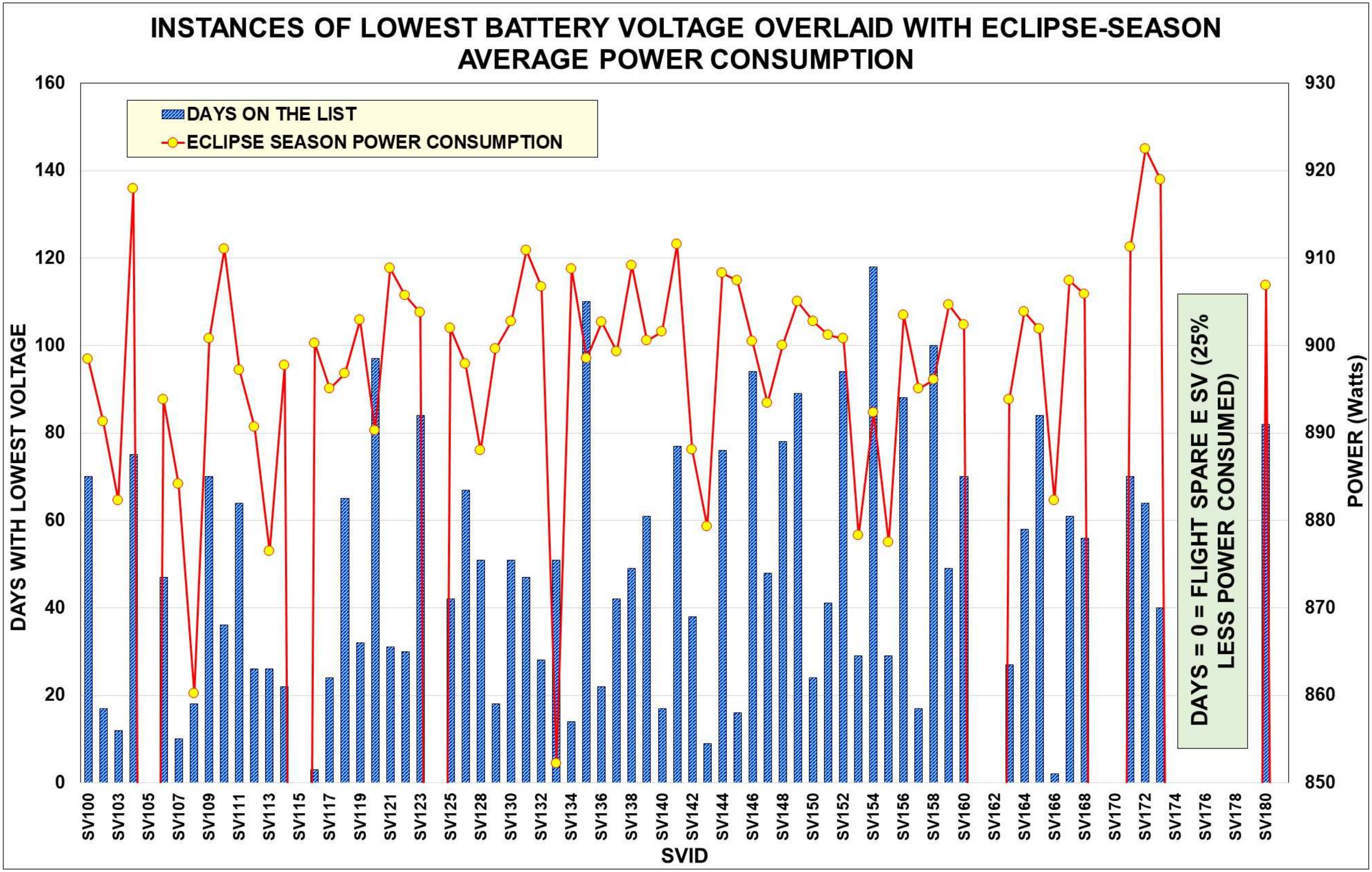


- Trend shows degradation taking years to reach a reserve-capacity voltage limit of 33.00

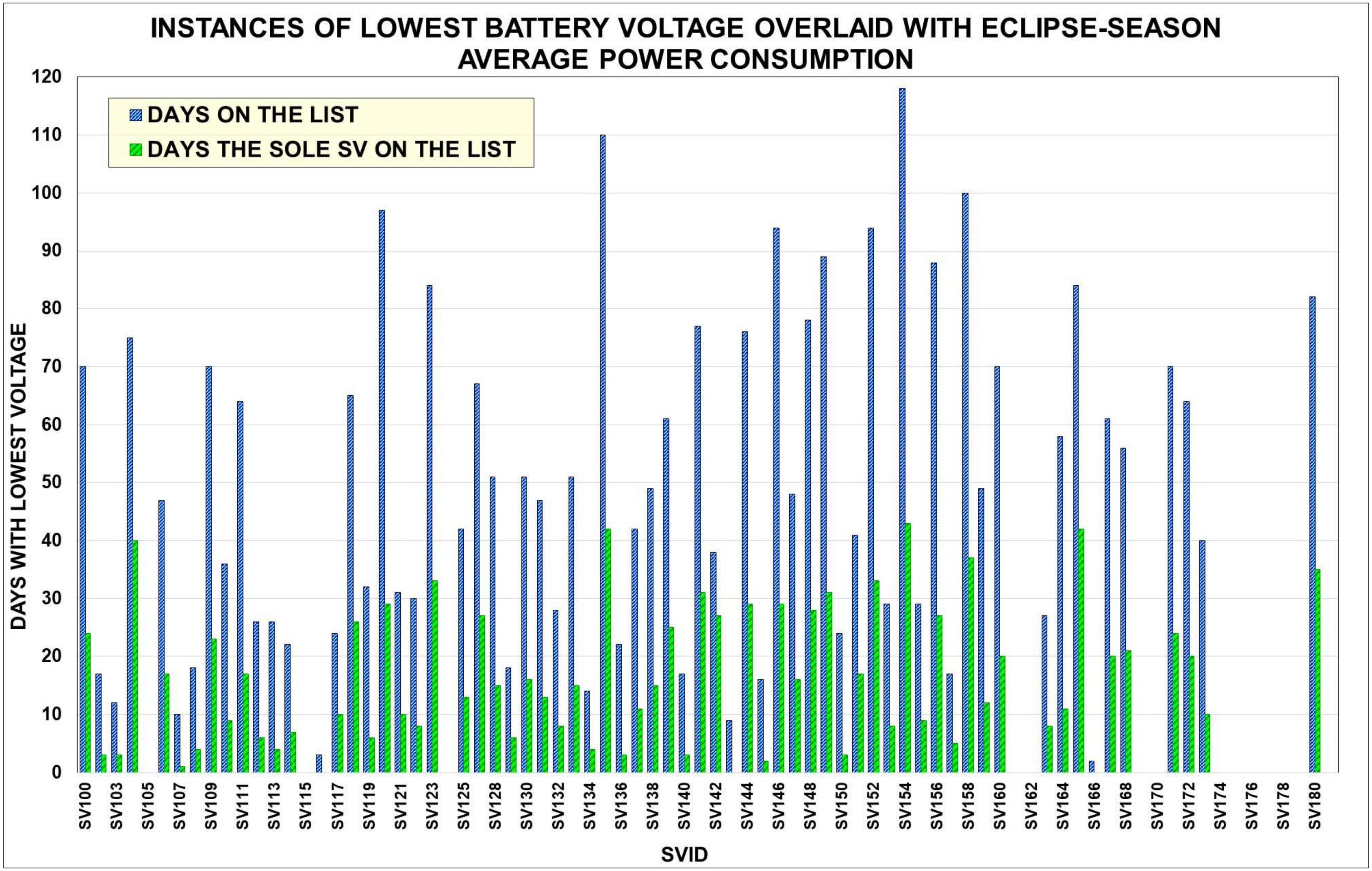
VALIDITY CONSIDERATIONS

- Linear curve-fit of the lowest voltage satellite(s) each day
- Uniform eclipse-season load of 898 watts; 12 watt sigma
- Broad participation across the constellation
  - Every Mission SV is on the list at least 3 times from 1/19/19 - 2/25/24 (HPL permanently on; most stable load configuration); average 49 times
  - On 1094 out of 1863 days, a single SV had the lowest voltage. But for the remainder (41.3%), there were 2 – 10 SVs tied for lowest
- Going forward, any satellite that appears frequently on the daily list (or by itself) could be singled out for closer scrutiny and/or removed from constellation-wide trending
- Keeps with our approach to compare across launches, planes and constellation in other performance measurands

UNIFORM SV POWER CONSUMPTION AND BROAD PARTICIPATION IN VOLTAGE TREND



NO ONE SV IS DRIVING THE CONSTELLATION-WIDE VOLTAGE TREND



CONCLUSIONS

- Dating back 27+ years (to iridium Block-1), it has been important to make performance comparisons across the constellation
  - To understand and document Iridium fleet idiosyncrasies
  - To detect even the slightest anomalies
- Always a need to continuously evolve methods to measure battery performance and try to predict battery life
- We think that trending battery discharge voltage this way complements that data we're receiving from ongoing life-cycle testing at Thales, as well as our accounting of DOD cycle counts as a function of established life-cycle curves

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