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L3 communications

Power Combining Considerations for Prometheus TWTAs

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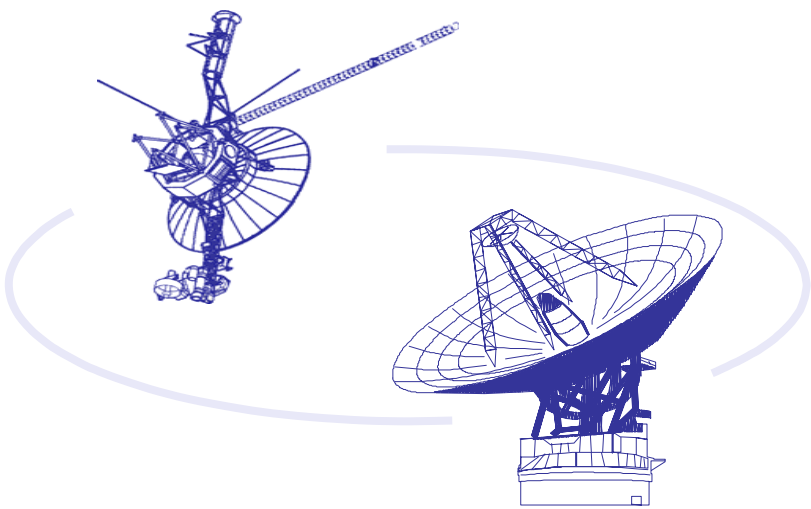
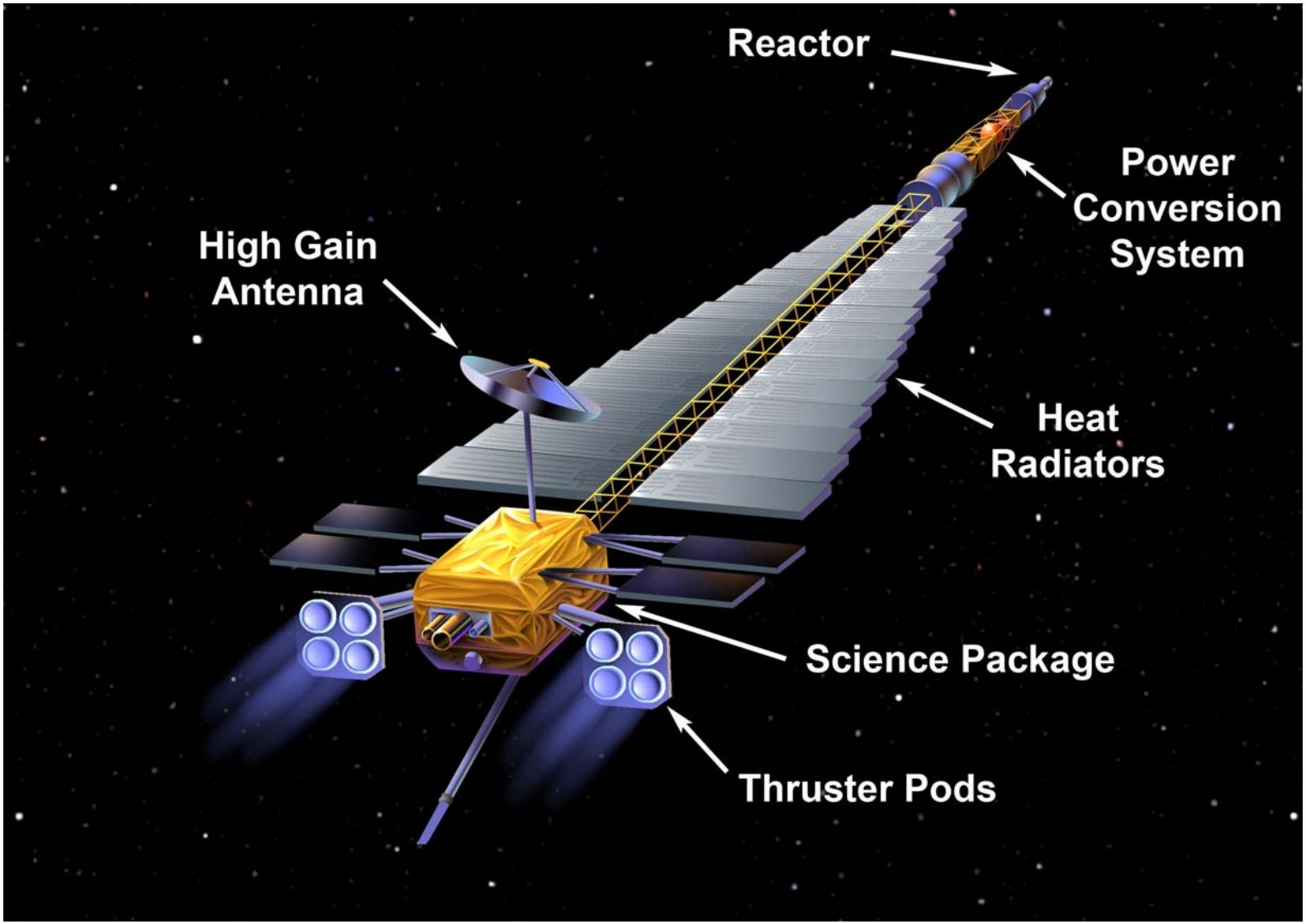


Introduction

- NASA planning a nuclear-electric spacecraft
  - Higher exhaust velocity allows more ambitious missions than chemical propulsion
  - Spacecraft series known generically as “Prometheus”
- One mission considered is to Jupiter’s icy moons
  - Jupiter Icy Moons Orbiter (JIMO)
  - Callisto, Ganymede, Europa
- Spacecraft will orbit each moon in turn
  - Collect data for several months
- Spacecraft will have large prime power capacity for scientific instruments and communications equipment

Prometheus Spacecraft



Communications Requirements

- Science package may generate up to 50 Mbps of data
- 6.2 A.U. (9.3×10^8 km) path length
- Data rate requires use of 32 GHz deep space allocation
- Link calculations result in 1 kW RF CW power needed
  - Greatly exceeds current space-qualified 32 GHz RF sources (e.g., 35 W TWTA for MRO)
- Power and modest bandwidth suggest klystron or EIK
  - However no significant history of space use for these devices
  - (But see CloudSat presentation elsewhere in conference)
- Recent improvements in Ka-band TWTs also suggest power combining
  - 1 kW obtainable from four 250 W devices in parallel
  - Combining inherently redundant

Power Combining

- Combining has significant history of space use (e.g., DTH TV broadcasting, Sirius Satellite Radio, etc.)
- NASA actively pursuing higher power 32 GHz sources
  - 100 W TWT developed, 100 W TWTA in work for MTO
  - JIMO developing 180 W TWT (See L-3 ETI TWT presentation elsewhere in conference)
- Network combining usual method, but spatial combining offers several advantages
  - Reduced susceptibility to multipaction & RF breakdown
  - Electronic beam steering as adjunct to mechanical
  - JPL has done considerable work investigating “cluster” antennas
- Power combining susceptible to phase and amplitude errors

100 W and 180 W Ka-Band TWTs

Four-Beam Cluster Antenna

Spatial Superposition of Four Carriers

$$E(t) = A\sin(\omega t) + B\sin(\omega t + \phi_1) + C\sin(\omega t + \phi_2) + D\sin(\omega t + \phi_3)$$

$$\langle E^2 \rangle = \int_0^T E^2(t)\,dt \Big/ \int_0^T dt \qquad (T = 1/f = 2\pi/\omega)$$

$$\langle E^2 \rangle_{nom} = 8A^2 \qquad \text{(all amplitudes equal \& no phase errors)}$$

$$P_{rel} = \langle E^2 \rangle / \langle E^2 \rangle_{nom}$$

$$P_{rel} = (1/8)\,[\ \tfrac{1}{2}(1 + b_2 + c_2 + d_2) + b\cos\phi_1 + c\cos\phi_2 + d\cos\phi_3 + bc\cos(\phi_1 - \phi_2) + bd\cos(\phi_1 - \phi_3) + cd\cos(\phi_2 - \phi_3)\ ]$$

Amplitude and Phase Variations

- Prediction of ΔP_{rel} requires estimate of amplitude and phase variations
- Two major underlying sources:
  - E_k and/or I_k variations due to EPC drift and aging
    - Effect of ΔE_k completely dominates ΔI_k
  - TWT gain changes with age
- Magnitude of underlying sources estimated empirically
  - Values used in worst-case analyses
- Amplitude and phase variation then predictable via TWT modeling code such as NRL's CHRISTINE 3-D
- Modeled 999HA (180 W) as proxy for future 250 W TWT
  - Assumed underlying variations normally distributed & input drive levels adjusted to keep TWT at saturation

Modeling

- **Two cases modeled: five years of TWTA operation and 20 years of operation**
- **Five year case represents expected usage for JIMO**
  - **Ka-band TWTAs only used to transmit high-rate science data to Earth**
  - **Only occasional "health checks" planned during Earth-Jupiter cruise phase**
- **20 year case is maximum reasonable usage for any other deep space mission (e.g., Neptune/Pluto probe, Kuiper Belt, etc.)**

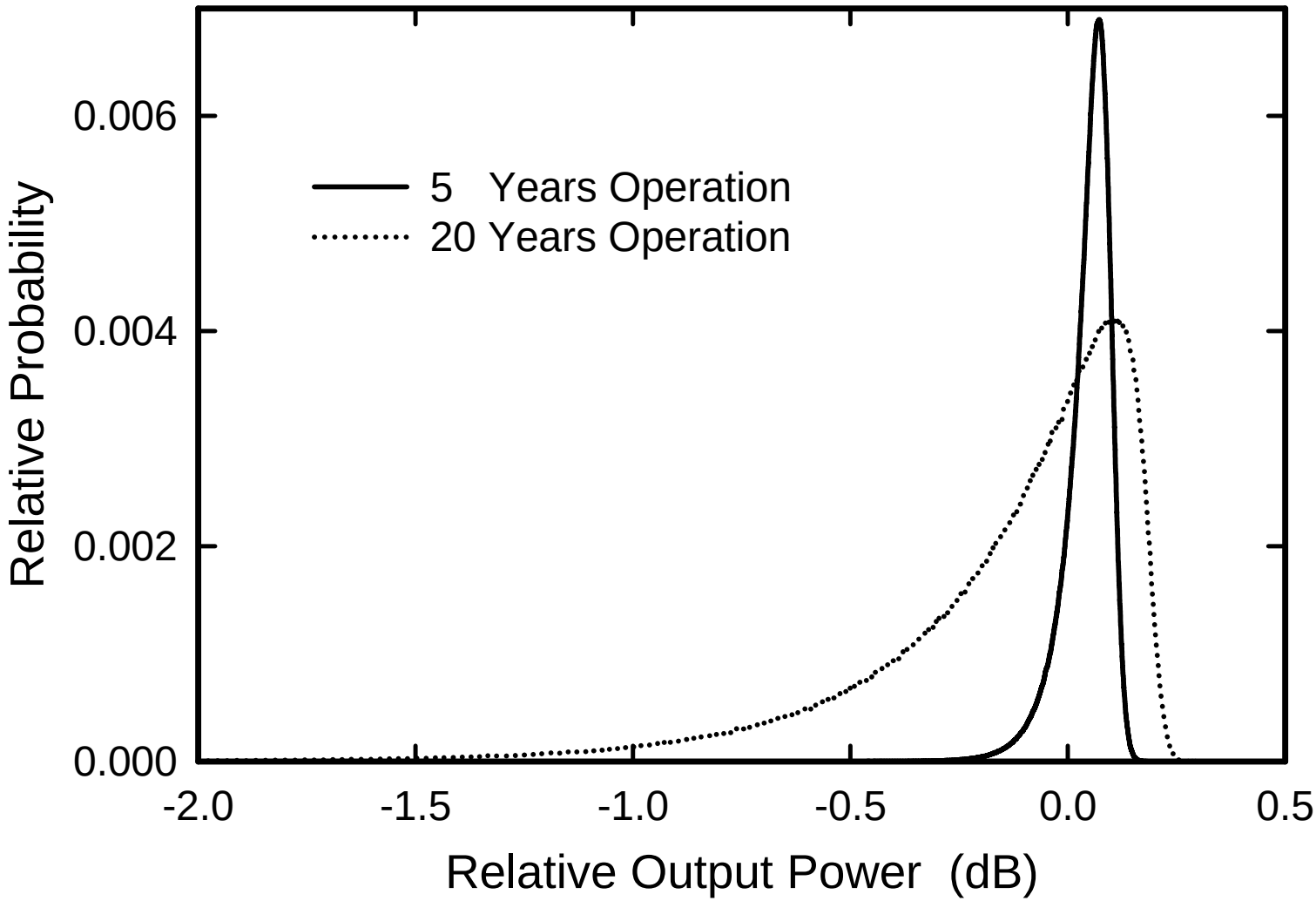
TWT Amplitude and Phase Predictions

	Five Years	20 Years
Phase Variation	±8.6º	±20.6º
Amplitude Variation*	+0.07±0.02 dB	+0.13±0.03 dB

*Assumes I_k constant (by servo loop in EPC) and ignores any de-focusing or other I_b reductions

- These results input to 5 million trial Monte Carlo simulation to predict expected behavior of four power-combined TWTAs

Distribution of Monte Carlo Results



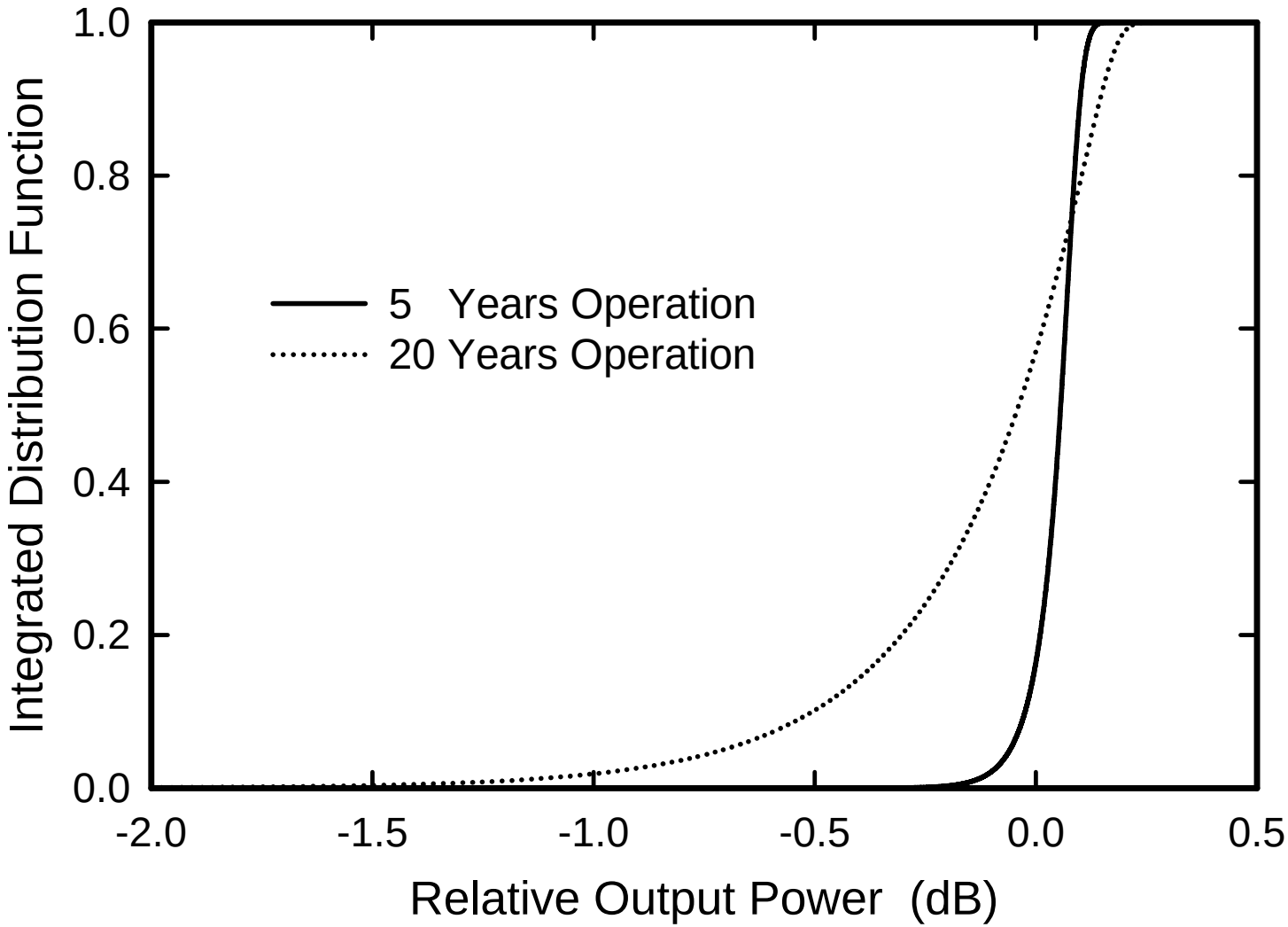
Monte Carlo Statistics for P_{rel}

(all in dB)	Five Years	20 Years
Best Case	+0.20	+0.29
Mean	+0.05	-0.11
Std. Dev.	0.01	0.10
Worst Case	-0.82	-4.5

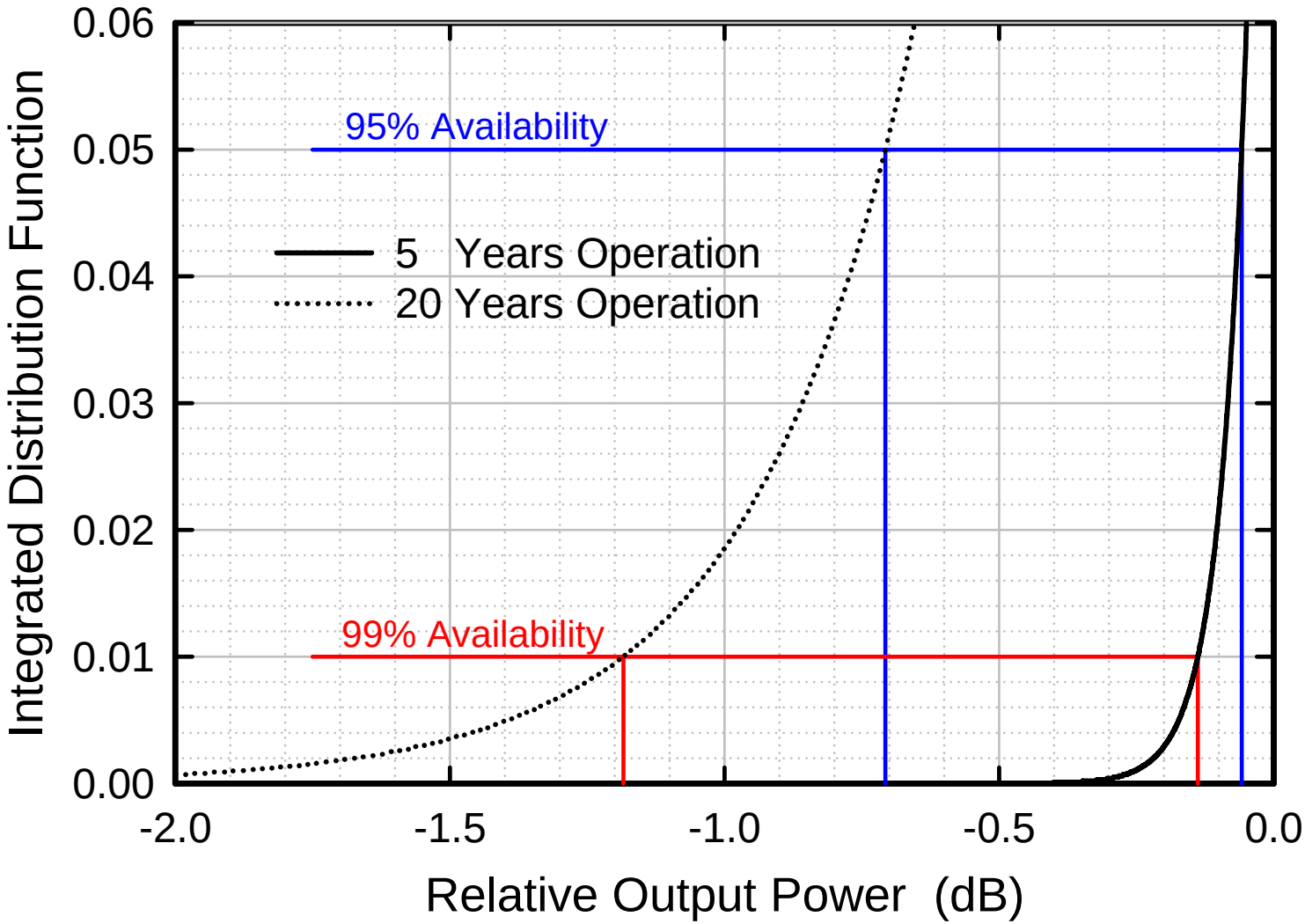
Cumulative Distribution Function

- **Integral of distribution function**
  - **Use histogram as proxy**
  - **More useful method of interpreting Monte Carlo results**
- **Link budgets calculated to ensure a specified link availability**
- **What's important is percent of time RF power greater than some specified minimum**
  - **100% link availability usually not necessary**
  - **Data on deep space probes usually acquired, then stored on-board for possibility of multiple transmission to Earth**

Cumulative Distribution Function



CFD Expanded



Conclusion

- The combining errors of four spatially-combined TWTAs have been modeled using characteristics of currently available devices
  - Errors occur due to inability to control phase and amplitude variations within the TWTAs
- During the JIMO Ka-band TWTA's five years of operation, 99% of the time the combining loss should be no worse than 0.14 dB
  - Expected output power 970 watts at 99% confidence level
- Even for 20 years of operation, loss should be less than 1.2 dB 99% of time
  - Expected output power 760 watts at 99% confidence level
- This analysis has not considered other elements in transmit chain
- Future TWTAs should have improved characteristics