In-Space Power Transfer
Bouncing the Light - Fantastic!

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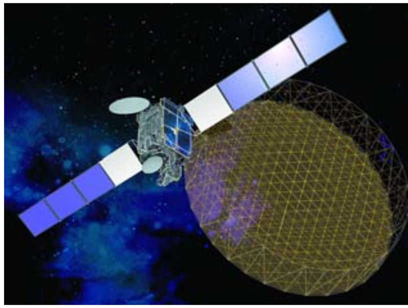

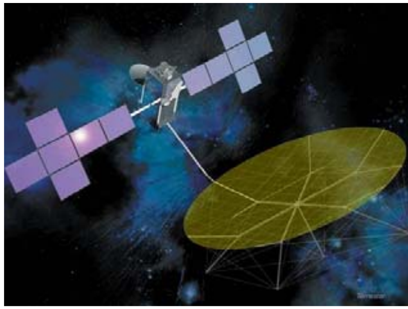

Outline

- Power transfer as a key fractionation element
- Light distribution vs conversion
- Applications drivers - capability and cost
- Centralization and fractionation
- Power transfer architectures and resource vehicle
- Mission vehicle concepts
- Formation concepts and simulations
- Conclusions

Power transfer for fractionation

- A monolithic spacecraft makes its own power with an expensive solar array[1], typically $750/W
- For missions involving many vehicles in formation, centralizing power generation continues to be of interest
  - Potential cost and complexity savings
- Fractionation[2] of power collection involves a Resource Vehicle (RV) supplying energy to a formation of Mission Vehicles (MV)
  - Heterogeneous fractionation: solar energy collection separated from power conversion
  - May enable power cost below $100/W by avoiding photovoltaics
- Subject of current SS/L study for DARPA of In-Space Power Transfer
  - Concentrated sunlight distribution - avoiding multiple conversions
  - Architecture, CONOPS and applications assessment
  - Vehicle and formation design
  - Cost/benefit and development assessment

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Why concentrated light distribution?

- **Previous concepts typically involve conversion of sunlight to electrical power before distribution**
  - **Power distribution as RF is too inefficient**
    - **Net system efficiency ~3%**
    - **Major additional losses at large path lengths**
  - **Power distribution by lasers is too inefficient**
    - **Net system efficiency ~5%**
- **What's different about this new approach?**
  - **Uses mirrors to concentrate, collimate and target direct sunlight to formations of fractionated spacecraft over path-length of a few km**
  - **Uses low-cost, 30%-efficient heat engines in mission vehicles to avoid high-cost solar cells, batteries and electronics**
  - **Avoids conversion losses of sunlight to direct current and direct current to RF or laser beam**
  - **Net system efficiency is 20-25%**

Comparison of Power Transfer Schemes

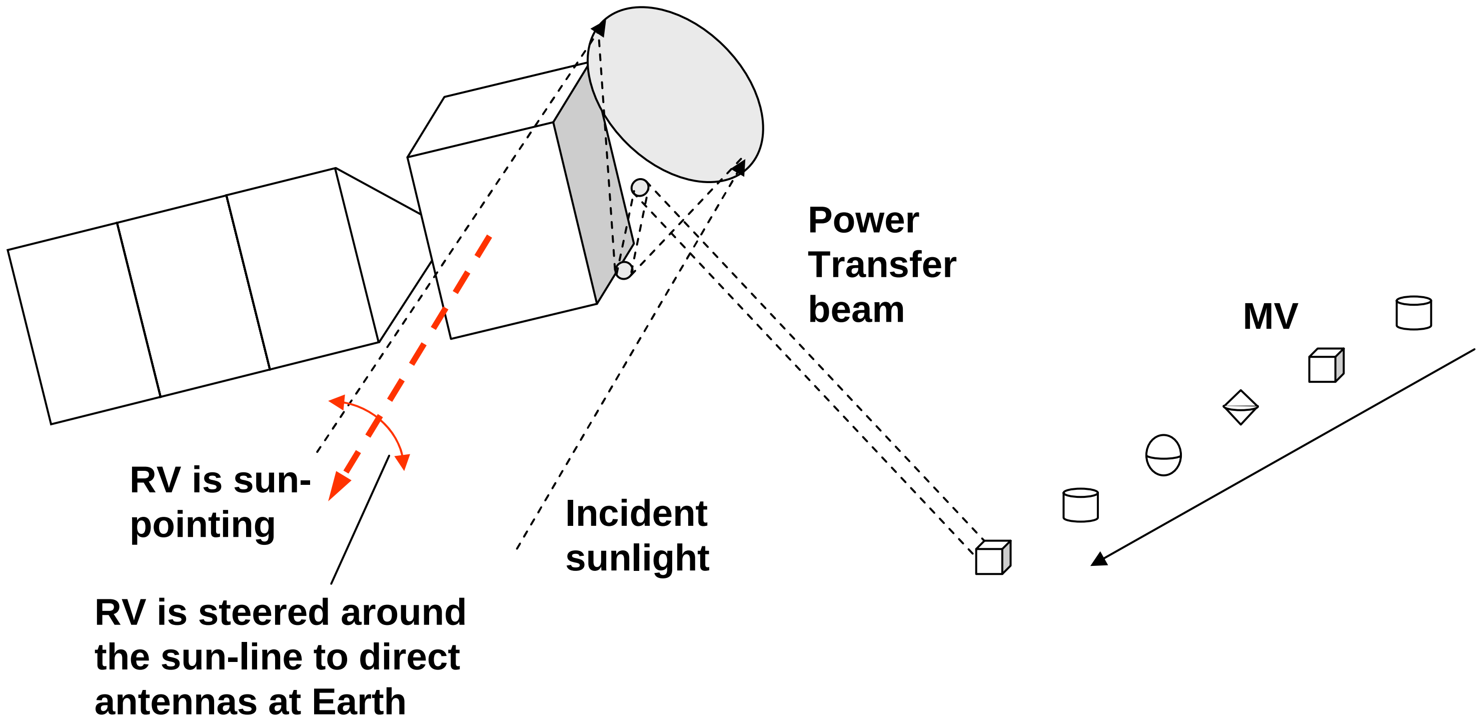
Efficiency Term	Power Transfer Scheme		
	Concentrated Sunlight	**Microwave (S-band)**	**Active Optical**
	Multiple mirrors[3] aboard the support vehicle focus sunlight into a beam	DC power from support vehicle solar arrays is fed to transmitters for RF power transfer	DC power from support vehicle solar arrays is fed to LED arrays for visible light power transfer
Sunlight-to-DC conversion in support vehicle	N/A	30%	30%
Lines, high-voltage in support vehicle	N/A	50%	~100% (No high voltage)
Conversion of DC to power transfer beam	90%	50%	20% (Reference 4)
Free-space propagation*	~100%	50%	~100%
Conversion of power beam to DC aboard mission vehicle	30%	90%†	60%‡
System	**25%**	**3%**	**4%**

* Free-space propagation assumes a path-length of 200 m for the RF case, 1000 m for the optical power transfer systems

† Rectenna efficiency was obtained from a paper[5] by Yoo and Chang

‡ Efficiency for conversion of monochromatic light to electricity is high because the wavelength of the light is matched to the band gap of the solar cells.

Power Distribution from Resource Vehicle (RV)



- The RV concentrates solar power collected by a big mirror into a 0.1-m diameter beam with intensity of ~100 suns
- A formation of MV, each of lower cost than the RV, and possibly of a variety of different types, receive the concentrated power in turn
- Missions for formations spread over a few kilometers span, or clusters of spacecraft, are discussed in the literature[6, 7, 8]

Benefiting Missions in Capability and Cost

Capability

- LEO formation missions needing large apertures of ~1-2 km
  - High resolution Synthetic Aperture Radar (SAR)
    - Tactical / theater
    - Continuous mapping
  - High resolution optical imaging
  - Detection of electromagnetic radiation with 100+ m wavelength
- Missions needing flexibility in sensor insertion/upgrade
  - Distributed platforms for correlated sensor suites
    - NPOESS-like objectives but with relaxed constraints
- Missions with payloads too large to launch on a single platform

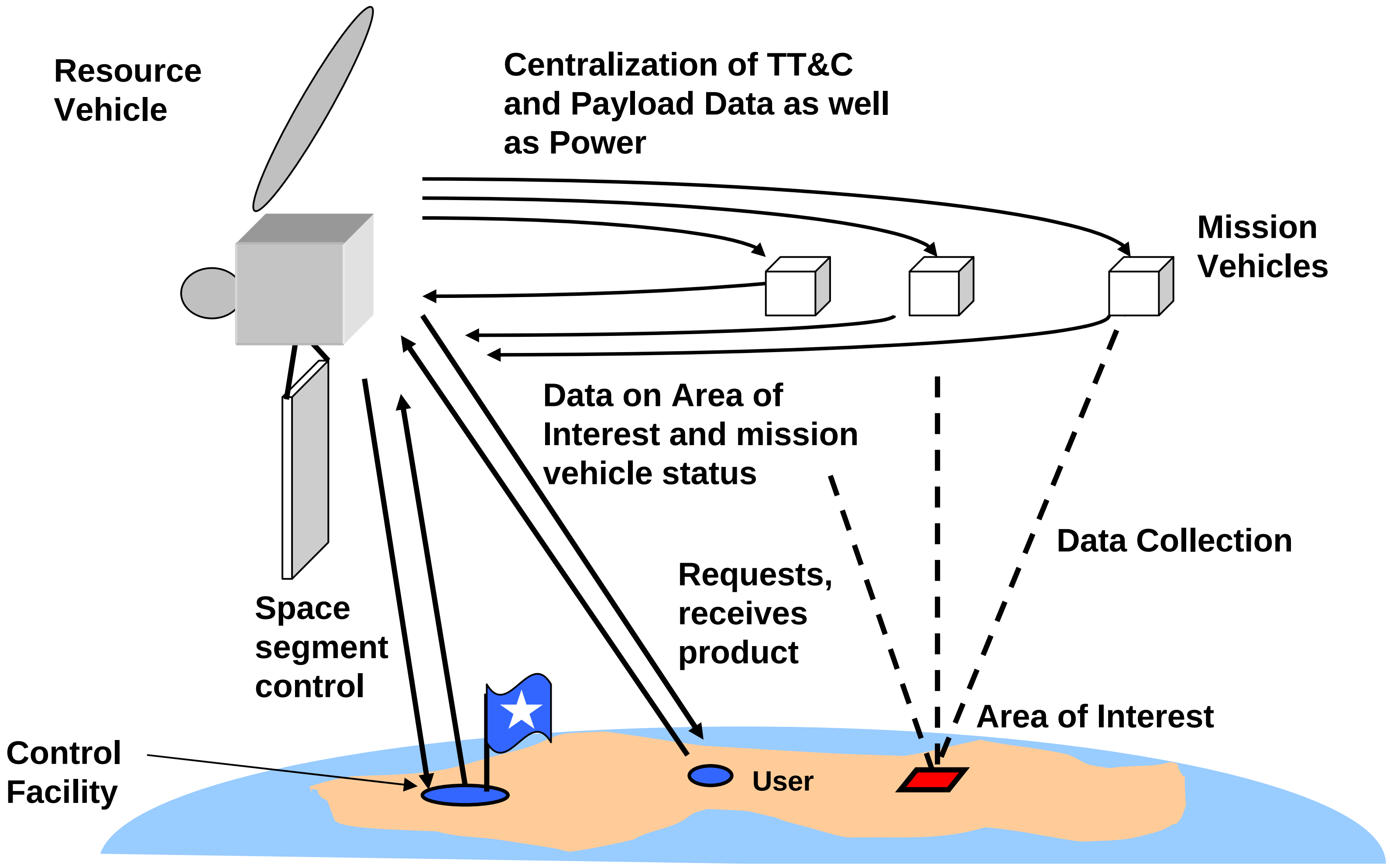
Cost & Complexity

- Centralized power/other functions enables low cost sensor MVs
- MVs do not need to point a power collector while imaging

Centralization and fractionation

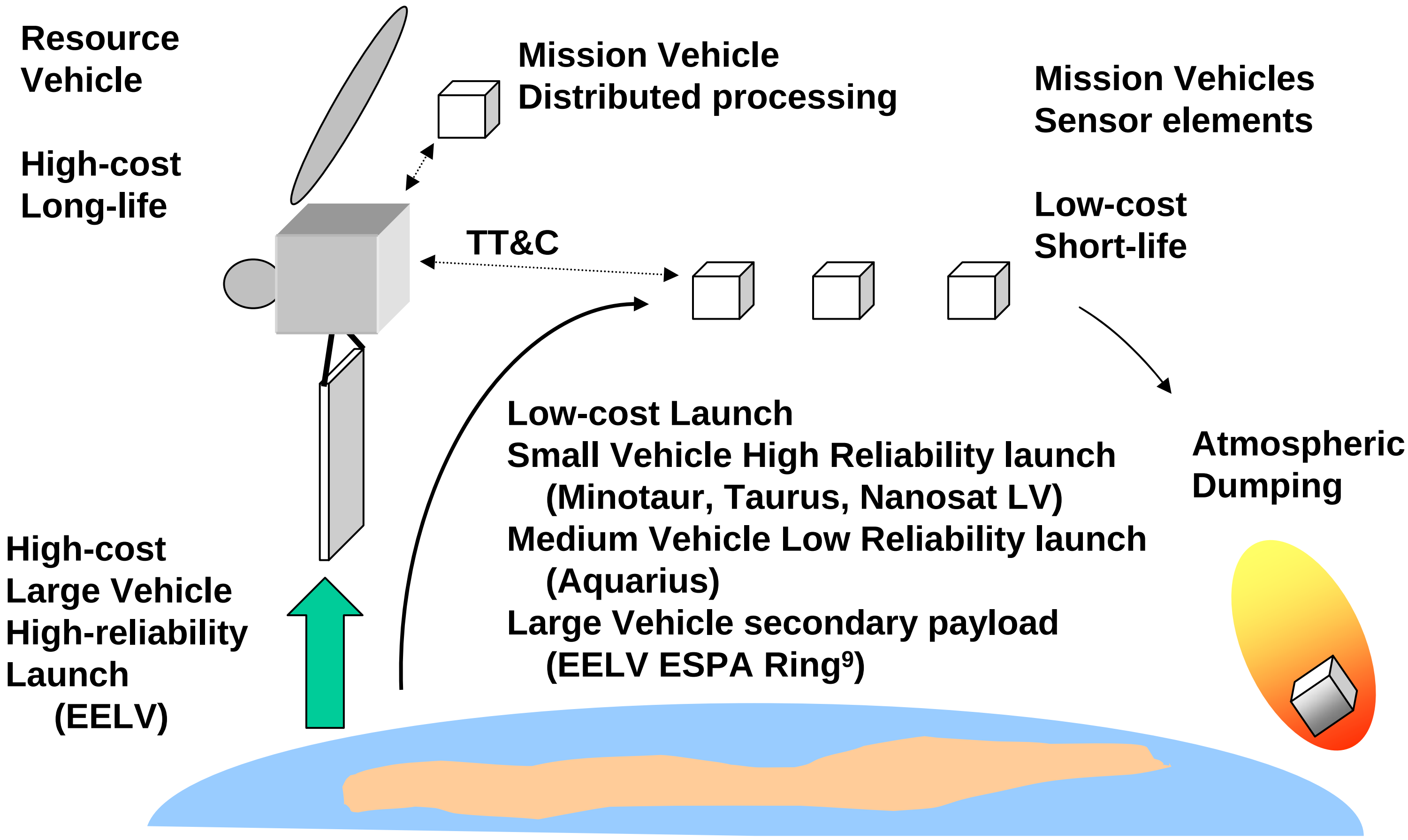
- Power collection centralization permits reduction in complexity and cost of individual sensor spacecraft in a multi-satellite cluster
- The presence of a central power collector spacecraft invites centralization of other functions, if effective
  - Consider cost, mission reliability and fault tolerance, initial formation establishment
- We are assessing potential centralization of
  - Mission data aggregation, processing and downlink
  - Intra-formation data exchange
  - Formation command and telemetry links
  - Orbit Determination and control
  - Attitude Determination and control
- Centralization *is* a form of heterogeneous fractionation
  - Same opportunities, risks and issues

System Architecture



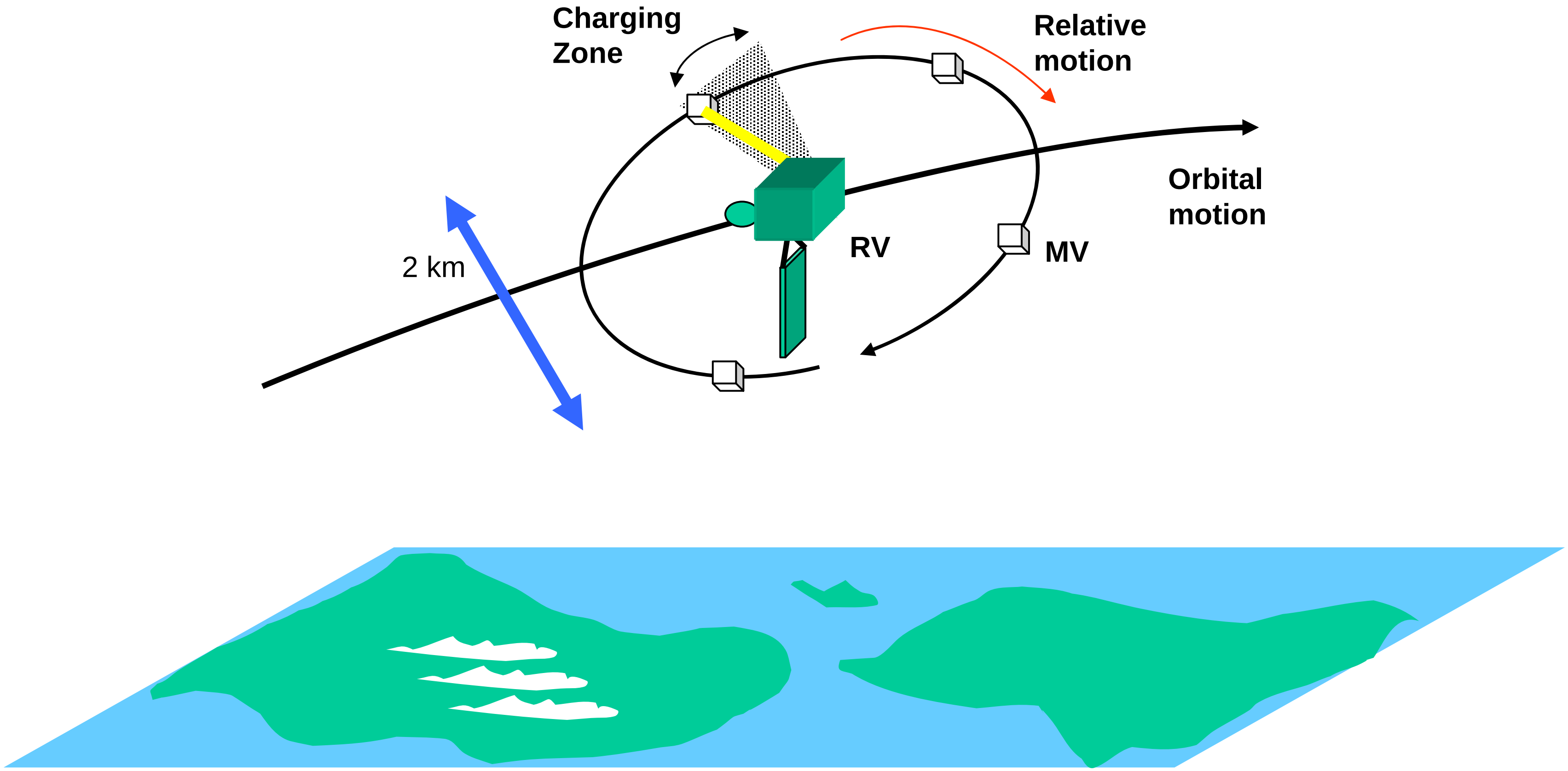
- Mission Vehicle TT&C and Payload Data could be routed through the Resource Vehicle

RV lifetime: 10-15 years, MV lifetime: 0.5-2 years



- System architecture permits nearly continuous upgrade or reconfiguration of Mission Vehicle (MV) formation
- Specialized MV could provide occasionally upgradeable distributed processing -- or initial processing of data might be performed by all MV

Candidate circular formation of spacecraft

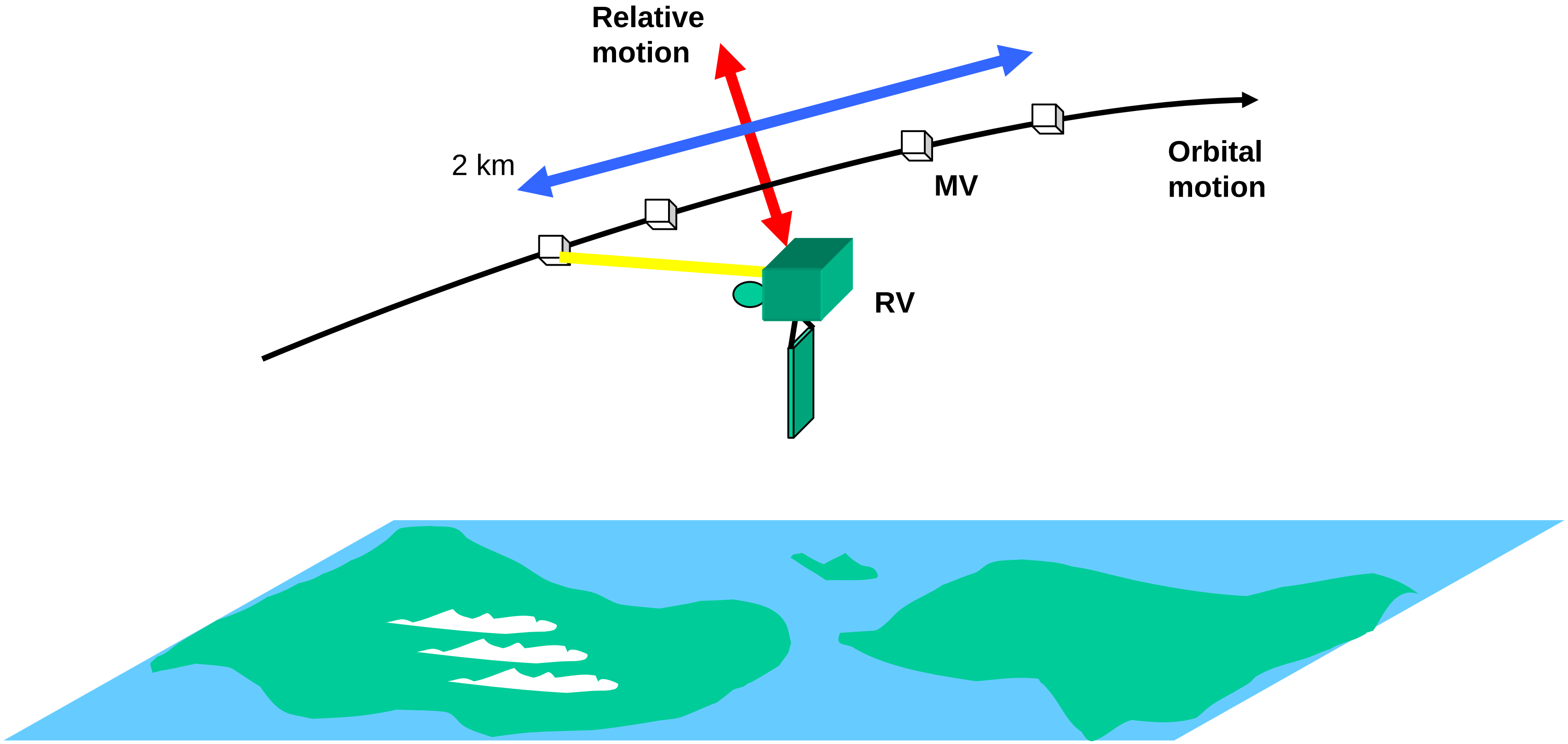


- The RV would be in the center of the formation and distribute power to MV as they traverse a “charging zone”

Candidate circular formation of spacecraft - 2

- Computer demonstration of formation flying with power transfer

Candidate linear formation of spacecraft

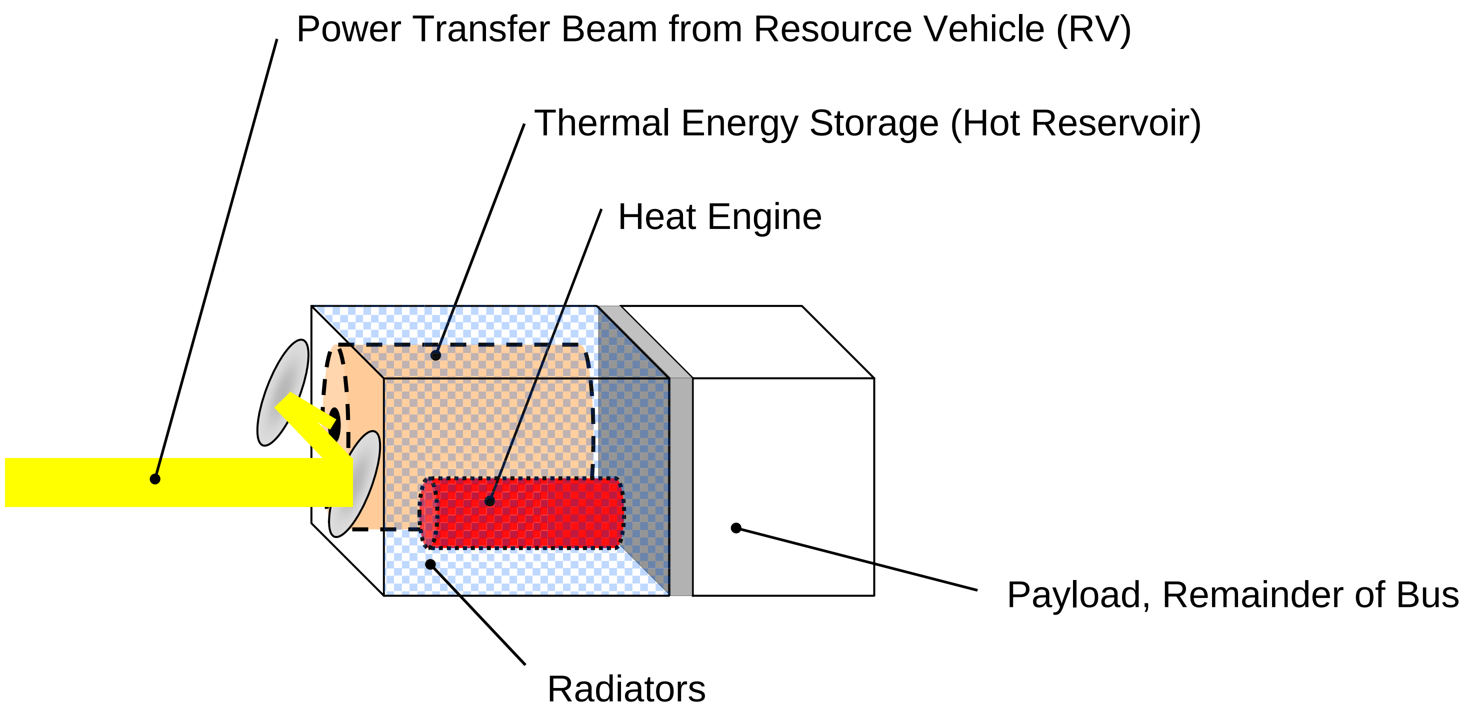


- The MV are arranged in a linear formation in a common orbit and the RV is in an orbit with a significant wedge angle to this common orbit so that it comes into line-of-sight with each MV

Candidate linear formation of spacecraft - 2

- Computer demonstration of formation flying with power transfer

Mission Vehicle (MV) Layout



- **Within the MV the power transferred from the RV is absorbed as heat and then converted to electrical power by a heat engine for use by the payload and by the spacecraft bus**

MV overall design

- MV size and power level
  - Small MV
    - Optimal size might be small to fit within small launch vehicle or many MV in medium size launcher, or on EELV ESPA ring[9]
  - Larger MV
    - Fractionated from power-supplying RV to derive benefit in agility and stability
    - Need for any major component of MV to sun-point eliminated
- MV size and thermal control
  - Can thermally isolate low temperature payload such as IR sensor but requires dedicate high temperature module
  - Small MV
    - Small size tends to require operation at elevated temperature
    - Deployable radiator may be needed for small MV with high power
  - Larger MV
    - Thermal control easier: larger radiator and no need to sun-point

Power Handling Considerations and Trades - 1

- **RV beam steering and beam dousing control**
  - **Partially douse the beam while acquiring to avoid harm to MV**
  - **Total dousing of the beam in a contingency**
- **MV Payload versus bus power**
  - **Tactical payload typically requires high power for short duration, bus requires more total energy over time but may operate at ~10% payload power level**
  - **Consideration affects energy storage, heat engine sizing**
- **MV energy storage: power transfer occurs ~10% of the time**
  - **Thermal energy storage, higher kJ/kg, but storing waste heat that will be passed by the heat engine as well as useful heat**
  - **Chemical energy storage, stores only electrical energy but necessitates a separate battery and supporting components**
- **MV contingency operations**
  - **Obtain survival power by directing heat trap at the sun**
  - **Sufficient power to operate bus at reduced level, no payload operations**

Power Handling Considerations and Trades - 2

- **MV Heat Engine type**
  - **Dynamic – 30+% efficiency, moderate temperature**
  - **Thermionic – ~12% efficiency, higher temperature, no moving parts**
- **MV Heat Engine disposition**
  - **Power level size for surge vs. continuous operation, or both**
  - **Intermittent vs. continuous operation**
  - **High power level – run during charging with small thermal energy storage and large chemical battery**
- **MV Thermal Energy Storage (TES)**
  - **Phase Change Material for near-constant temperature through cycle**
  - **Internal heat distribution may require high-temperature conductor grid**
  - **Re-radiation: heat leakage through aperture used to admit power beam**
- **MV Chemical Battery: Considerable heritage but low kJ/kg**
- **Launch and Early Orbit Operations (LEOP) considerations**
  - **MV may be launched separately from RV**
  - **Initial power-up of MV hot-side reservoir**

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