UNDERSTANDING HIGH-THROUGHPUT SATELLITES:

MARKET DISRUPTIONS, TECHNOLOGY, AND VALUE ANALYSIS

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OUTLINE

01 Understanding the technology

02 Markets for HTS: anchor tenant and growth areas

03 Implications for operators and manufacturers

04 Value models of wide-beam satellites and HTS

05 Monte-Carlo value analysis of HTS, comparison with wide-beams

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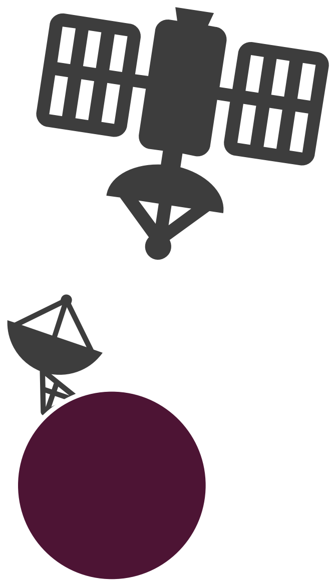

UNDERSTANDING THE TECHNOLOGY

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- High-Throughput Satellites (HTS) are defined by two related key technological features:

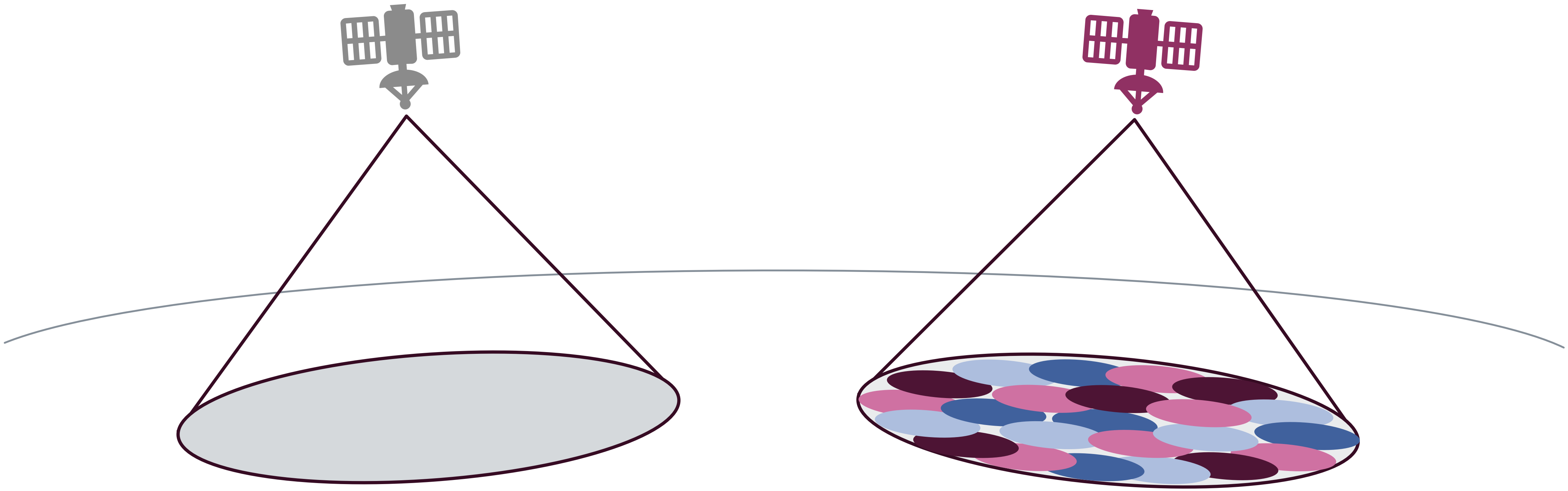
1. The use of **spot beams** covering a small geographic area, with many beams (low 100's) tessellated together to cover a region of interest;
2. The **frequency reuse** of the allocated bandwidth in non-adjacent spot beams.

- This is in contrast with traditional communication satellites that use only a single wide-beam (or just a few).

UNDERSTANDING THE TECHNOLOGY

Traditional Wide-Beam Satellite

High-Throughput Satellite



UNDERSTANDING THE TECHNOLOGY

Input:
The limited resource

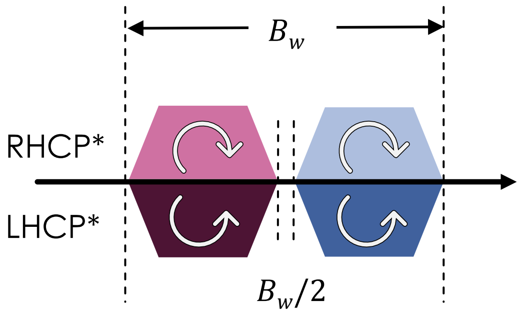
The HTS work-around

Significantly
expanded resource

Output:
Total throughput

Allocated bandwidth, B_w → **"Colors"** per spot beam → **Frequency reuse** in non-adjacent spot beams → Total bandwidth, B_{total} → Spectral efficiency, β → Total throughput, R_{total}

Example of four colors



* right/left hand circular polarization

$$B_{total} = \underbrace{\left(\frac{N_p N_b}{N_c}\right)}_{\text{frequency reuse factor}} B_w (1 - \eta_{guard})$$

N_p: number of polarization (1 or 2)
N_c: number of colors
N_b: number of beams
η_{guard}: guard band, typically 5% to 10%

$$R_{total} = \beta \cdot B_{total}$$

β: spectral efficiency

UNDERSTANDING THE TECHNOLOGY

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For example:

- Allocated bandwidth, $B_w = 3\ GHz$ with 2 sub-bands.
  - Number of polarizations, $N_p = 2$
  - Number of colors, $N_c = 4$
  - Number of spot beams, $N_b = 72$
  - Guard band, $\eta_{guard} = 0$
- Total bandwidth, $B_{total} = \left(\frac{2 \cdot 72}{4}\right)(3\ GHz) = \mathbf{108\ GHz}$

UNDERSTANDING THE TECHNOLOGY

$$B_{total} = \underbrace{\left(\frac{N_p N_b}{N_c}\right)}_{\text{frequency reuse factor}} B_w(1 - \eta_{guard})$$

N_p: *number of polarizations* (1 *or* 2)
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- The allocated bandwidth of 3 GHz has turned into an effective total bandwidth of 150 GHz!
- This total bandwidth (GHz) is in turn transformed into throughput (Gbps) through the intercession of spectral efficiency, β.

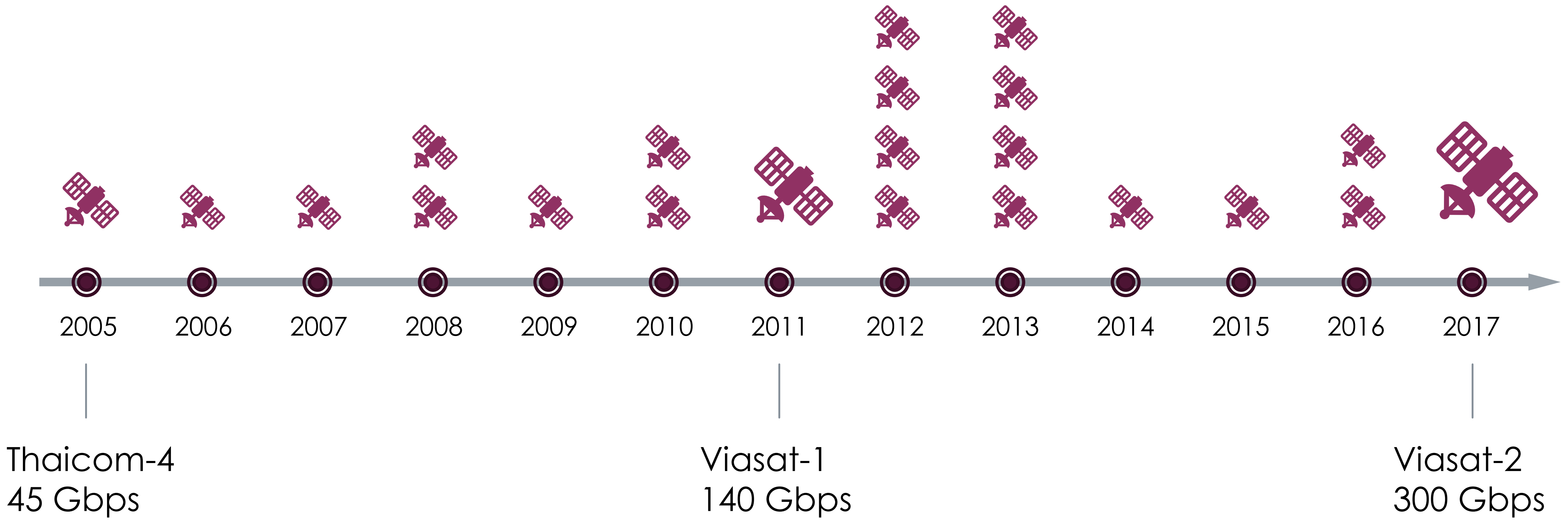
$$R_{total} = \beta \cdot B_{total}$$

β: *spectral efficiency*

- Total throughput, $R_{total} = \left(3\,\frac{Gbps}{GHz}\right)(100\ GHz) = \mathbf{300\ Gbps}$

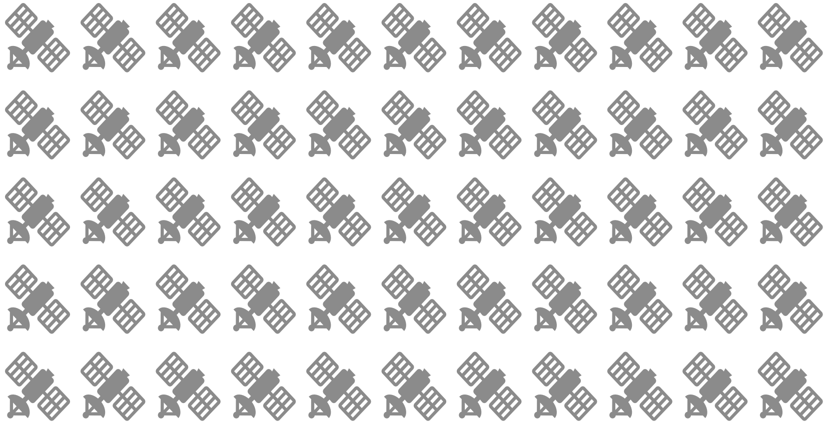
UNDERSTANDING THE TECHNOLOGY

- Timeline of GEO HTS launches



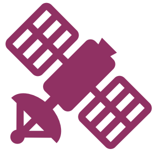
UNDERSTANDING THE TECHNOLOGY

Traditional Wide-Beam Satellites



Intelsat GEO Fleet (50)
combined throughput: **120 Gbps**

High-Throughput Satellite



Viasat-2 GEO HTS
throughput: **300 Gbps**

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MARKETS FOR HTS: ANCHOR TENANT AND GROWTH AREAS

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Critical Markets for Success

1. **Consumer broadband**
   - Residential connectivity, aeronautical/maritime mobility
   - Remote corporate connectivity, connecting the unconnected

2. **Government connectivity and support for military**
   - Department of Defense
   - Support for military, new war-fighter applications

3. **Data relay / cellular backhaul**
   - Remote base stations

4. **Internet of things (IoT) applications**
   - Not currently seen as ripe for HTS solutions
   - the connected car might be an exception.

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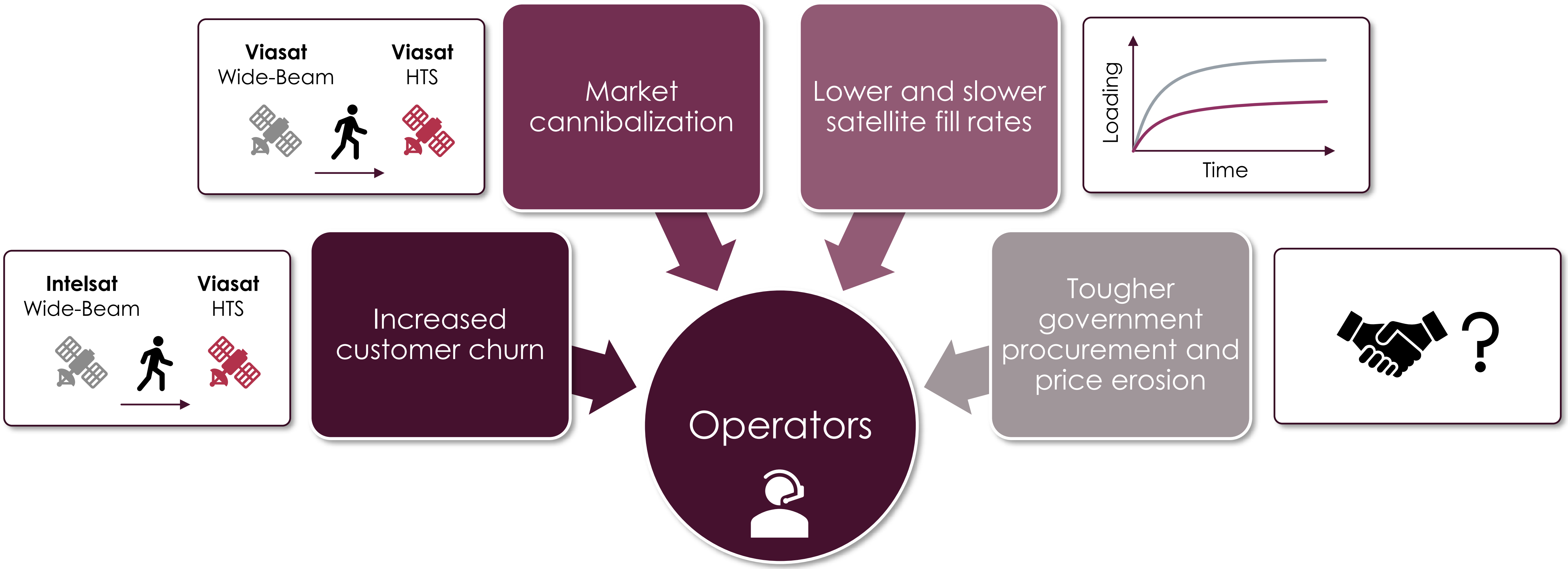
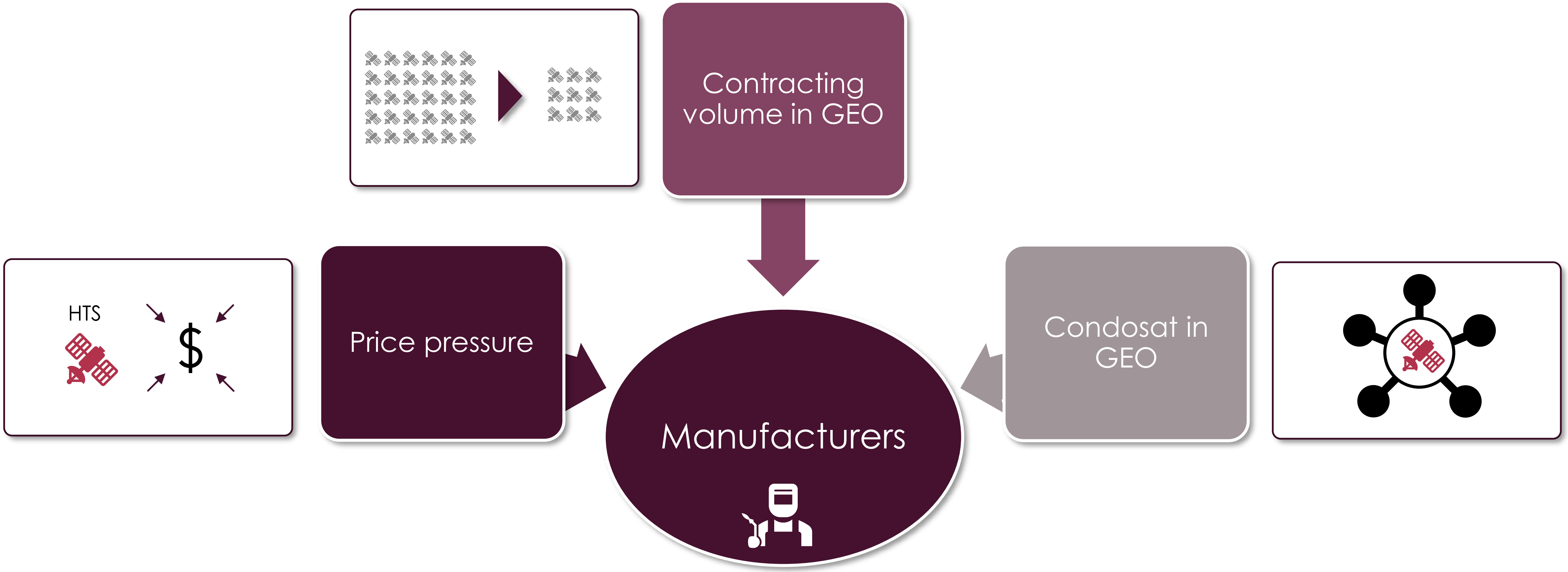


IMPLICATIONS FOR OPERATORS AND MANUFACTURERS



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VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

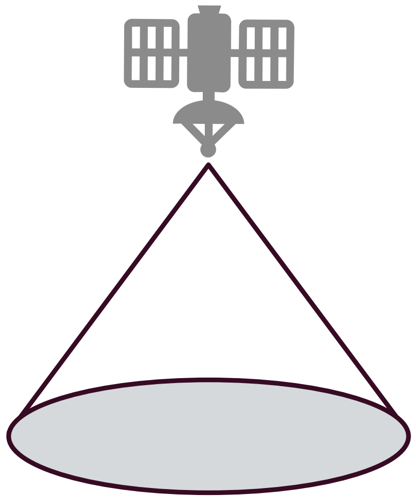
- We define the Net Present Value (NPV) of a satellite as the difference between all revenue accrued and all costs incurred from the perspective of discounted cash flow.

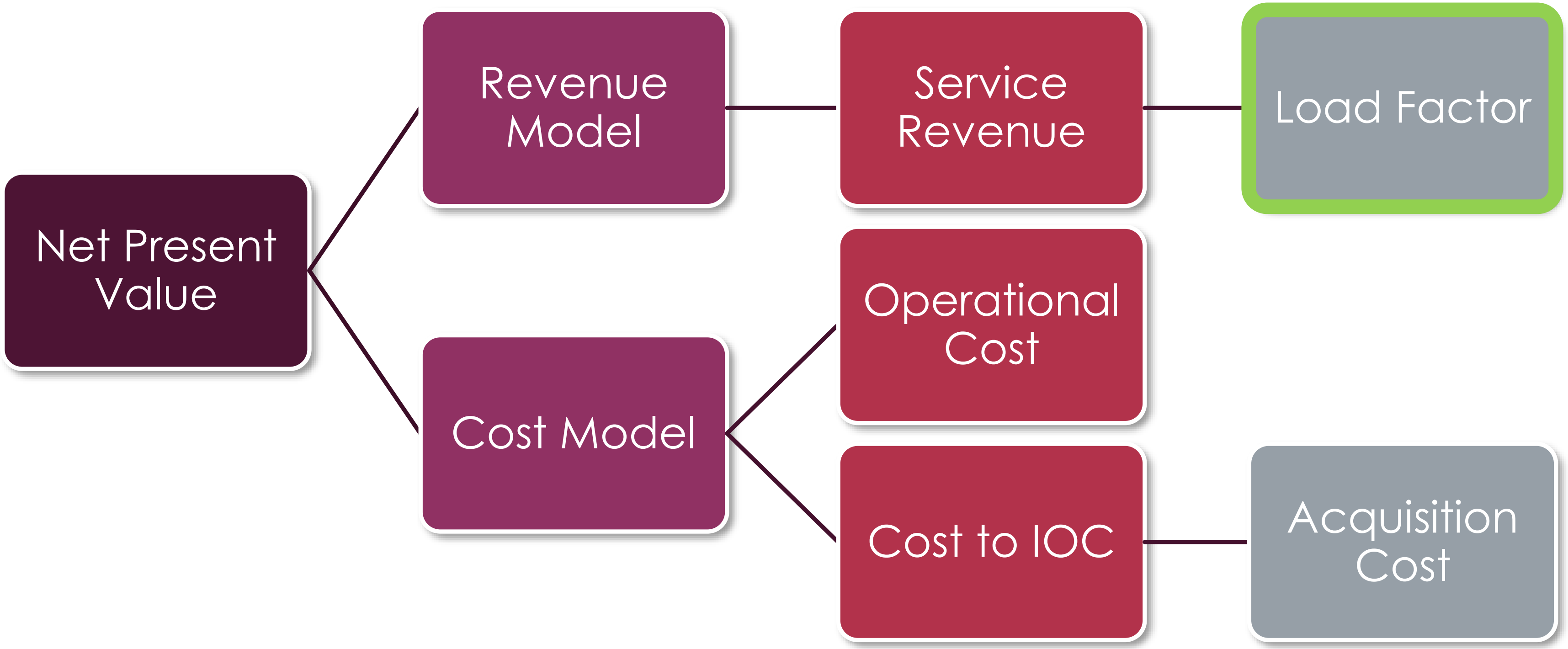
$$NPV \equiv Present\ Value\ of\ Revenue\ Accrued\ -Present\ Value\ of\ Costs\ Incurred$$

- All the following analytics are focused on accurately capturing the revenue and cost models of a satellite.

VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

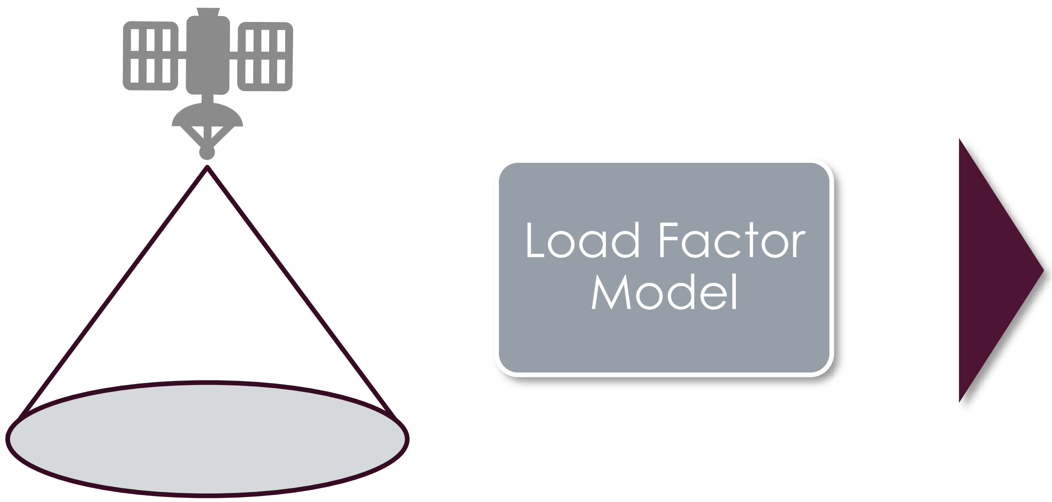
- Wide-beam satellite value model





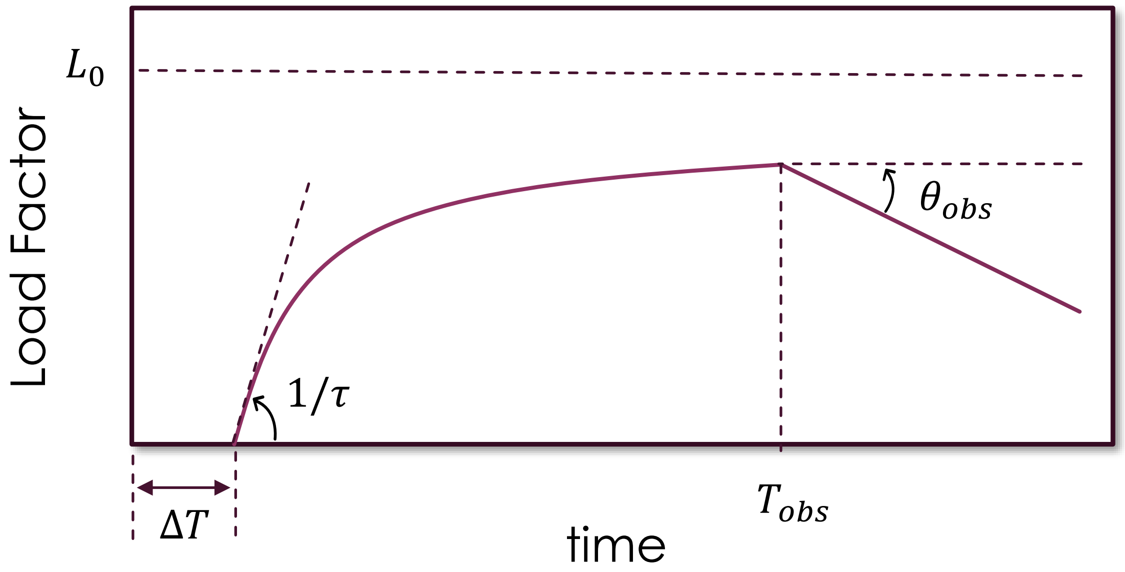
VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

- Wide-beam Load Factor Model:



τ reflects time to 95%

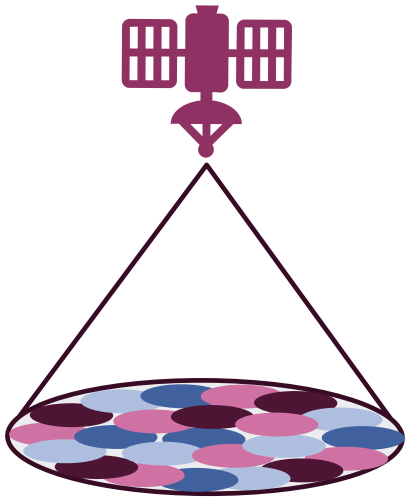
θ_{obs} reflects intensity of obsolescence

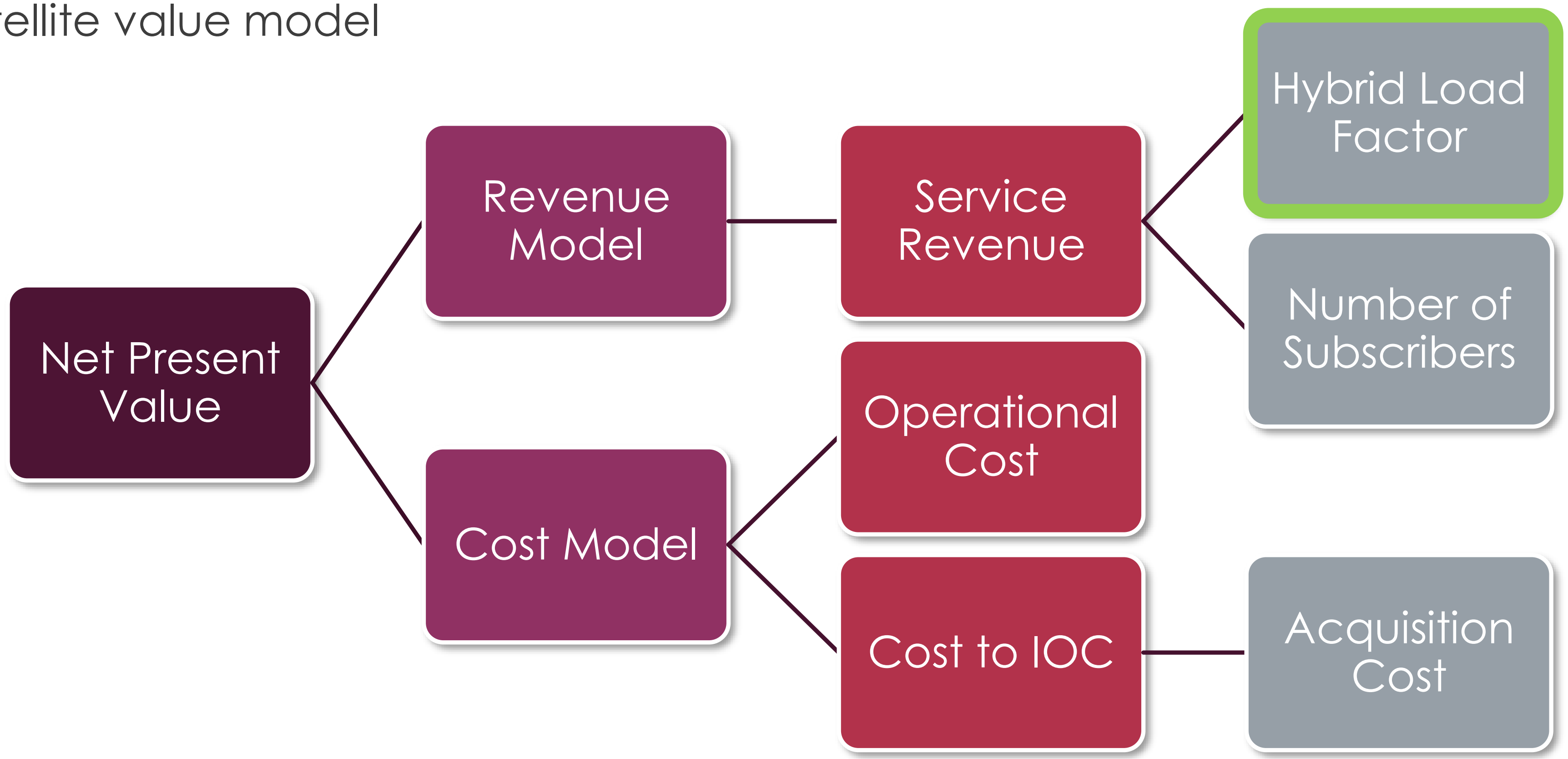


$Load\ Factor \equiv \%\ of\ leased\ transponders$

VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

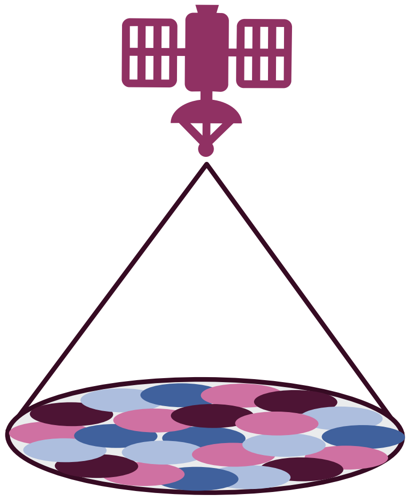
- High-throughput satellite value model



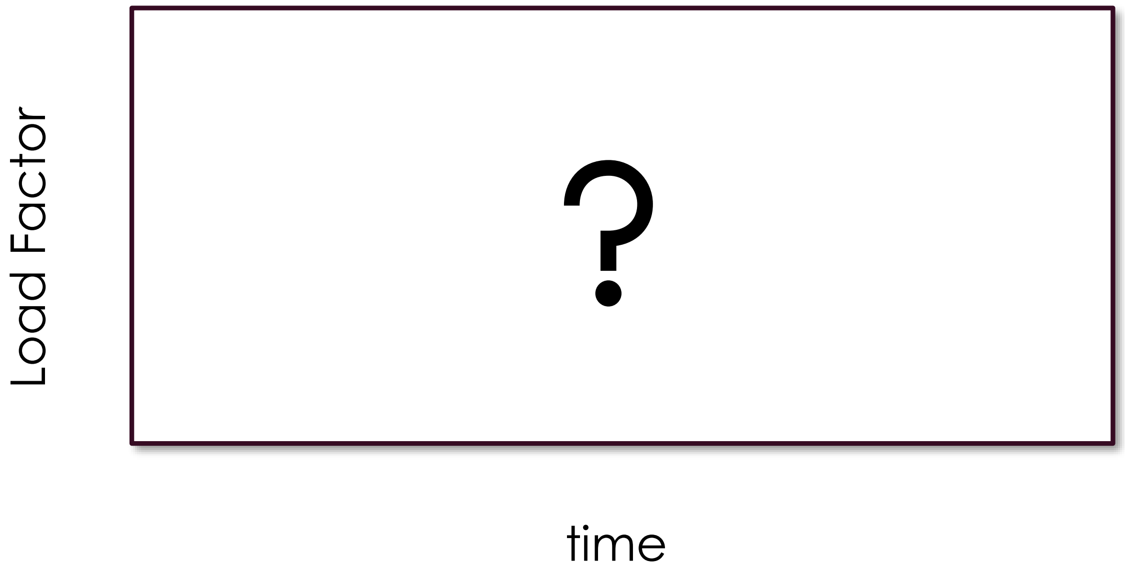


VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

- HTS load factor model…

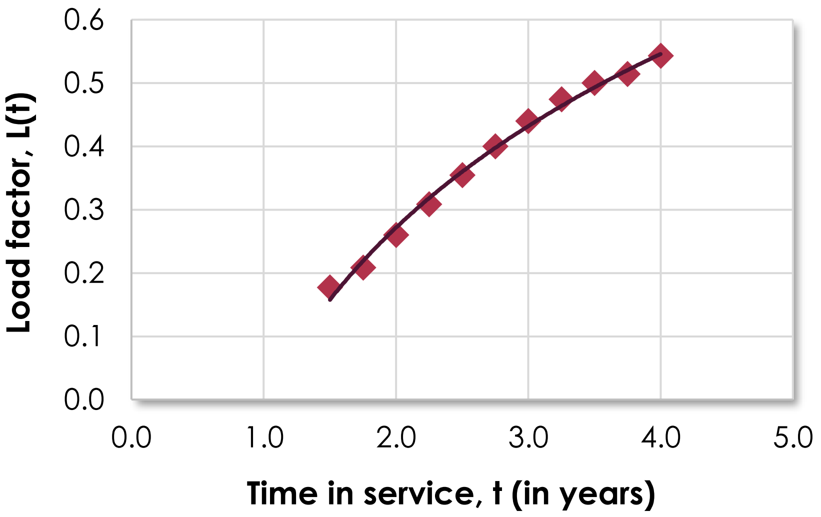


Load Factor Model

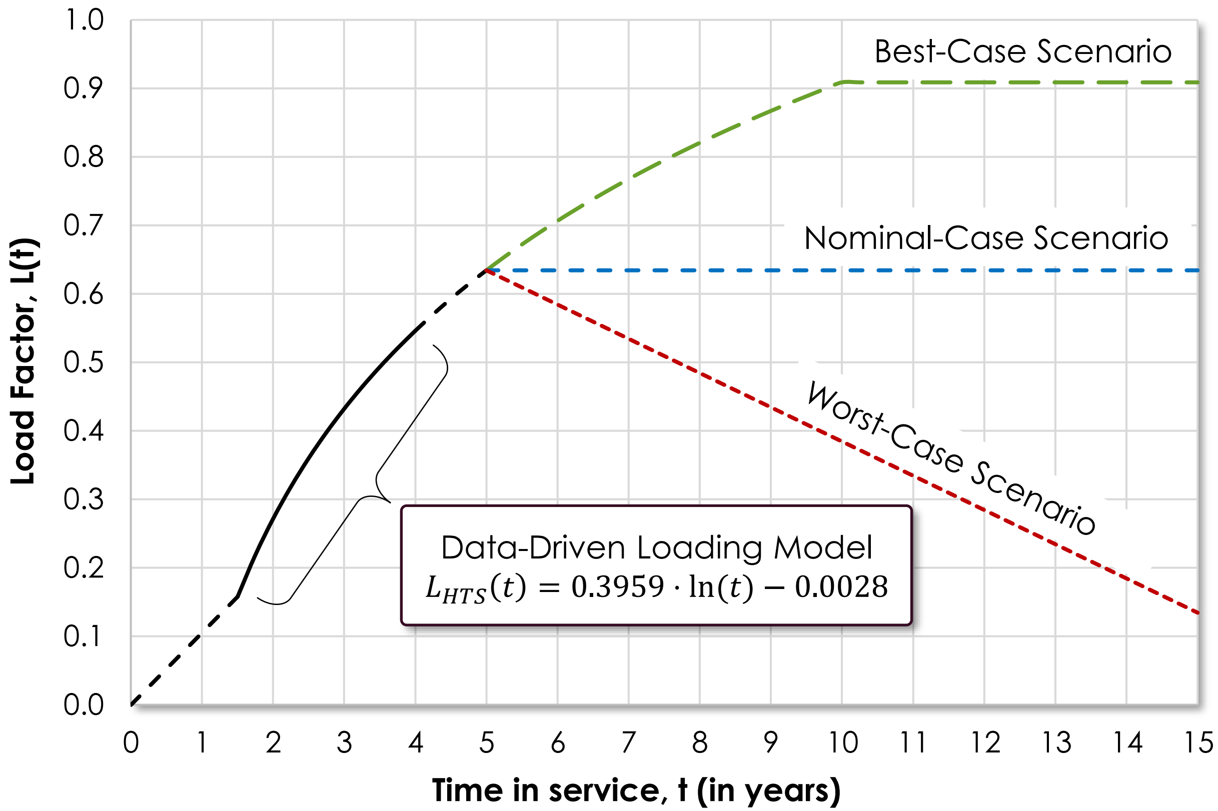


VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

- HTS load factor model: Hybrid Data-Driven and Scenario-Based Model

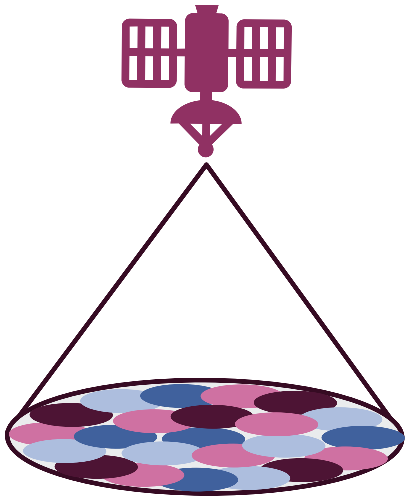


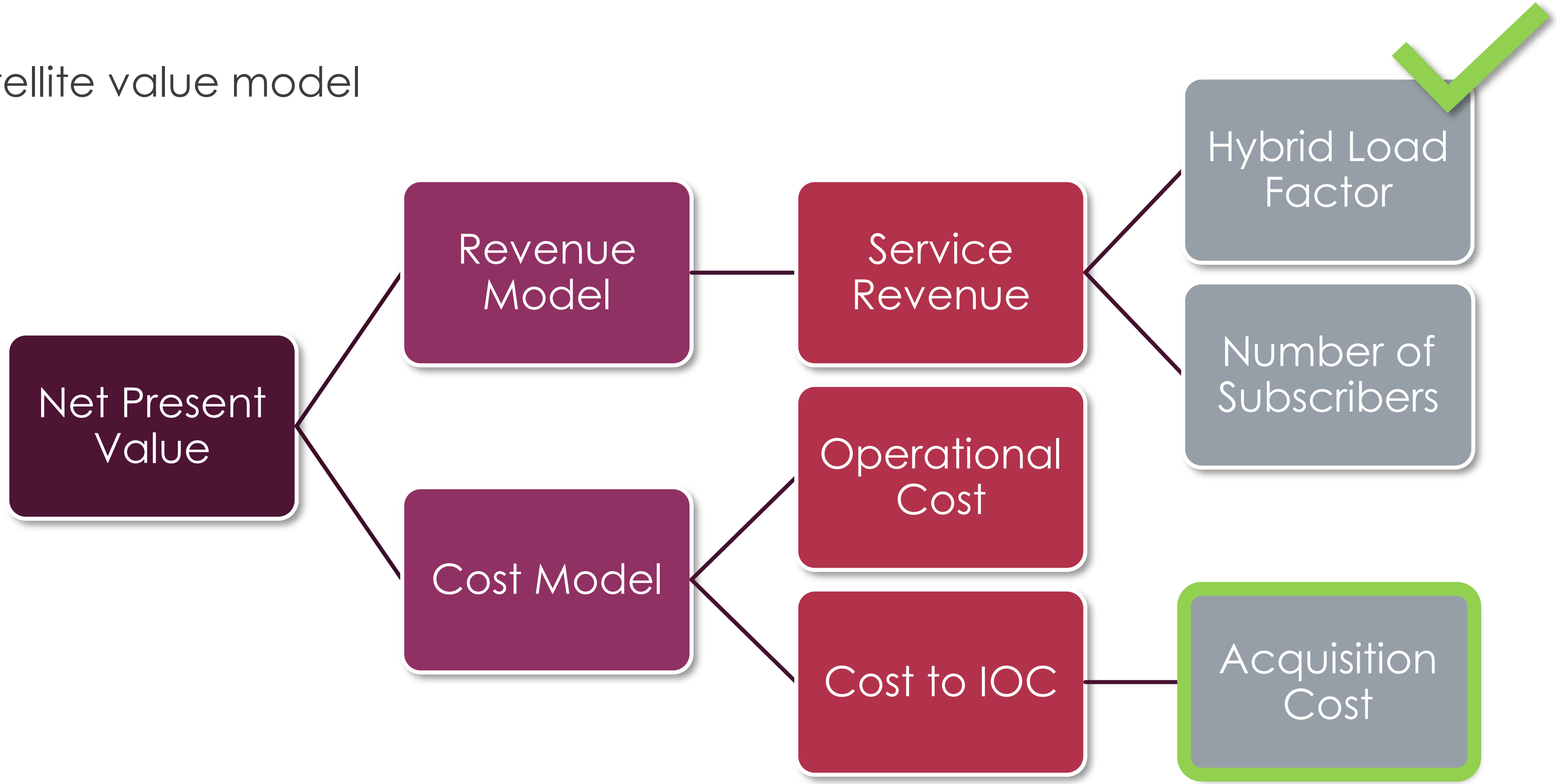
Data-Driven Loading Model
$L_{HTS}(t) = 0.3959 \cdot \ln(t) - 0.0028$



VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

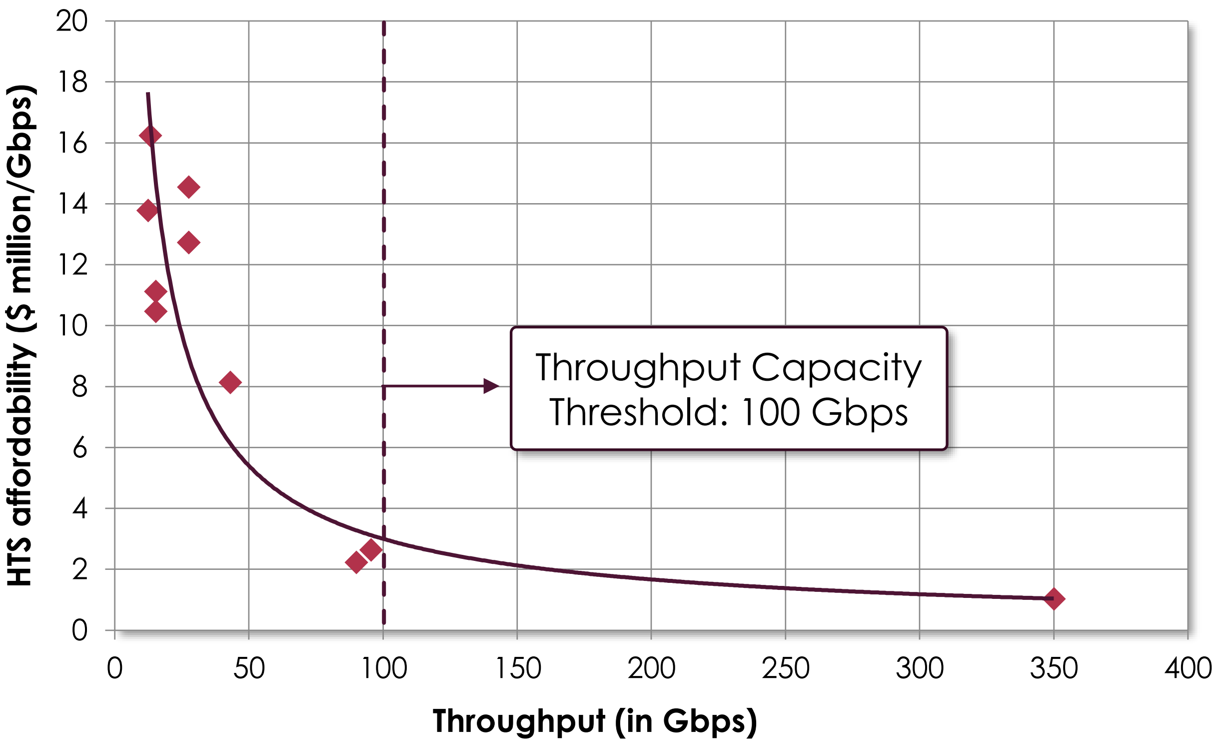
- High-throughput satellite value model





VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

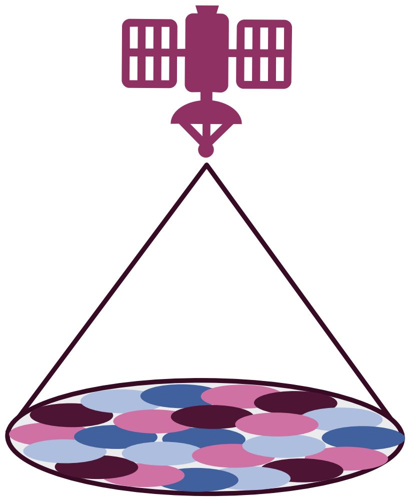
- HTS acquisition cost model: Affordability-Throughput Map

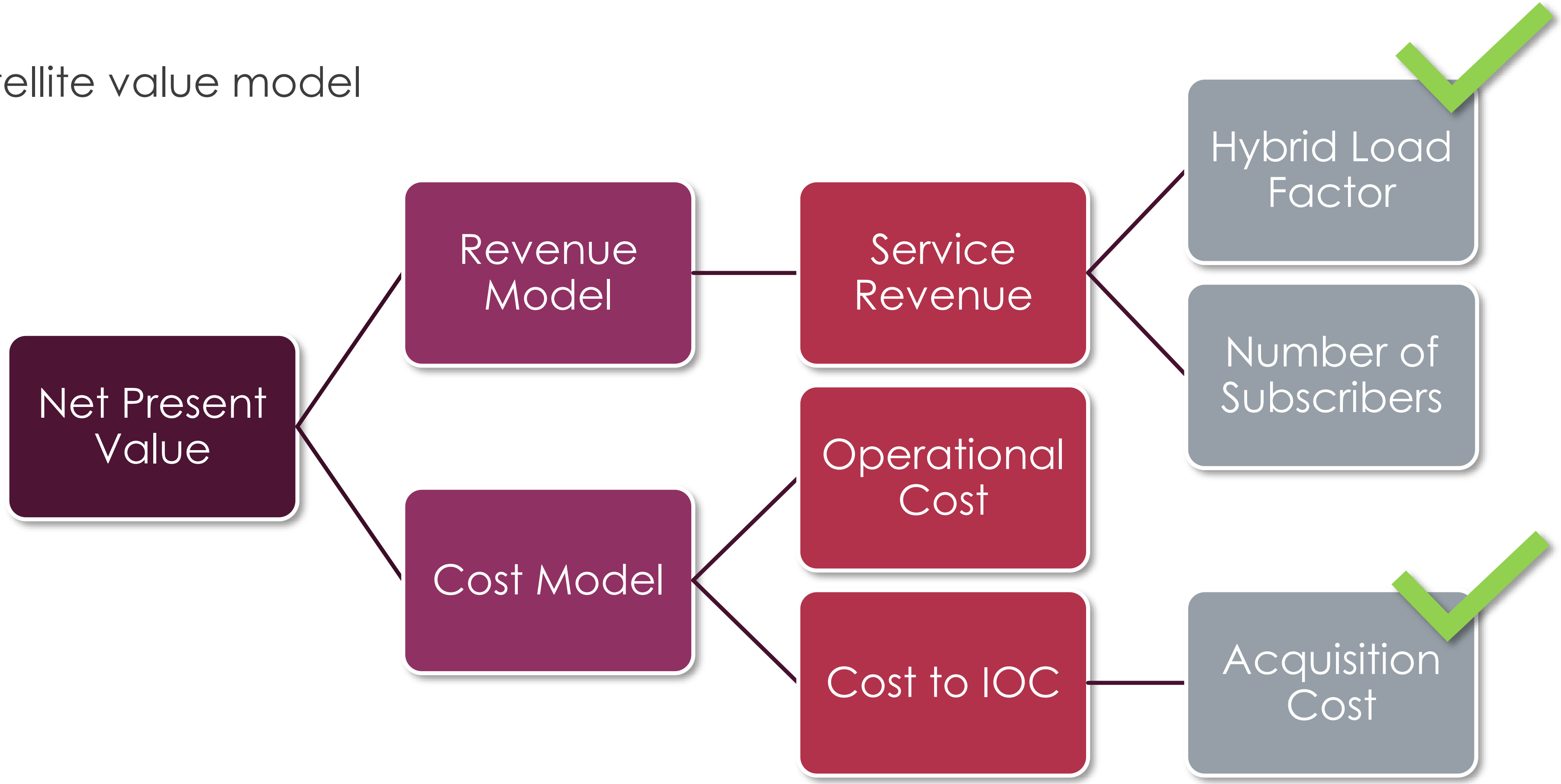


- Remarkable power relationship between HTS affordability and throughput ($R^2 = 0.89$)
- Clear and substantial economies of scale in the cost of connectivity to be reaped in designing higher throughput satellites
- Throughput capacity threshold: 100 Gbps → difficult to justify GEO HTS below this threshold

VALUE MODELS OF WIDE-BEAM SATELLITES AND HTS

- High-throughput satellite value model





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MONTE-CARLO VALUE ANALYSIS OF HTS AND COMPARISON WITH WIDE-BEAM SATELLITES

MONTE-CARLO VALUE ANALYSIS OF HTS AND COMPARISON WITH WIDE-BEAM SATELLITES

- NOT a Monte-Carlo simulation:

$$NPV = NPV(x_1, x_2, \dots, x_{42})$$

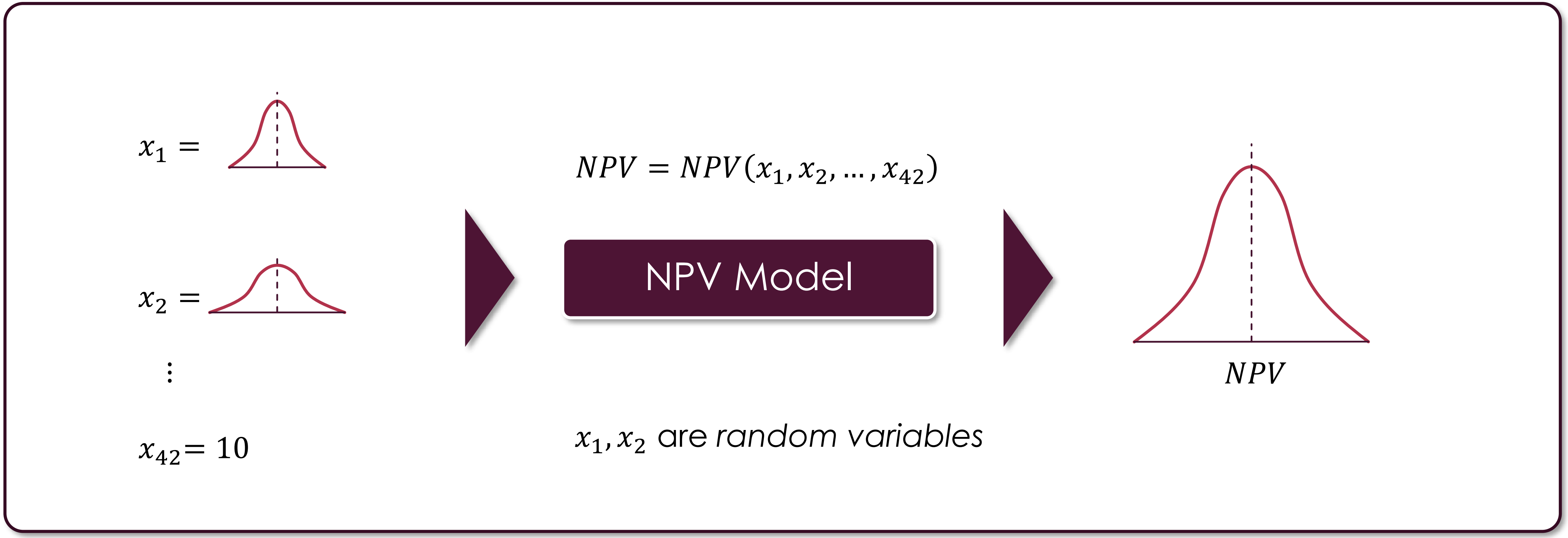
$$x_1 = 3$$
$$x_2 = 40$$
$$\vdots$$
$$x_{42} = 10$$

→ Net Present Value →

$$NPV = \$100\ m$$

MONTE-CARLO VALUE ANALYSIS OF HTS AND COMPARISON WITH WIDE-BEAM SATELLITES

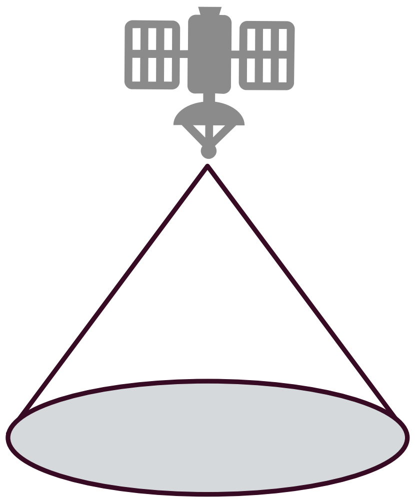
- A Monte-Carlo simulation:

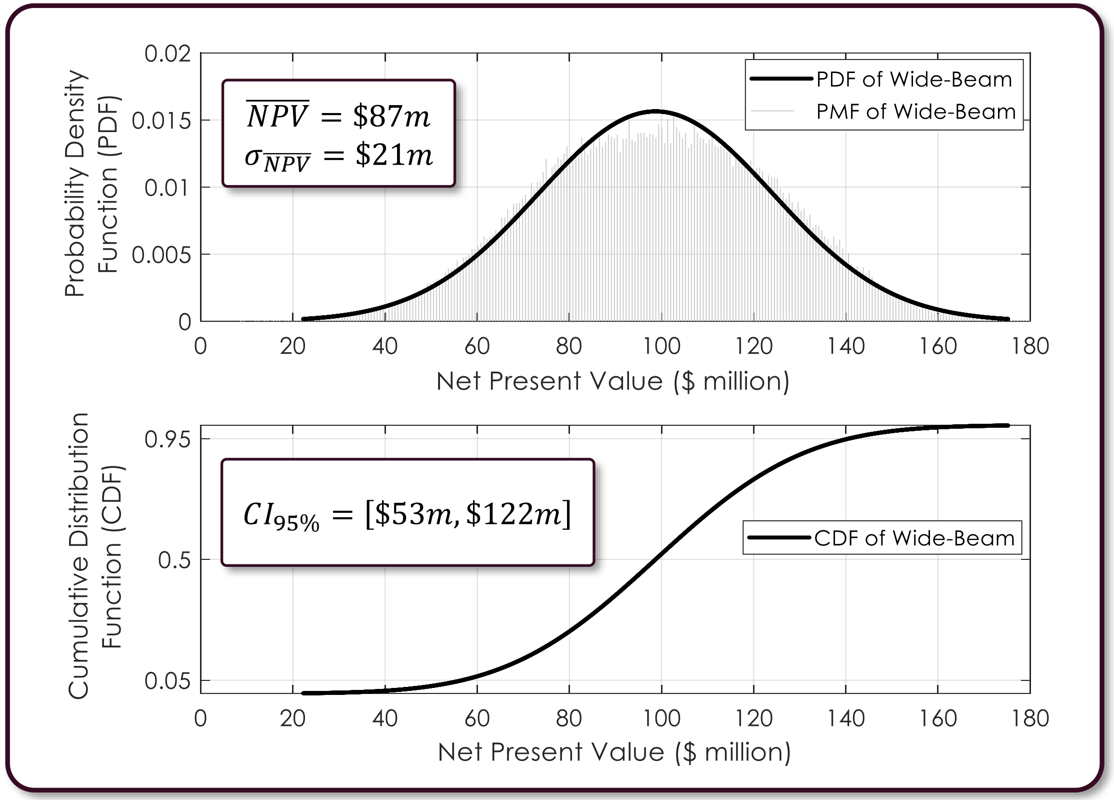


MONTE-CARLO VALUE ANALYSIS OF HTS AND COMPARISON WITH WIDE-BEAM SATELLITES

- Monte-Carlo simulation of the NPV of a **mid-sized traditional wide-beam satellite**

Mid-sized wide-beam





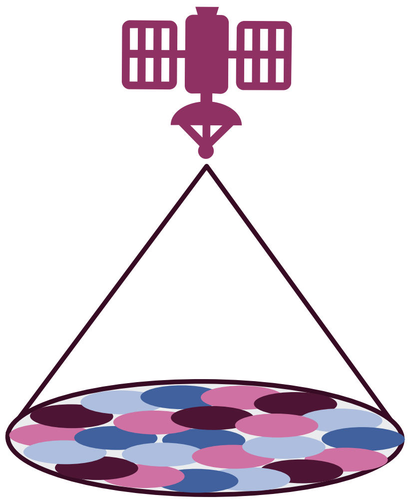
- The expected NPV for this wide-beam will be \$87m with a standard deviation of \$21m after a design life of 15 years on-orbit.

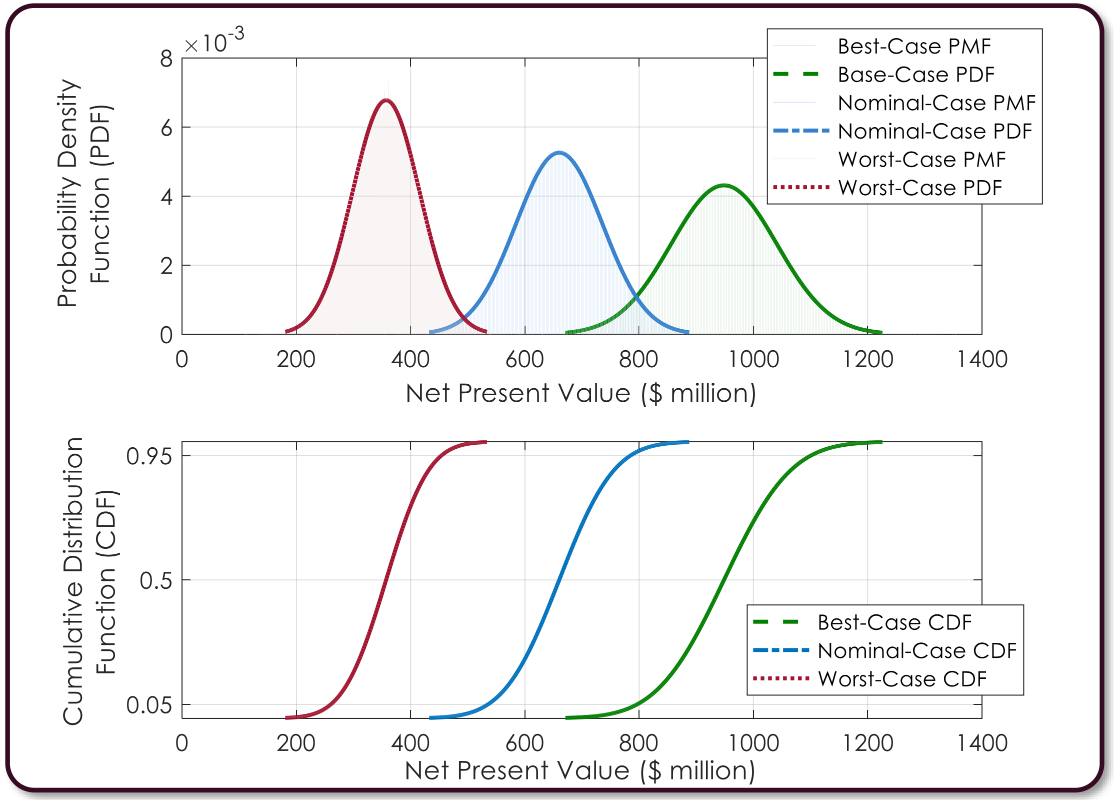
- The 95% confidence interval spans the \$53m to \$122m range.

MONTE-CARLO VALUE ANALYSIS OF HTS AND COMPARISON WITH WIDE-BEAM SATELLITES

- Monte-Carlo simulations of the NPV for a **mid-sized HTS under best-, nominal-, and worst-case scenarios**

Mid-sized HTS



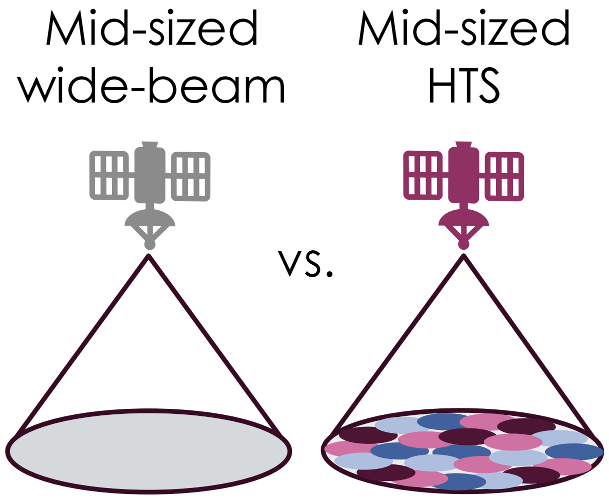


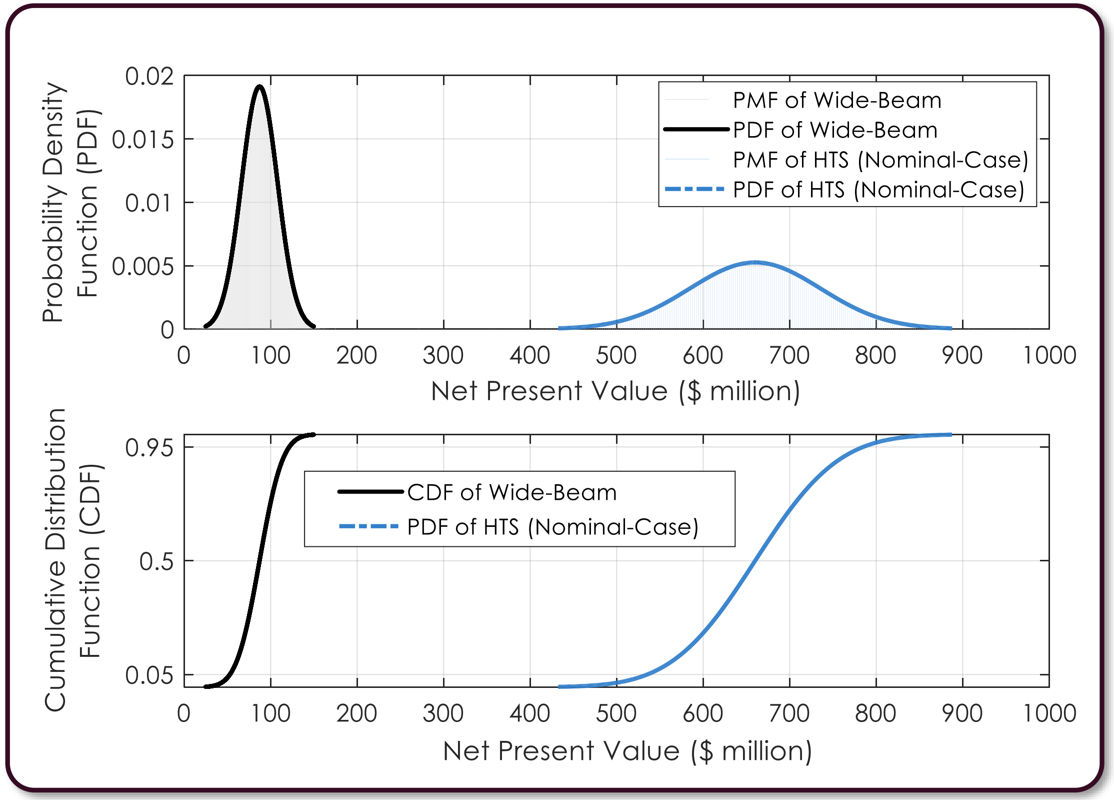
- The expected NPV for the nominal-case HTS will be \$660m with a standard deviation of \$76m after a design life of 15 years on-orbit.

- The 95% confidence interval for the nominal-case spans the \$535m to \$785m range.

MONTE-CARLO VALUE ANALYSIS OF HTS AND COMPARISON WITH WIDE-BEAM SATELLITES

- Comparison of nominal-case HTS and wide-beam satellite NPV results





- Medium-size HTS significantly outperforms the roughly equivalent wide-beam satellite
- The NPV volatility for HTS remains manageable, with significant upside potential and no downside risk (likelihood of NPV < 0)

CONCLUSIONS AND FINAL REMARKS

CONCLUSIONS AND FINAL REMARKS

- The underlying assumption: traditional broadband business model
  - *subscriber* is also the *payer*
- This need not be the only business model
  - e.g., connecting the unconnected

CONCLUSIONS AND FINAL REMARKS

- We only considered **a single satellite in GEO** (36,000 km). How these analytics can be adapted to LEO HTS constellations will be explored in a follow-up work.
  - OneWeb's LEO constellations of hundreds of high-throughput satellites (1200 km)
  - Amazon's project Kuiper (few thousand HTS in 600 km LEO)
  - SpaceX's project Starlink (several thousand HTS in 550 km LEO)

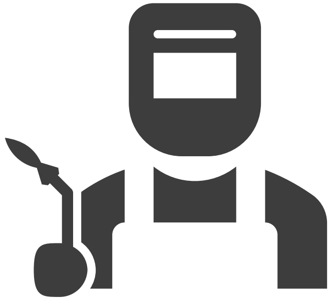
CONCLUSIONS AND FINAL REMARKS

- **“therefore send not to know for who the bell tolls, it tolls for [the wide-beam satellites].”**

  - poem by John Donne and used by Hemingway

CONCLUSIONS AND FINAL REMARKS

Thank you.



BONUS SLIDES

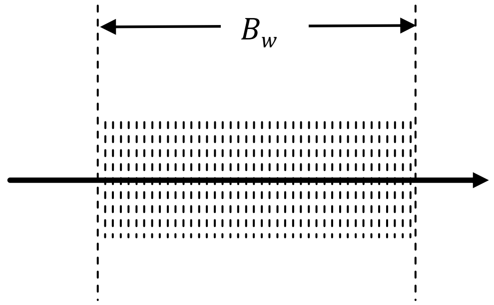
UNDERSTANDING THE TECHNOLOGY

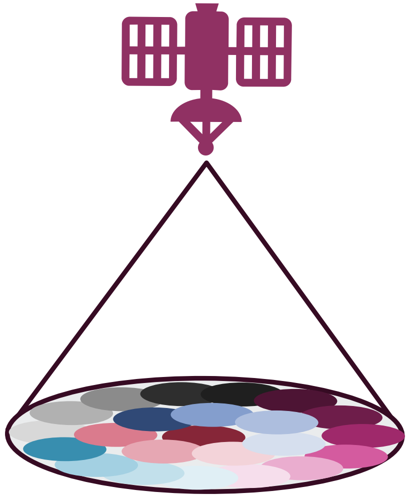
$$B_{total} = \underbrace{\left(\frac{N_p N_b}{N_c}\right)}_{\text{frequency reuse factor}} B_w(1 - \eta_{guard})$$

N_p: *number of polarizations* (1 *or* 2)
N_c: *number of colors*
N_b: *number of beams*
η_{guard}: *guard band, typically* 5% *to* 10%

- "Why not divide the allocated bandwidth by the number of spot beams available?"
- "That way, you would have 100 different spot beams each with their own unique frequency."

100 sub-bands!





UNDERSTANDING THE TECHNOLOGY

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- You'd run into resolution errors on both the transmitting and receiving end.
- i.e., it becomes difficult (if not impossible) to distinguish between signals of similar frequency.

- Can you tell these apart?

UNDERSTANDING THE TECHNOLOGY

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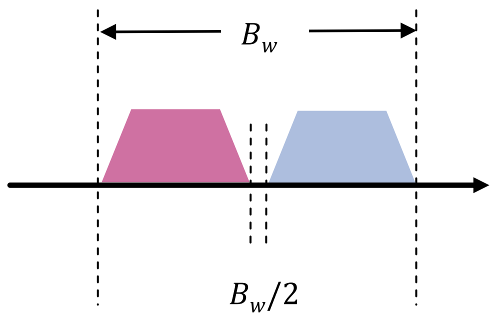
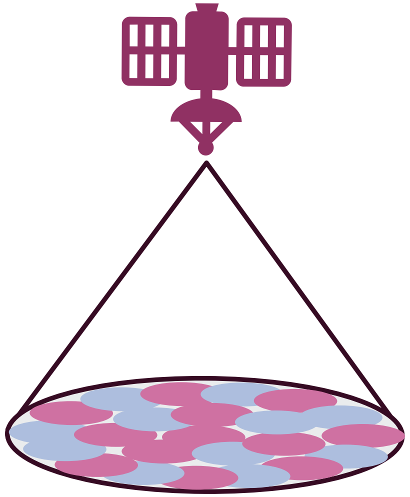
- "Okay so 2 or 3 sub-bands…with a buffer to prevent overlap (η_{guard})."
- "Why bother with circular polarization then?"

2 sub-bands.





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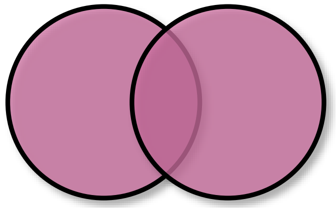
- You cannot tesselate your coverage area with only two sub-bands without two of the same colors being adjacent.
- Two different streams of information with the same frequency can become muddled.



- Imagine the receiver in the intersection of these two spot beams trying to decipher the signal from only one of them.

UNDERSTANDING THE TECHNOLOGY

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N_p: number of polarizations (1 or 2)
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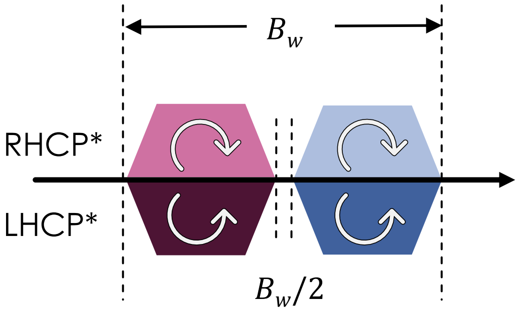
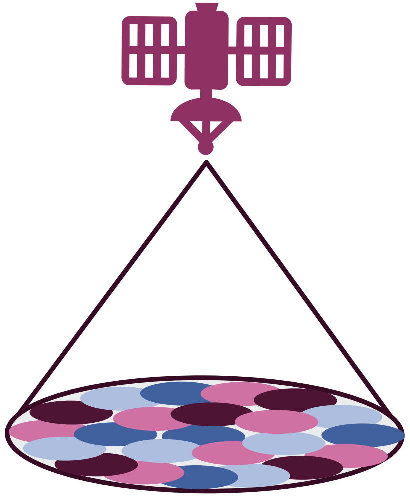
- "If only we had another degree of freedom to differentiate two spot beams in the same sub-band!"
- "What was that thing you were saying about circular polarization?"

Example of four colors



* right/left hand circular polarization



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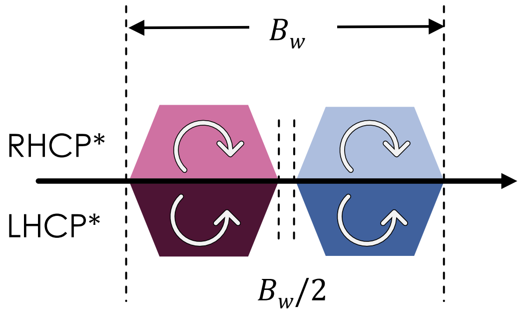
- Right- and left-hand circular polarization allows you to differentiate between signals from the same sub-band.
- Thus providing you with not 2, but 4 unique spot beams to tesselate your coverage area.

- Although they are the same sub-band frequency, these are easily distinguishable!

UNDERSTANDING THE TECHNOLOGY

Example of four colors



* right/left hand circular polarization

A word on the use of the word "color".

- In HTS nomenclature, a "color" is defined by a combination of sub-band and polarization type.
- Of course, technically, the physical color of an electromagnetic wave is only defined by its frequency, i.e., by the sub-band.