Electrical Systems

CSDC
Space Systems Design

Ross Gillett, P.Eng, FEC

Contents

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System Design Overview

- The Generic System Engineering Process - in sequence
  - Mission Goal
  - 'Operations Concept'
  - 'System Level' (Top Level) requirements
  - Design System Level architecture (incl Trade-Offs)
    - Interconnection of functional blocks, or 'configuration items'
  - Requirements (lower level)
    - Functional blocks or Components
    - Interface requirements between functional blocks
  - Detailed design, Test/Verification Planning
  - Manufacture
  - Test/Verify against all requirements

Repeat for lower levels, depending on complexity

System Design Process:

“Getting the team to design <u>one</u> solution”

- A process for developing team-based design
  Goal □ Ops Concept (”Use Cases” for S/W) □ System Requirements □ Component Requirements □ Detailed Design □ Verification (showing you met requirements)
- The "Goal" is the top level (preferably a single sentence)
- This is often called a “Waterfall Model” or V-Model
- Below is perhaps the most famous "Goal" statement in engineering history:

"... I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the earth".

- U.S. President J.F. Kennedy, 25 May 1961 -

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Waterfall Model (or V-Model)

Traditional, sure, but also still needed for multidisciplinary engineering

- Where failure cannot be tolerated in delivered products (i.e. spacecraft)
- When costs are high for any design iteration and cannot be reduced (such as some hardware-intensive projects)

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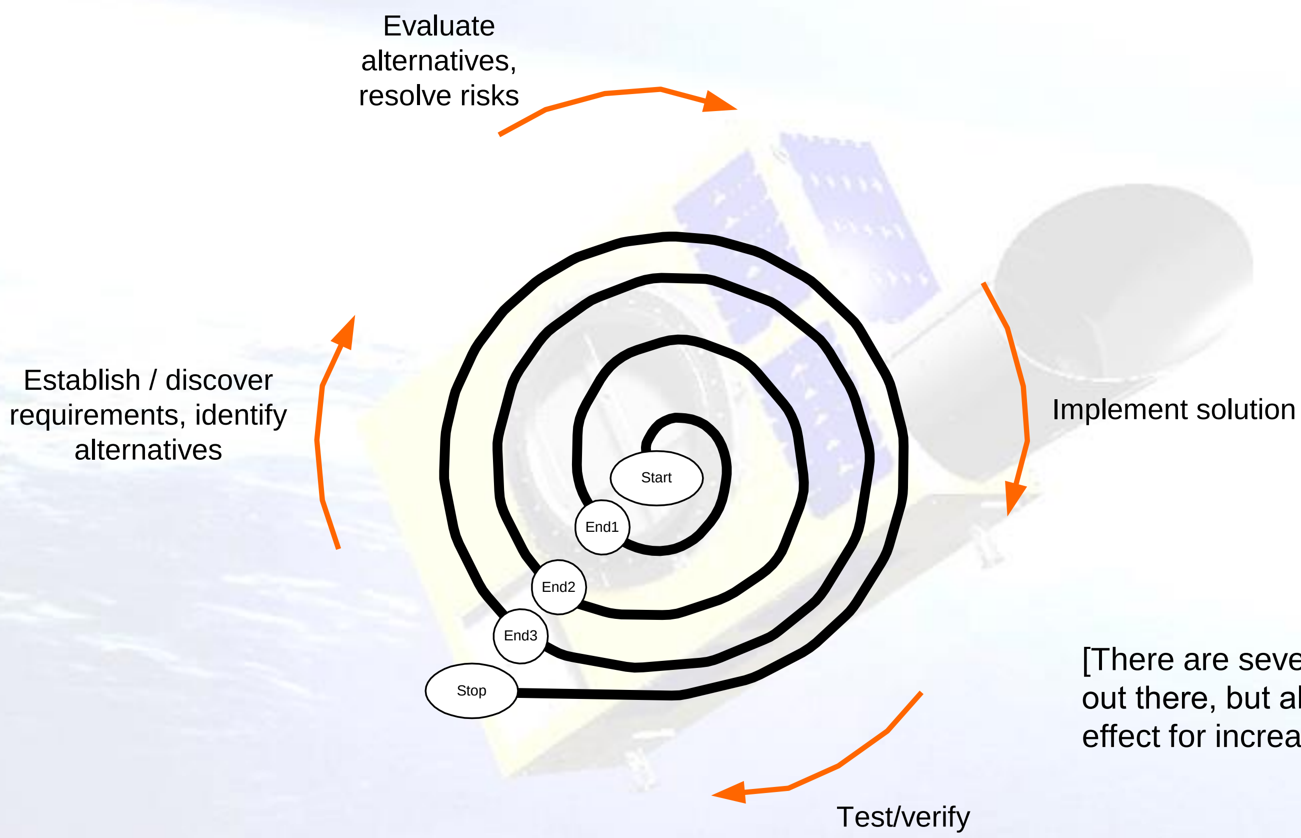
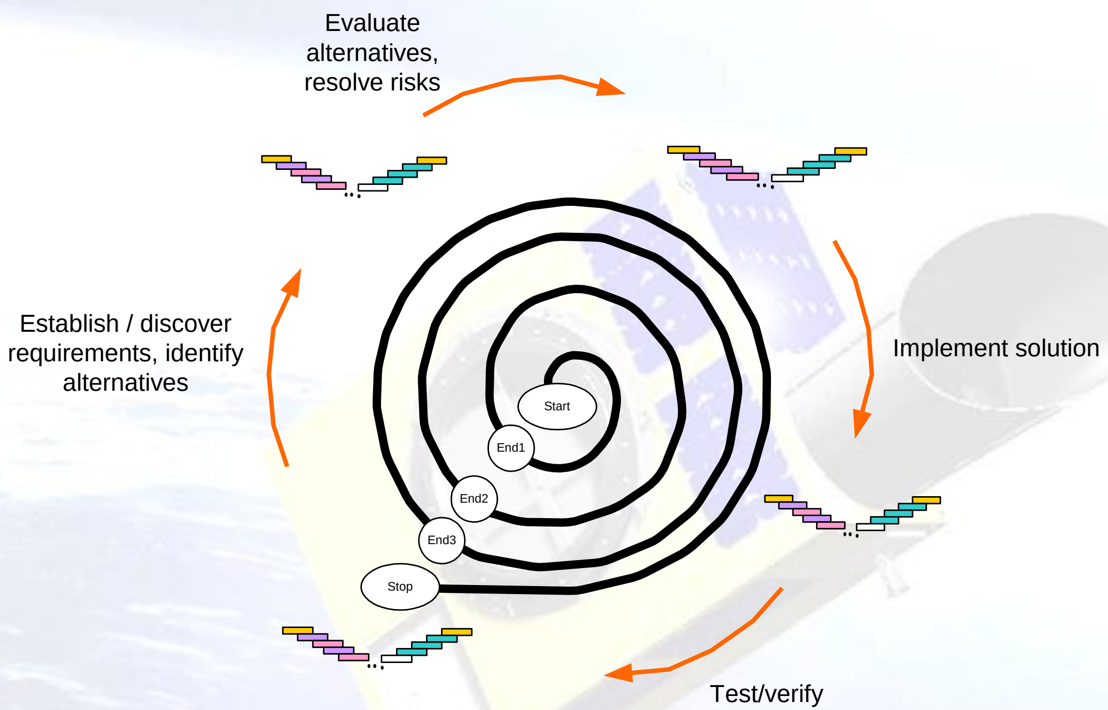
Spiral Development Model
(similar in structure to ‘agile’ but they have different time scales)

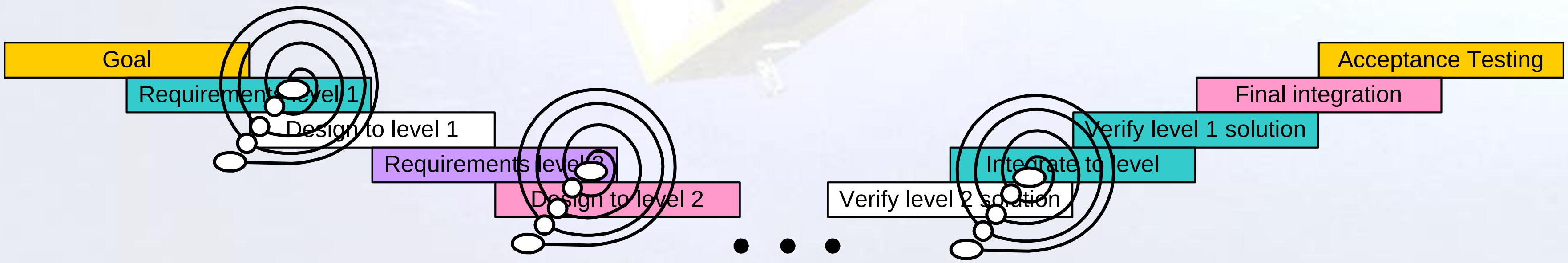


[There are several differing labels out there, but all show a ‘snowball’ effect for increasing functionality]

- More likely used in software projects, where iterations can be rapid and low-cost
- Does <u>not</u> mean you do not need requirements, planning, or verification

Projects can (usually) employ combinations





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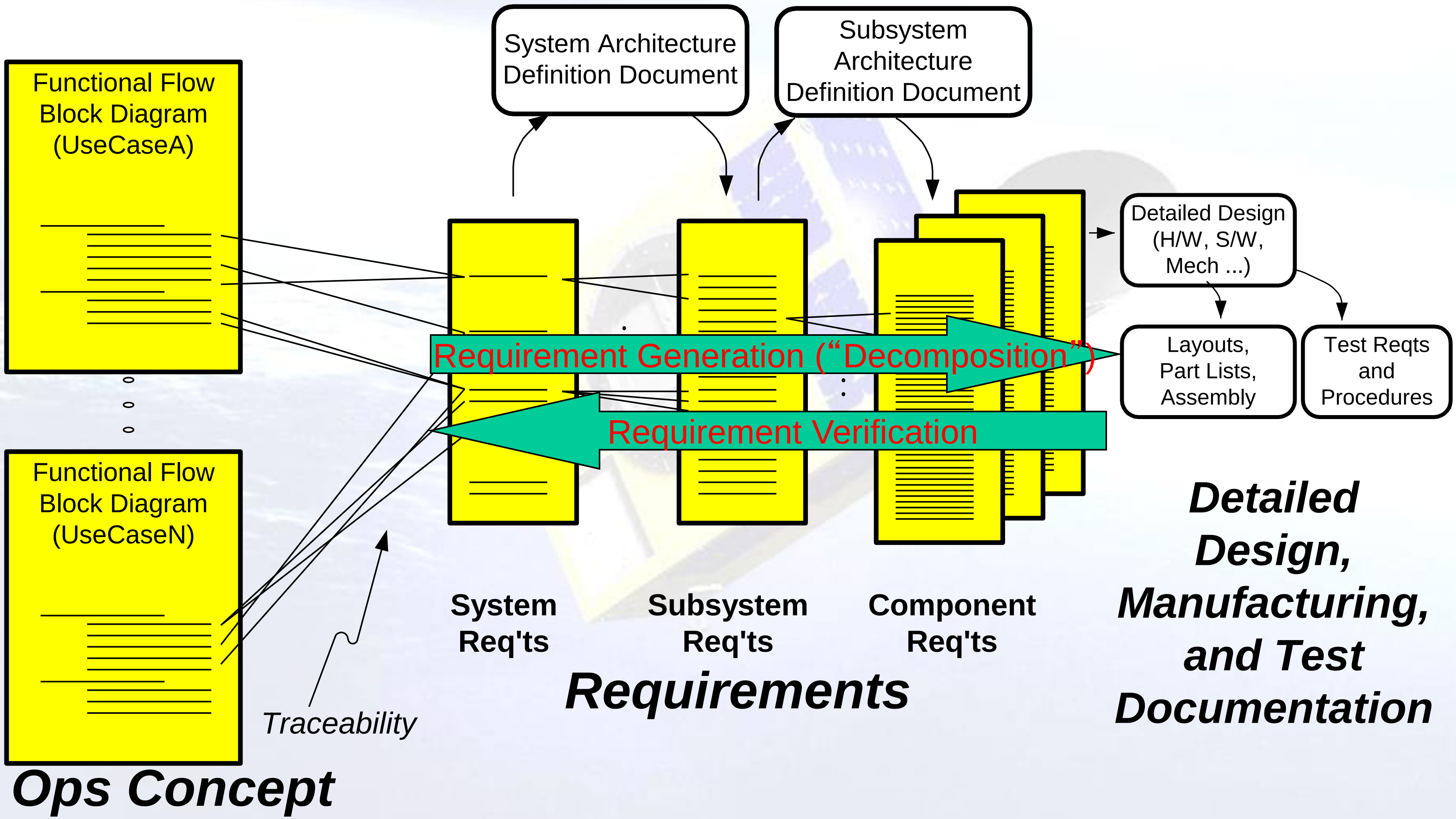
System Design Process
(Aerospace nomenclature shown)



Teamwork is essential for Engineering

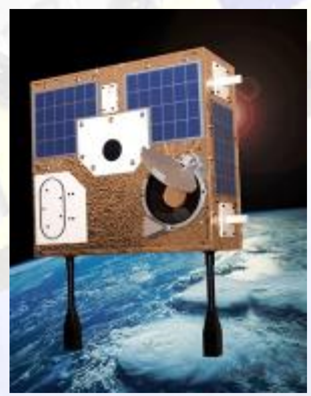
Most (all) great "engineering feats" were accomplished by large teams of people

Why is teamwork essential?

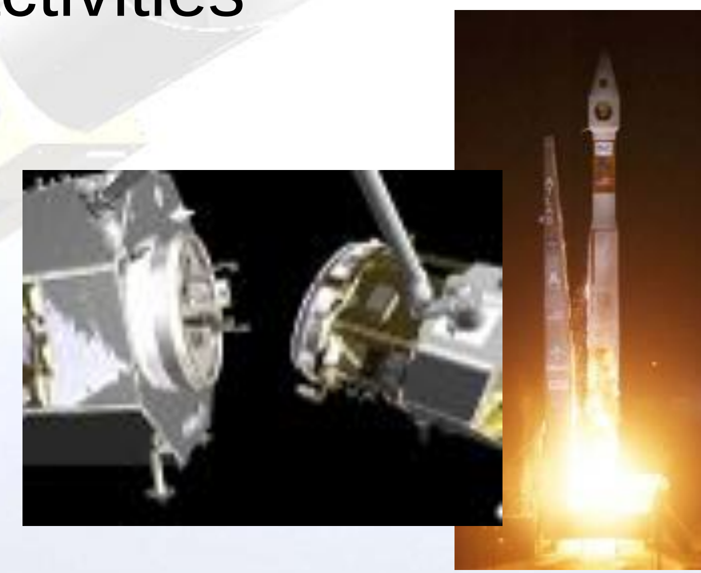
- There are not enough hours in one lifetime
- Teamwork = parallel design activities

The Apollo Missions

Canada's Canadarm2



Canada's MOST Microsatellite



Orbital Express
Satellite Servicing Demonstration Mission,
Launched February 2007

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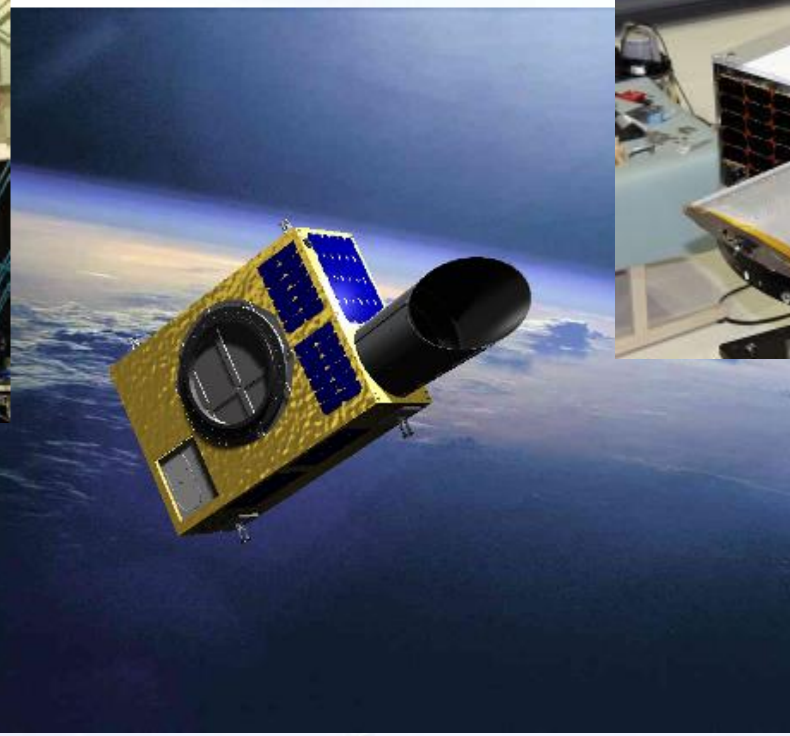
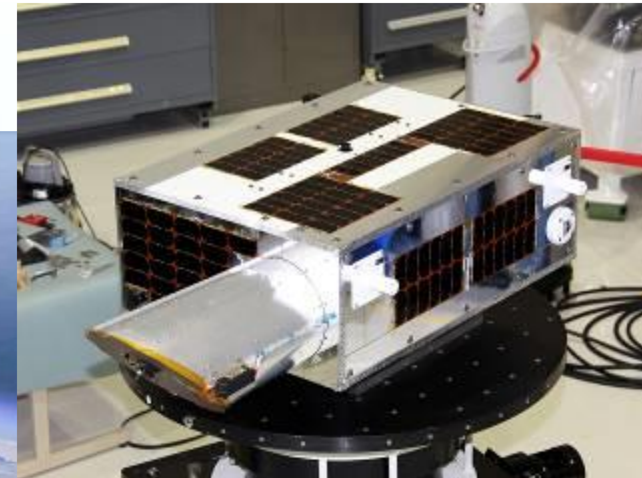
Teamwork example: ~~My Current~~ Project





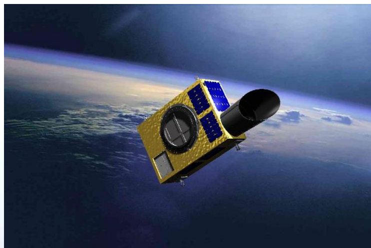
<u>Team:</u> More than 20 people over ~~three~~ ~~5~~ 6.5 years (i.e. approximately 130 person-years)

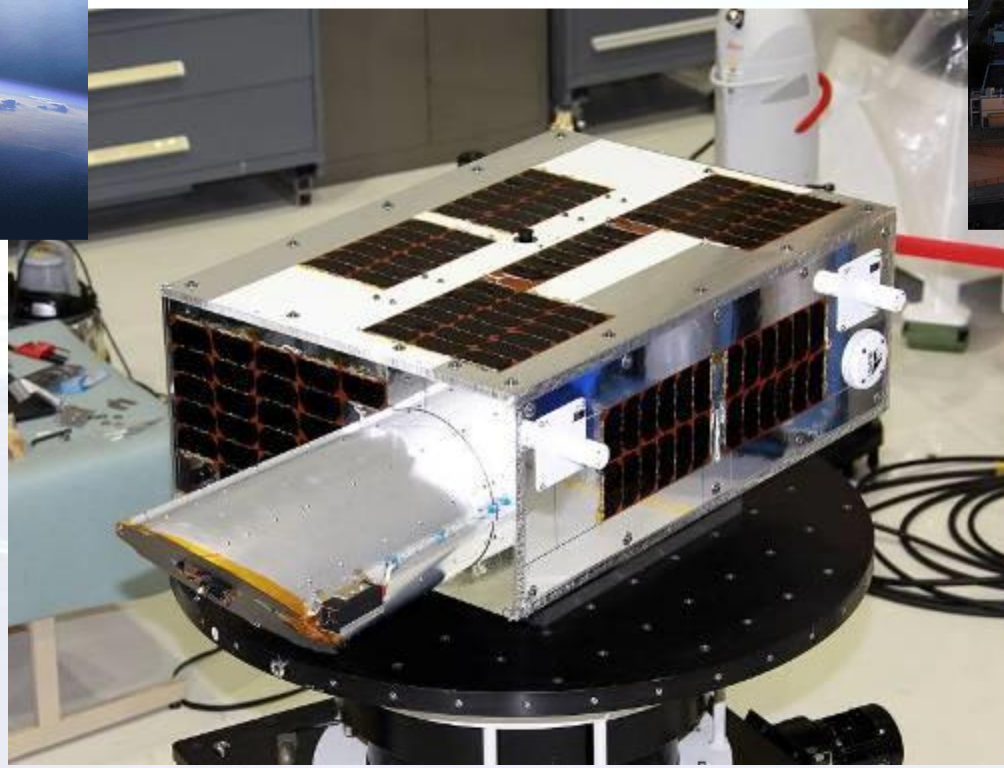
NEOSSat: ~~75 kg Microsatellite to launch in 2010~~

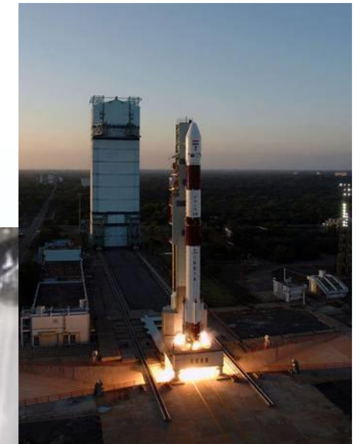
~~80 kg Microsatellite to launch in 2011~~

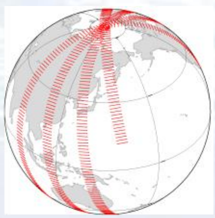
~~72.33 kg Microsatellite to launch 12 Dec 2012~~

Teamwork Example:









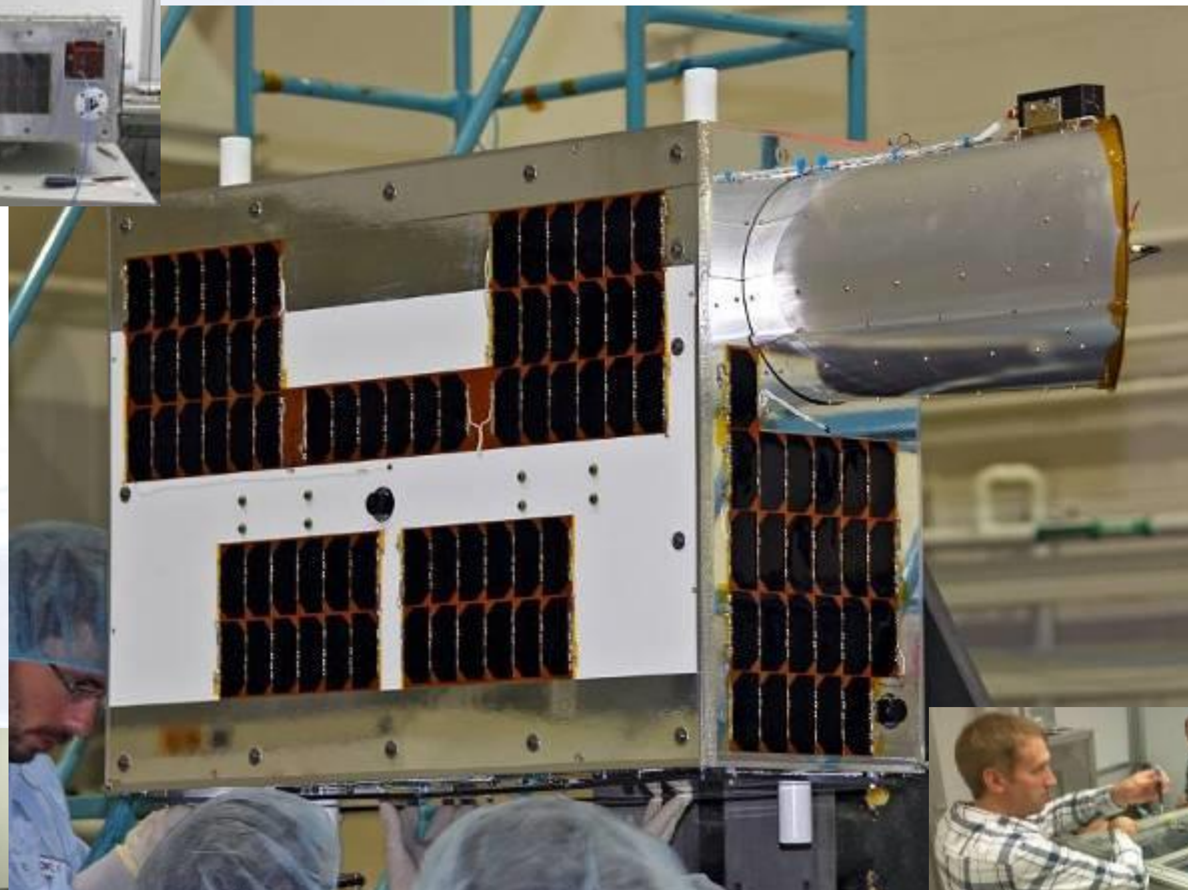
<u>Team:</u> More than 20 people over 6.5 years

(i.e. approximately 130 person-years)

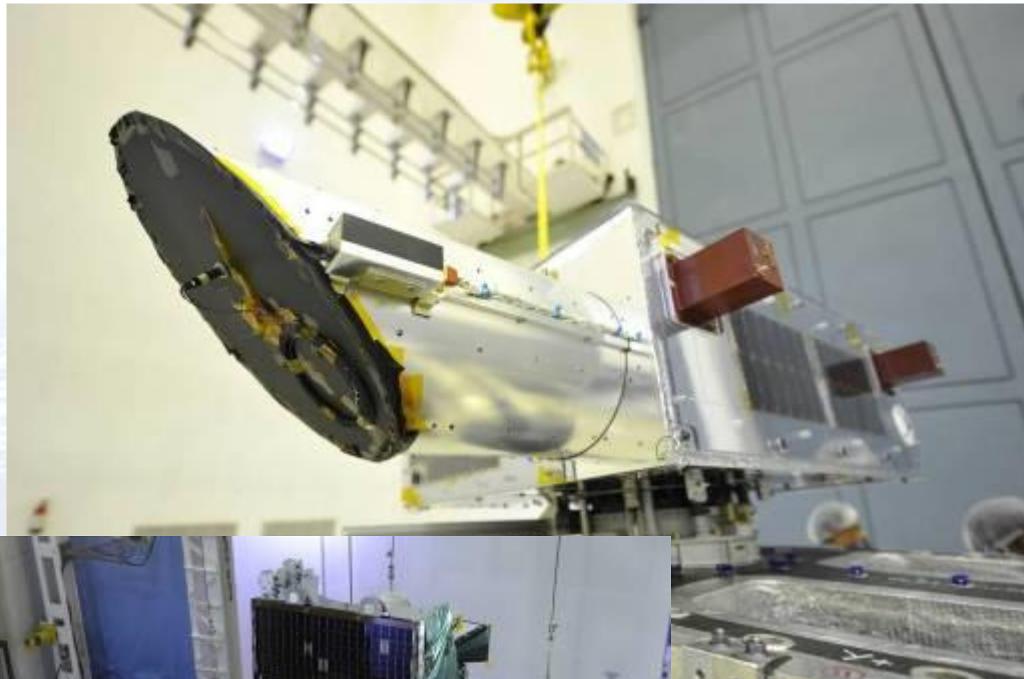
NEOSSat: 74.94 kg Microsatellite, launched 25 February 2013

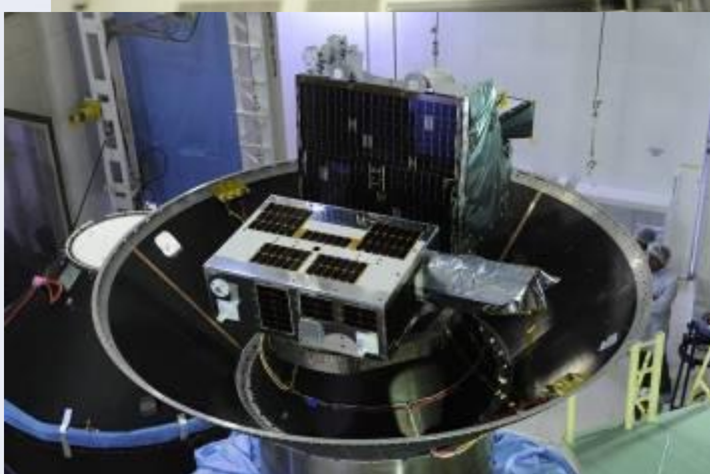
Projects and Timelines will change

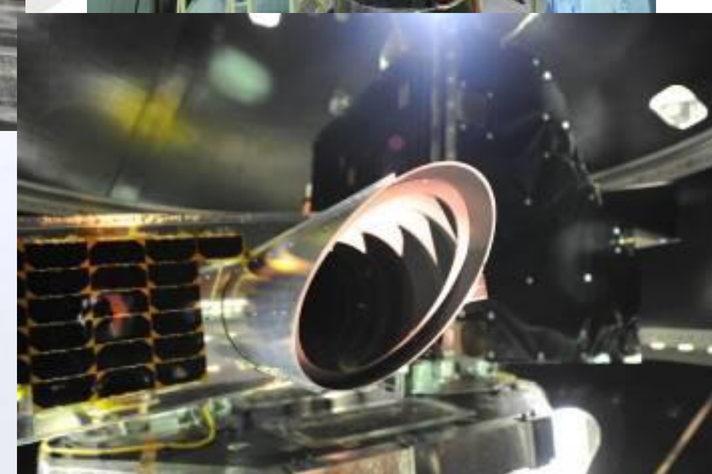
The Completed NEOSSat Spacecraft



NEOSSat In India before launch







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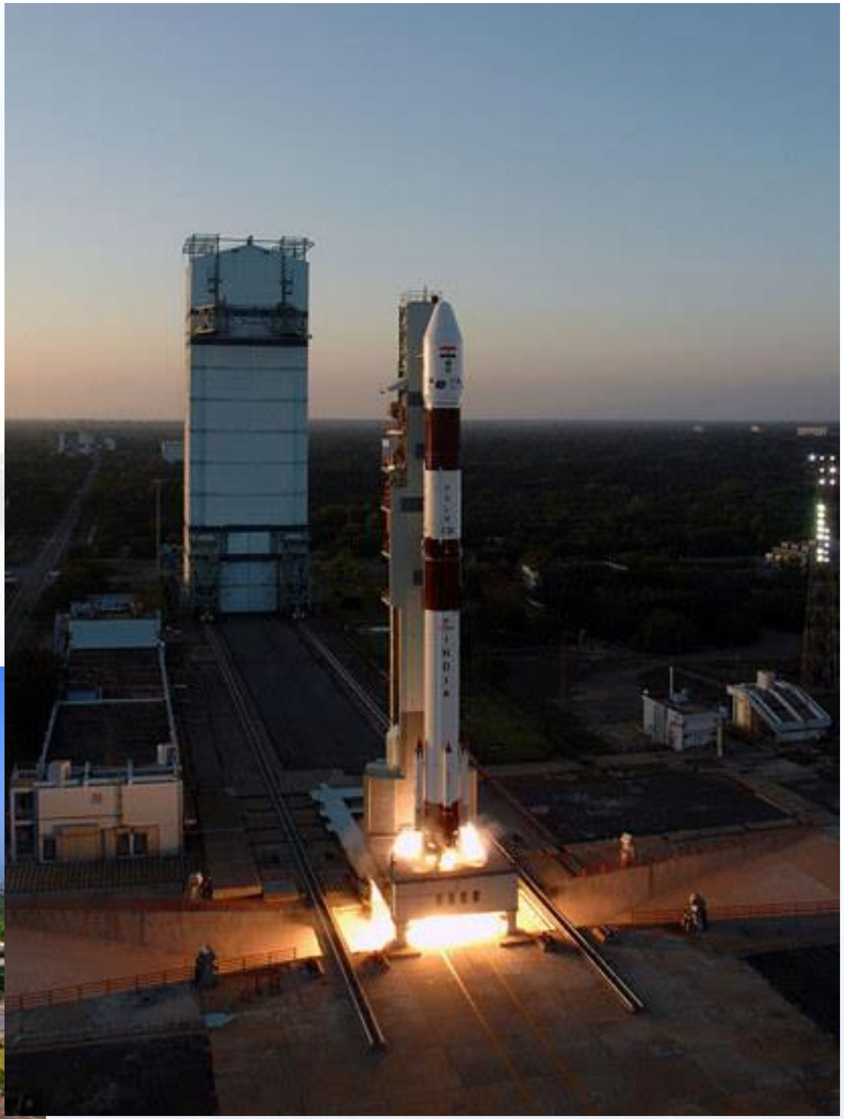
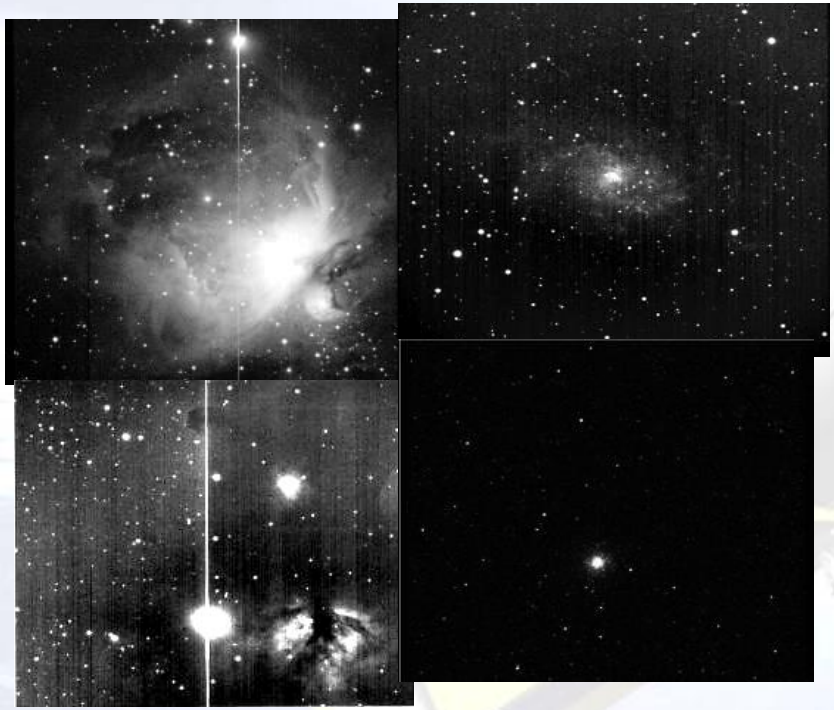
Launch – 25 February 2013



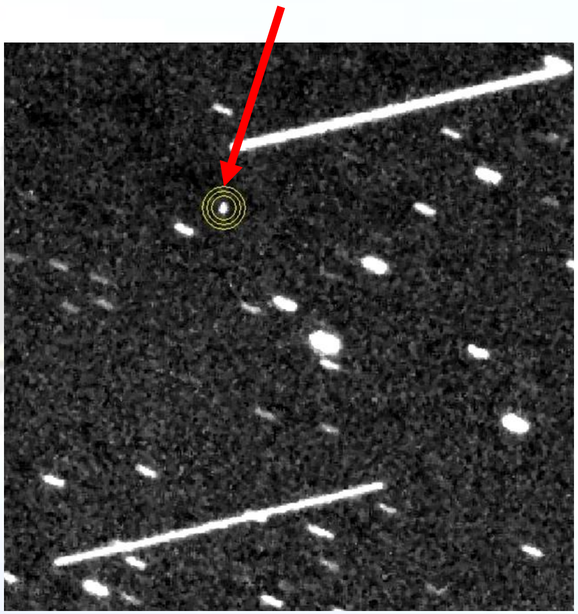
Some NEOSSat Images

"First light" Image



Various well-known astronomical targets

Asteroid 2012 TC4



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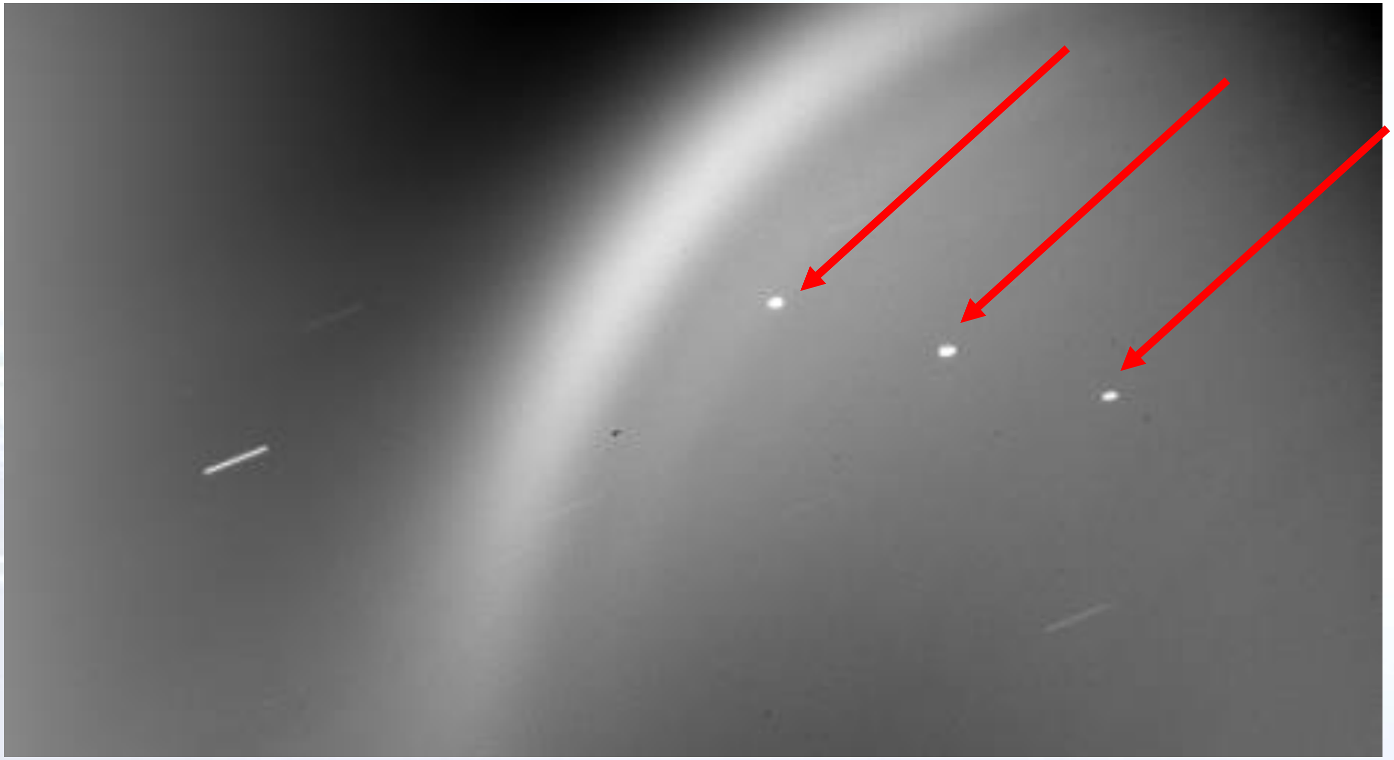
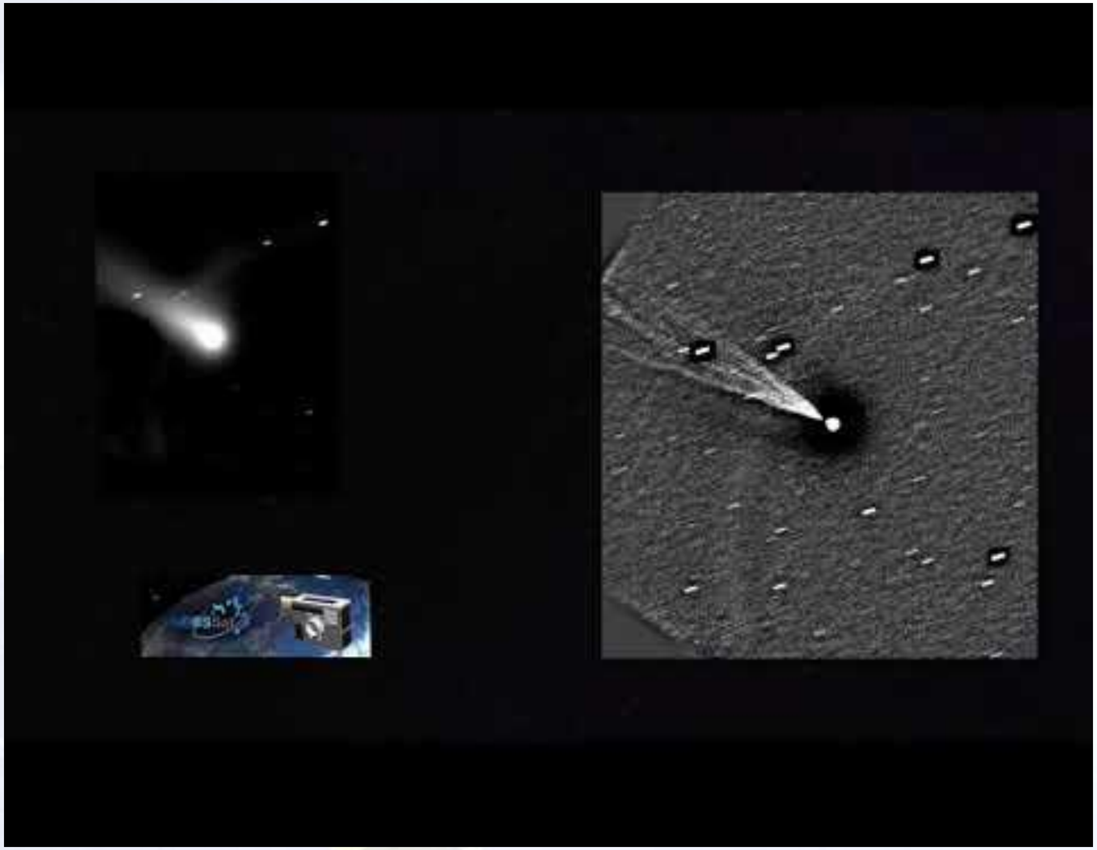
Recent NEOSSat Images



NEOSSat took an image of the three RadarSat Satellites just after their launch in June 2019

Recent NEOSSat Images



NEOSSat took images of
comet Neowise in the summer of 2020

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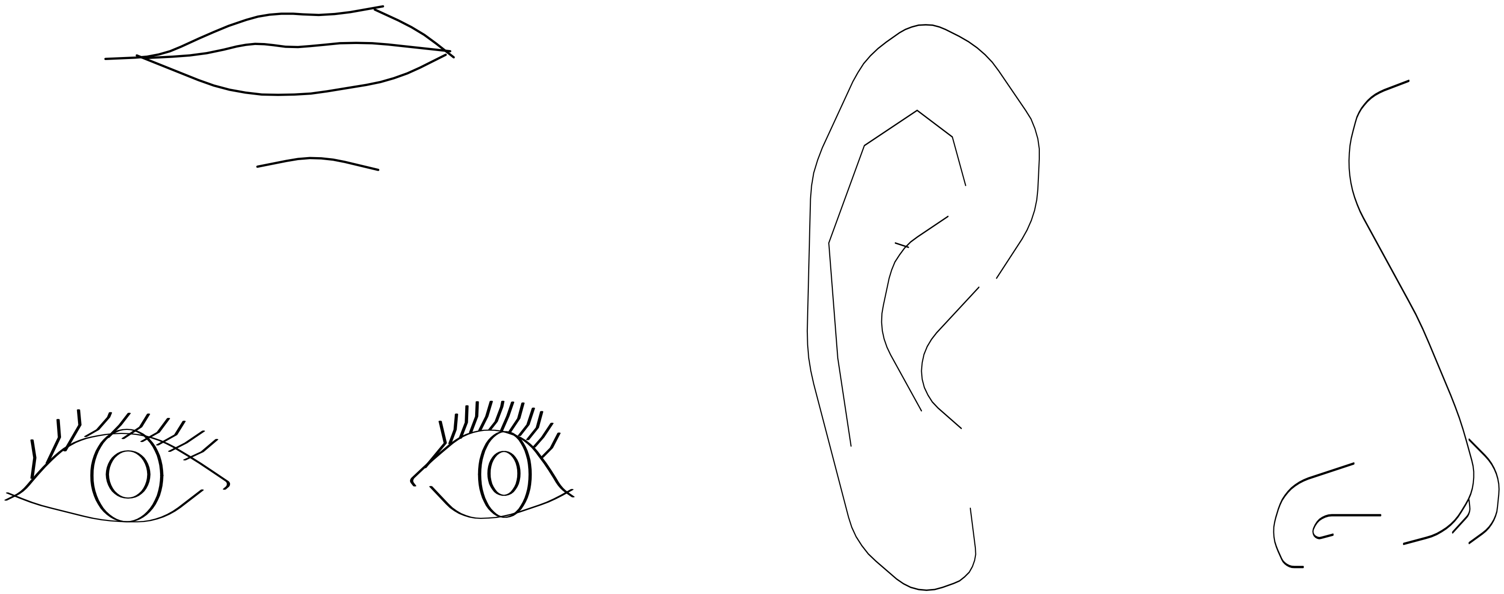
Back To Teamwork .... An Illustration

Suppose four talented sculptors decide to carve a face out of marble: One does eyes, one does the nose, one does the ears, and another does the mouth ....



All artists did a splendid job of their portion of the project …

Effective Engineering = Effective teamwork

Both images have:

- Same eyes
- Same nose
- Same mouth
- Same ear

So, which team had better sculptors?

No Design Process,
Ineffective Teamwork

Effective Teamwork
(each sculptor knew how the work needs to fit into the full 'system')

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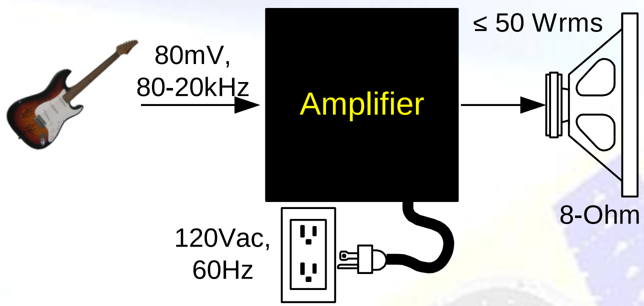
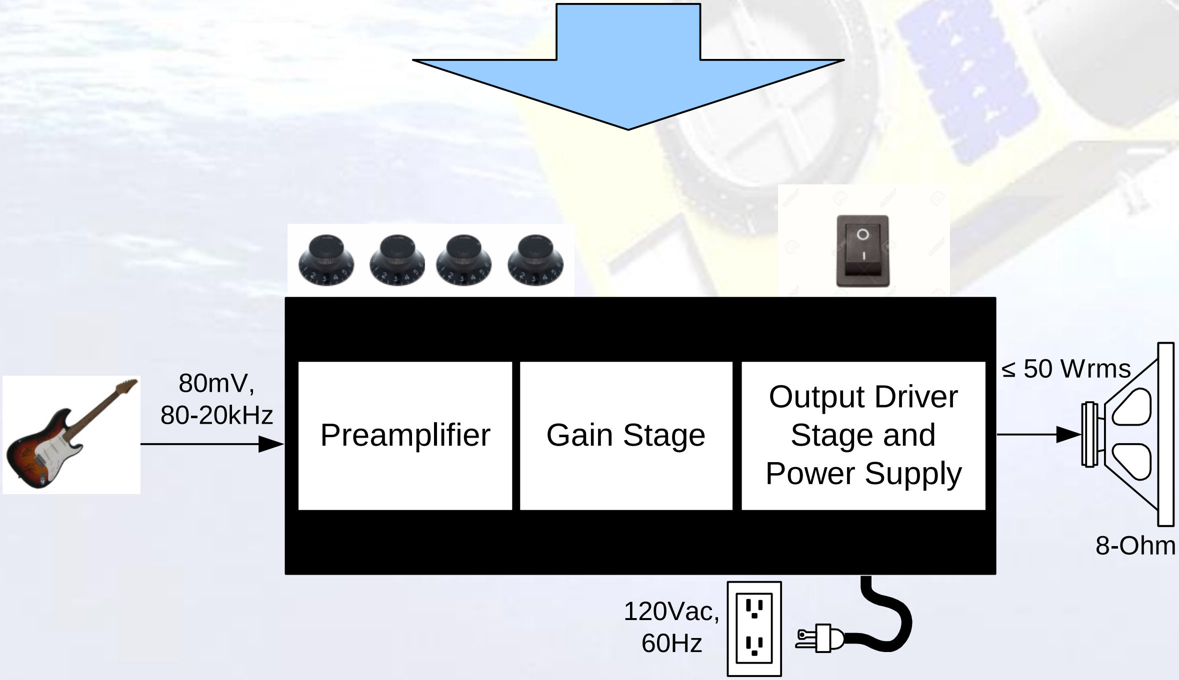
Project Example: Requirement-Driven Design



Initial Top Level (Goal)

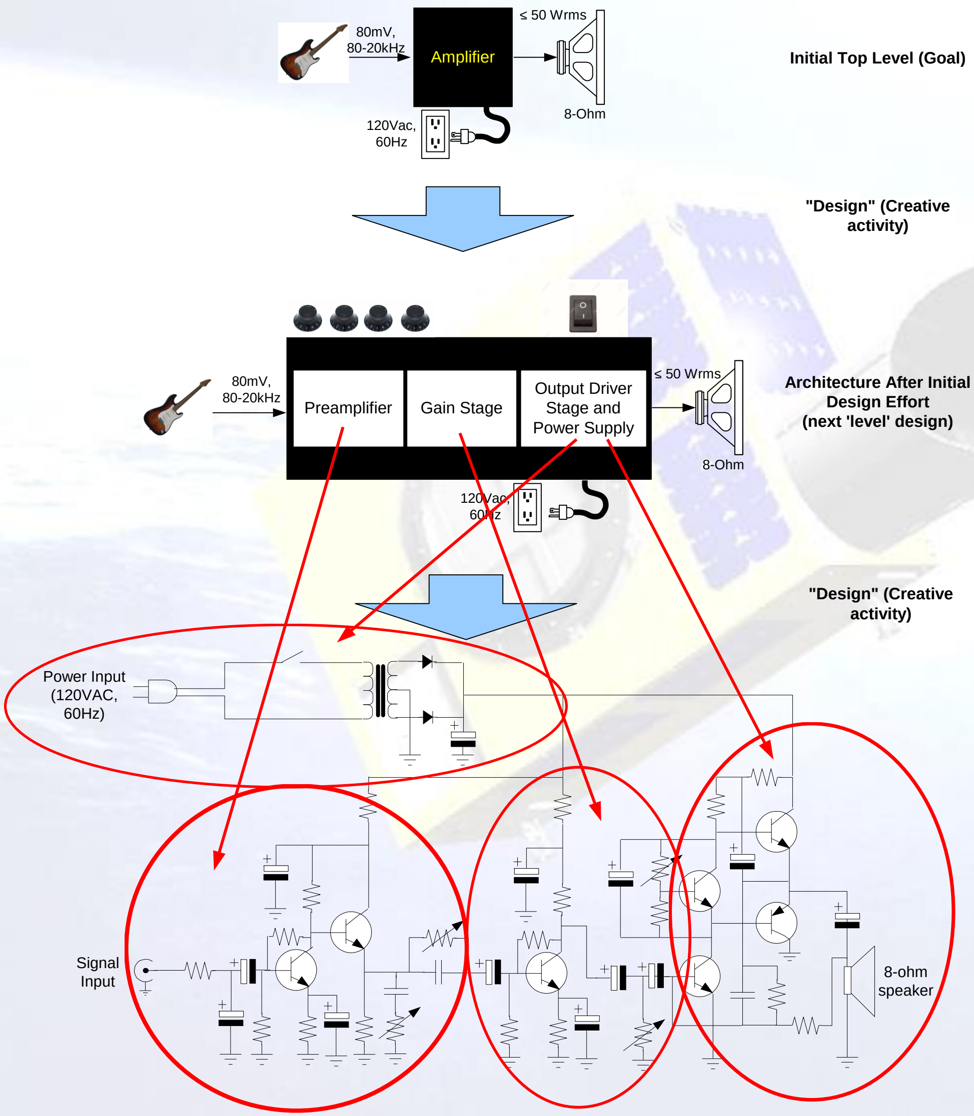
<u>Goal:</u> Use “wall-plug” electrical power to amplify the specified input signal to drive 50 Watts rms into a 8-ohm speaker

"Design" (Creative activity)



Architecture After Initial Design Effort (next 'level' design)

Project Example: Requirement-Driven Design



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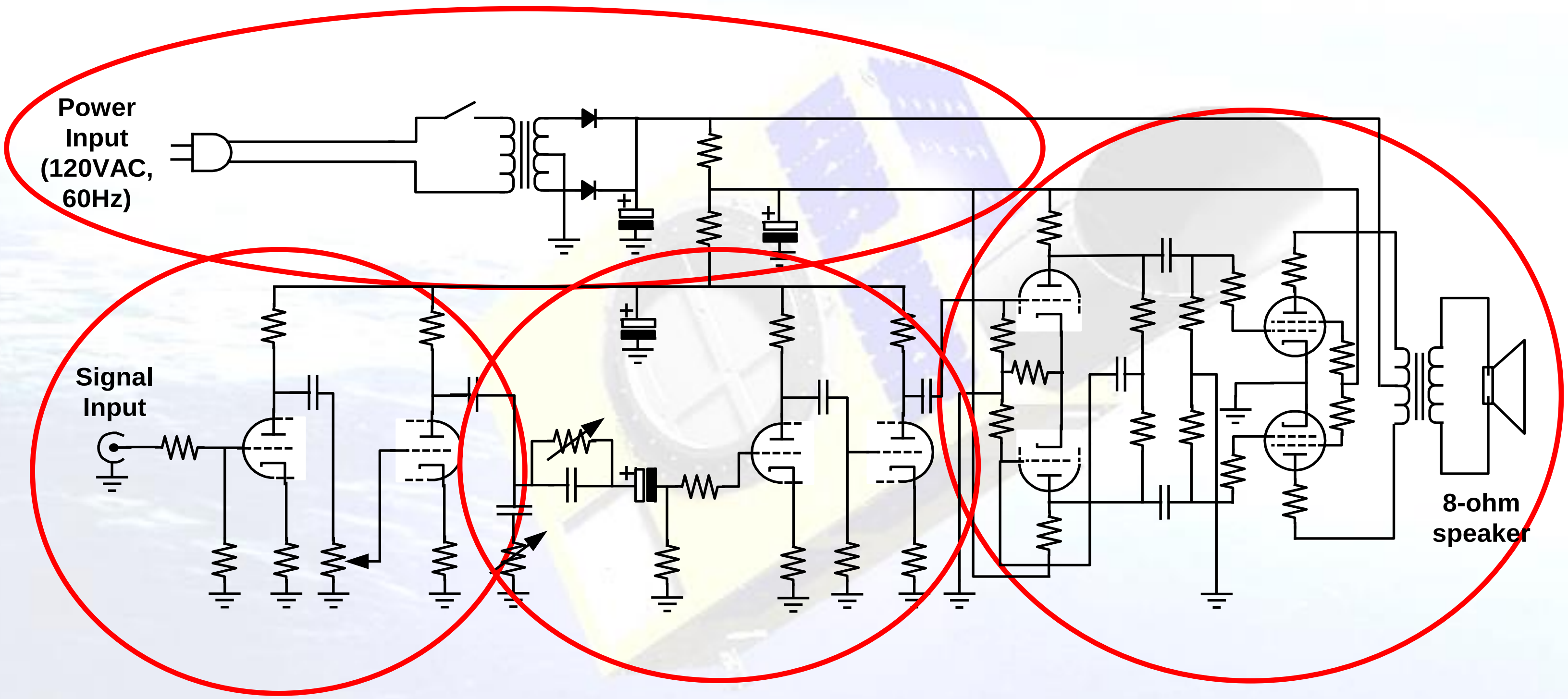
Alternate "Final Design"



Electrical Systems Design

Without <u>electrical systems</u>, any spacecraft is essentially space junk

Electrical Systems Design

- Electrical Systems Design:
  - Electrical architecture generation from requirements
    - Electrical Functional Interconnect Diagram
      - Decomposed to a suitable level
    - Power, Data, Video, Discrete-Circuit architectures often shown separately
  - Functional allocation and Requirements of all EPCEs (Electrical Power Consuming Equipment)
  - Initial physical layout of electrical equipment

Electrical Systems Design

- Electrical Systems Design <u>also</u> involves:
  - Power generation/storage/consumption analysis
  - Cabling interconnection definition and partitioning
  - Failure modes and failure tolerance consideration (impacts the architecture)
  - Critical component selection (to a limited extent)

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Electrical Systems Design (cont)

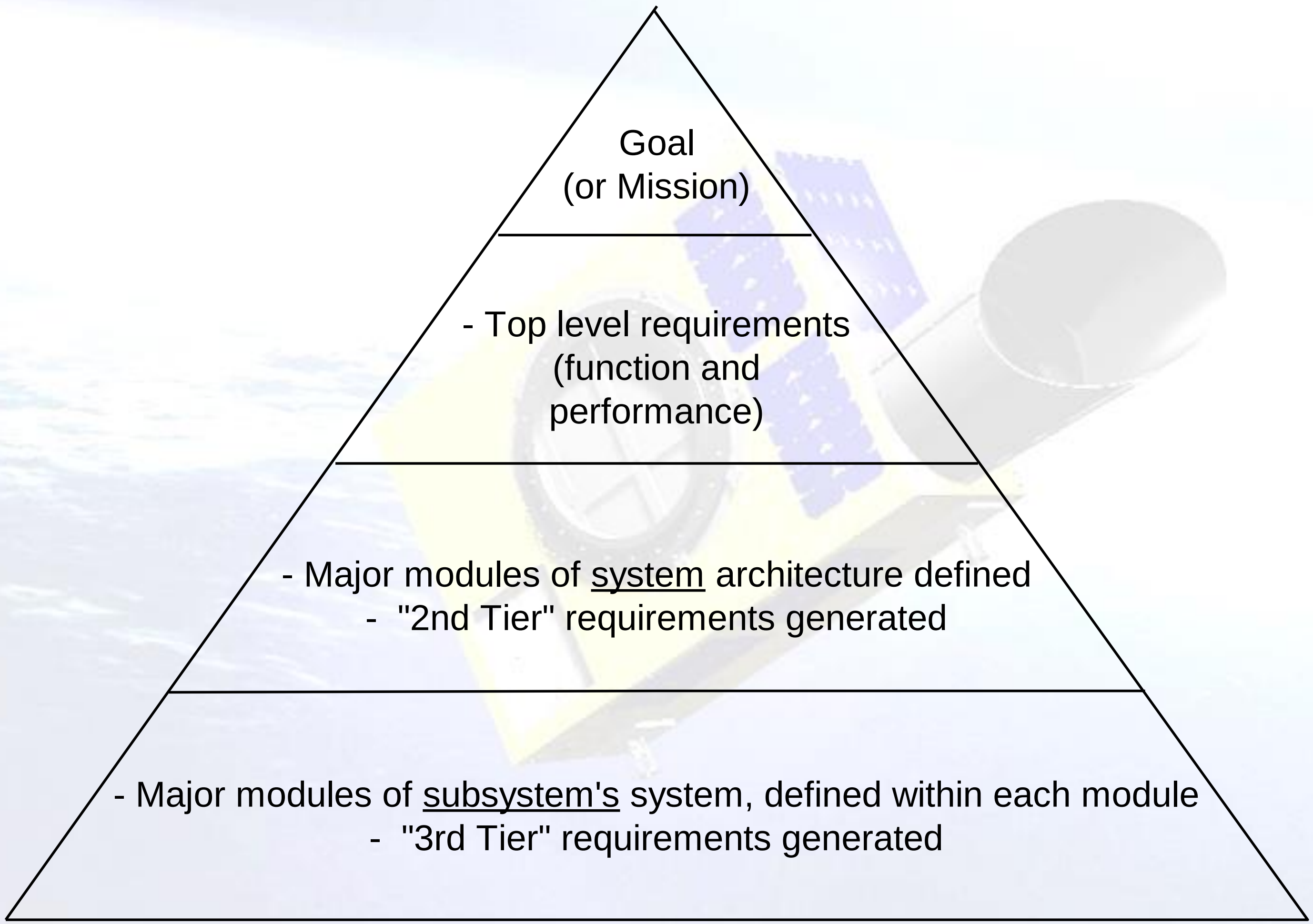
- Electrical Systems Design (generally) is NOT:

  Detailed circuit design and analysis, parts selection, PCB layout

- However,
  - No design can be performed solely as a ‘Top Down’ process
  - The detailed design process may lead to revising some 'Top Down' design decisions

Electrical Functional Block Diagrams

System Engineering - another model



The larger and more complex the system, the more 'levels' to define it

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Electrical Functional Block Diagram

- Electrical Functional Block Diagram(s):
  - System architecture looking at ... electrical functions (duh)
  - A subset of a System Diagram
  - Relationship and interconnections <u>between "electrical *functions*"</u>
  - First step in the electrical systems design process
    - Power, data, video interconnections
    - Misc electrical interconnections ('Discrete Circuits')
    - Not necessarily partitioning into physical units

Electrical Functional Block Diagram

- Simple steps to create EFBDs:
  - Identify functions that influence the "outside world" (external to your system):
    - *Driving* a motor/mechanism to move something
    - *Reading* a sensor
    - *Communicating data* to/from a lander or the Earth
  - Determine what electrical functions are needed to support these functions:
    - Drive *amplifiers* for motors and mechanism actuation
    - Sensor *signal conditioning/amplification* for sensors
    - Conversion circuitry to *read/convert* sensor values
    - *Processors* to receive commands, provide telemetry, and implement control loops
    - *Data* communication and distribution within your system
    - *Power* generation, energy storage, power distribution
    - et cetera

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Electrical Functional Block Diagram

- Simple steps to create EFBDs (cont):
  - Add functions that support the mission and operation:
    - Switching electrical power on/off to loads
    - Providing power and control for drive amplifiers
    - Protection/isolation for power switching
    - EMI filtering to isolate noise generators from sensitive circuitry
    - All of these can be left at a block level for now (don't decompose yet)
  - At this point you have the "Zero-Failure Tolerant" version of the design
  - Next look at failure tolerance requirements. You might add:
    - Duplication of critical functional blocks, interconnections, infrastructure
    - Isolatable power distribution nets with over-current protection.
  - Remember: Failure Tolerance always has a price tag ($, mass, volume, performance, complexity/MTTF)!

Electrical Functional Block Diagram

- Simple steps to create EFBDs (cont):

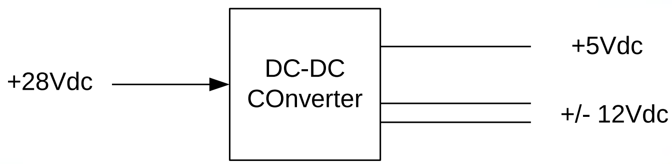
  Now look at more details pertaining to your functional blocks:
  - *This is illustrated in the upcoming "Example #2"!*
  - Type of motor drive responding to your requirements (e.g. select PWM or other variable output, or switch on/off)
  - Filtering switching noise created by motor drive circuits (i.e. add filters)
  - Data bus architecture - select topology of system, cabling, data throughput

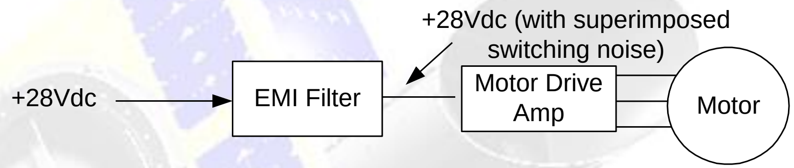
- Decompose the system as far as needed for your purpose

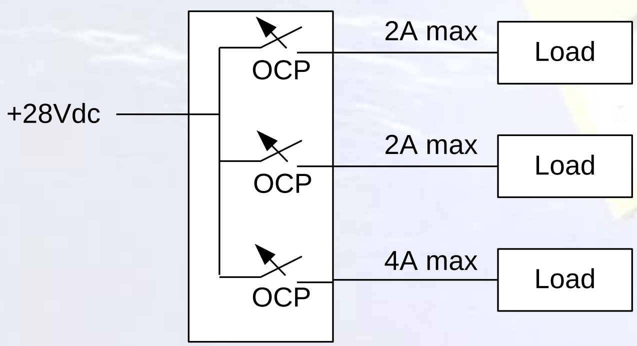
- Clearly represent the major architectures (Power, Data, Video, Discrete Circuits)
  - Show as separate or combined diagrams, depending on complexity

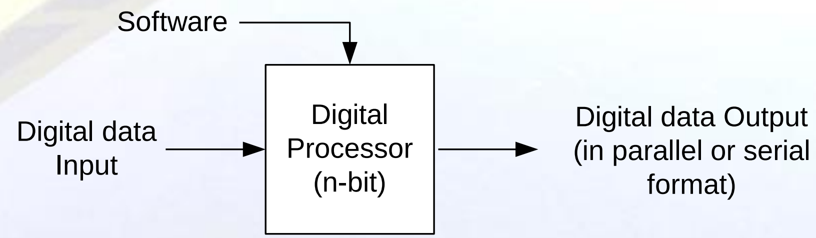
Basic Electrical Function Building Blocks

- Some EFBD basic electrical functions:









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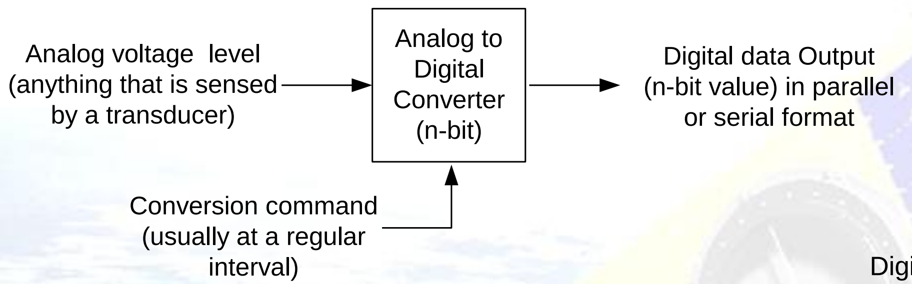
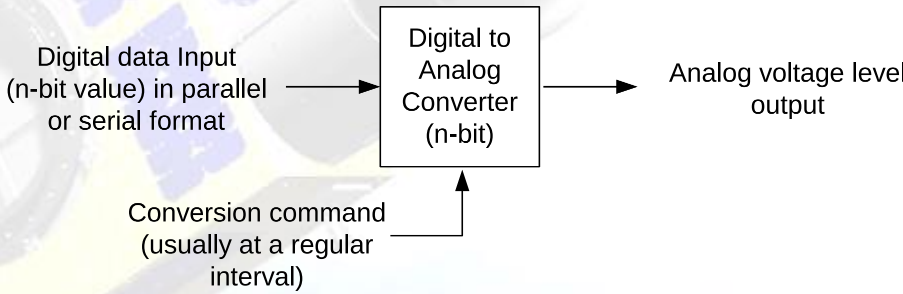
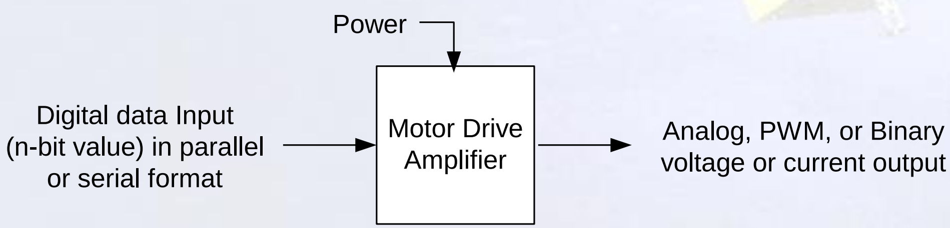
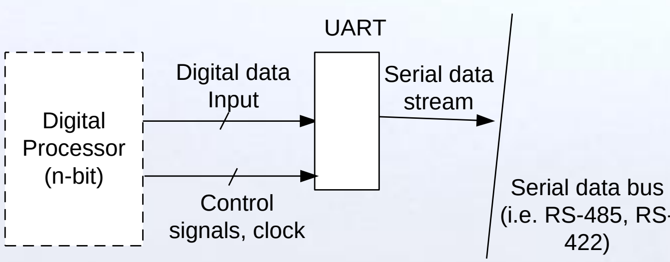
Basic Electrical Function Building Blocks (cont)

- Some EFBD basic functions (cont):









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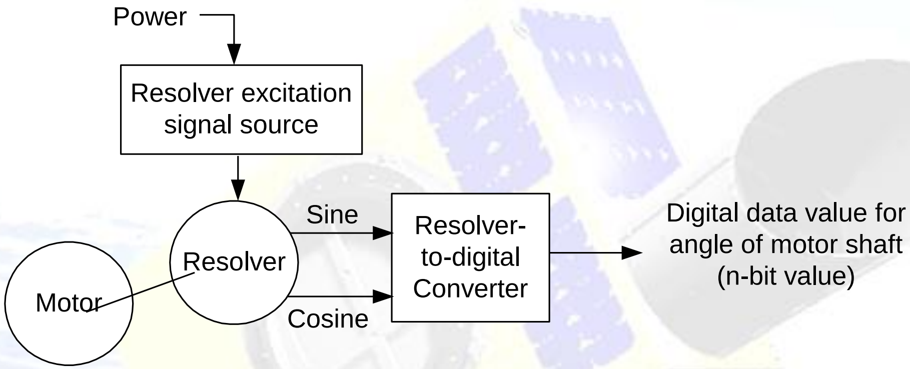
Basic Electrical Function Building Blocks (cont)

- Some EFBD basic functions (cont):



[*Resolvers are "rotary transformers" used to measure the rotation angle of a shaft*]

- Motor shaft angle can also be measured by potentiometers (analog), or with lower resolution using Hall Effect Sensors (analog), or encoders (digital, choose # of bits).
- Successive angle measurements are used for motor commutation and/or speed measurement or control
- Motor speed can be measured by tachometers

Example #2: Requirement-Driven Generation of a EFBD

If these are your system requirements for a manipulator:

- 4 degrees of freedom, plus image acquisition at the tip
- 3 controlled axes must have precise and varying rate control and position accuracy
- 1 controlled axis needs to only move a portion of the mechanism between two defined end points
- Camera showing a view of the workspace
- Power source compatibility: 28 Vdc ± 6 Vdc
- A defined minimum of electrical noise can be introduced onto the power rails (*so other subsystems do not receive this noise*)
- The system must operate reliably for many years in an unpressurized environment (*i.e. in space*)

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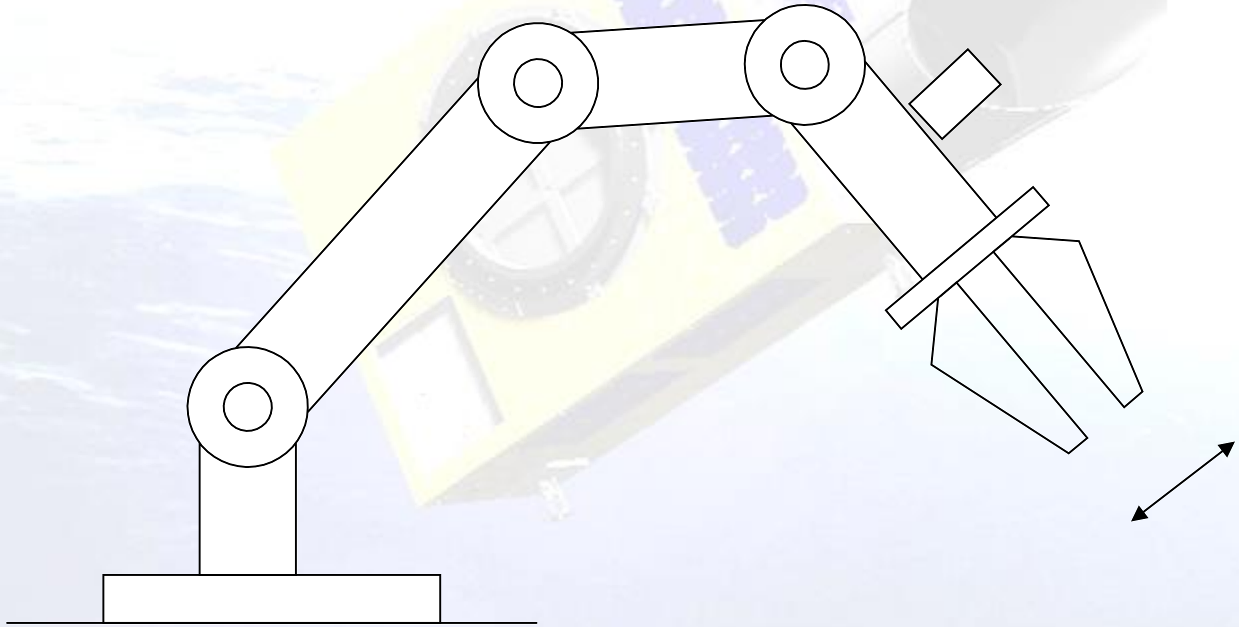
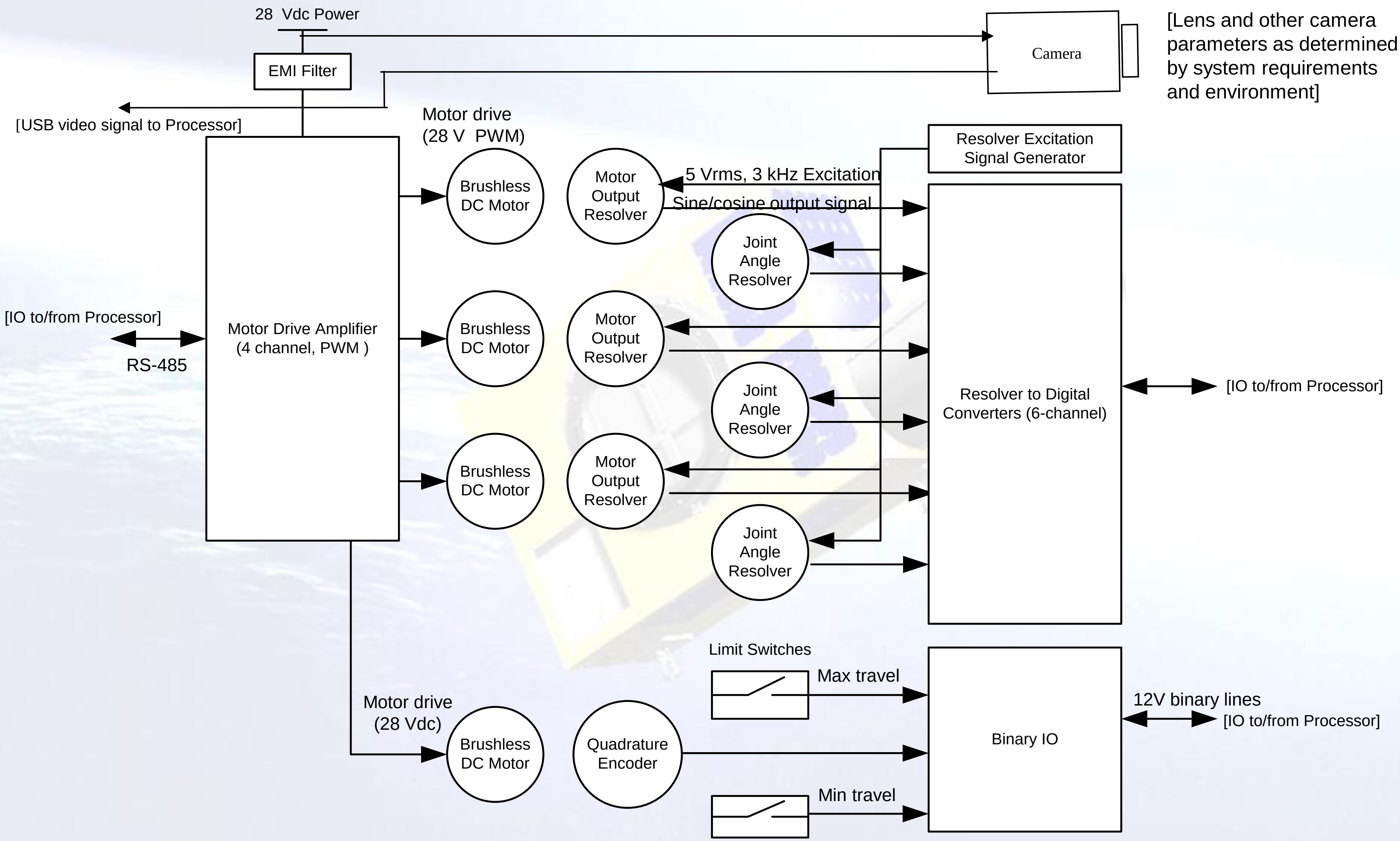
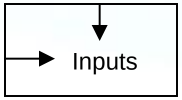
i.e. This is how the required manipulator *might* look

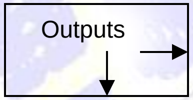


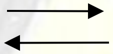
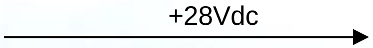
Example #2: EFBD Driven by Requirements



Drawing the EFBD Diagram(s)

- There are no hard rules, but the following make EFBDs and other block diagrams easier to read:
  - Inputs on the left or top of page, functional block, system 

  - Outputs on the right or bottom 

  - Avoid colour coding (b&w printing will eliminate information)
  - Denote direction of information or signal flow with arrow-heads
  - Avoid  (better to have )
  - Label all interconnections and blocks: 

  - Hierarchical drawings are good, but ensure top-level sheet has consistent labels with all lower-tier sheets so that there can be no confusion

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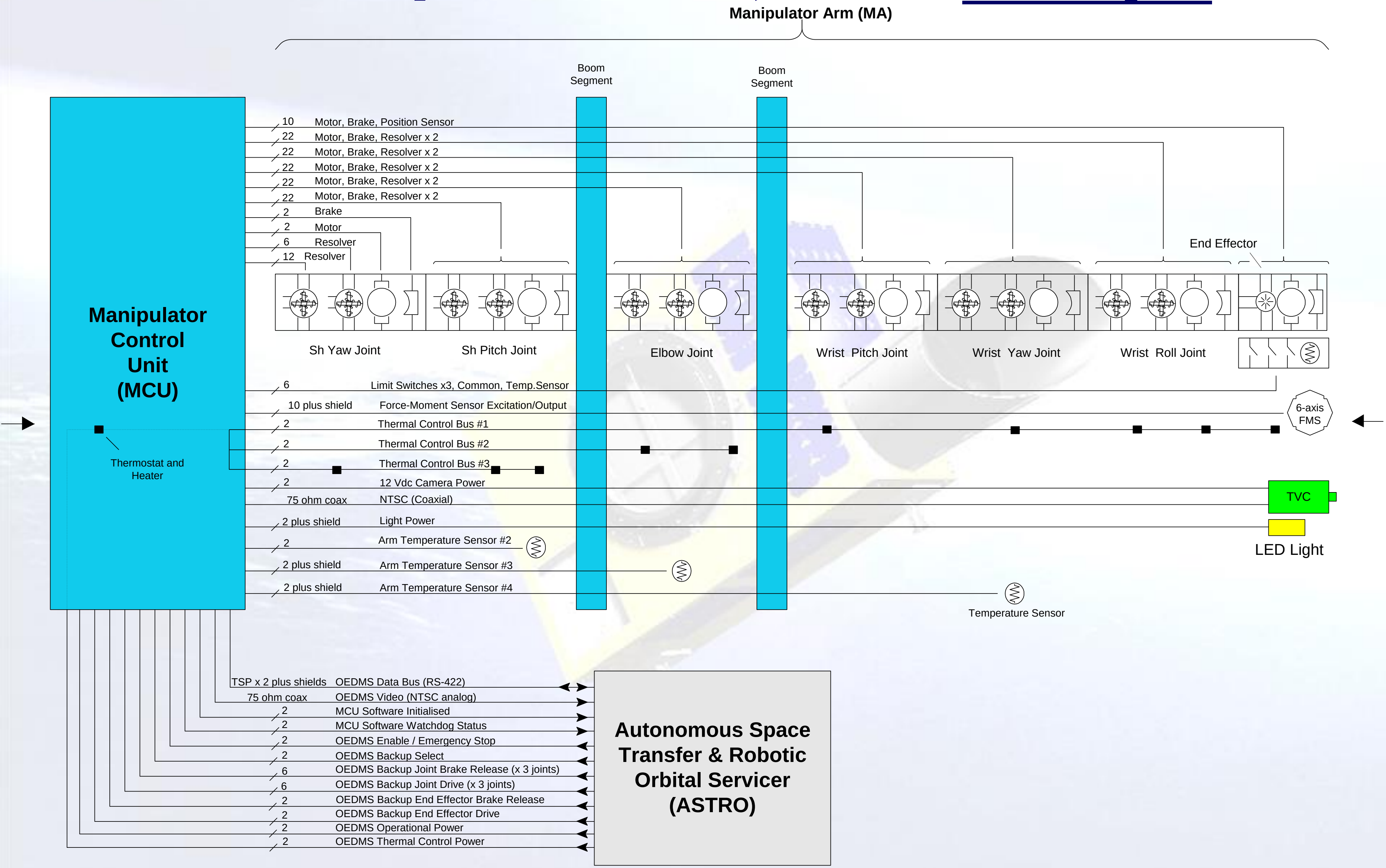
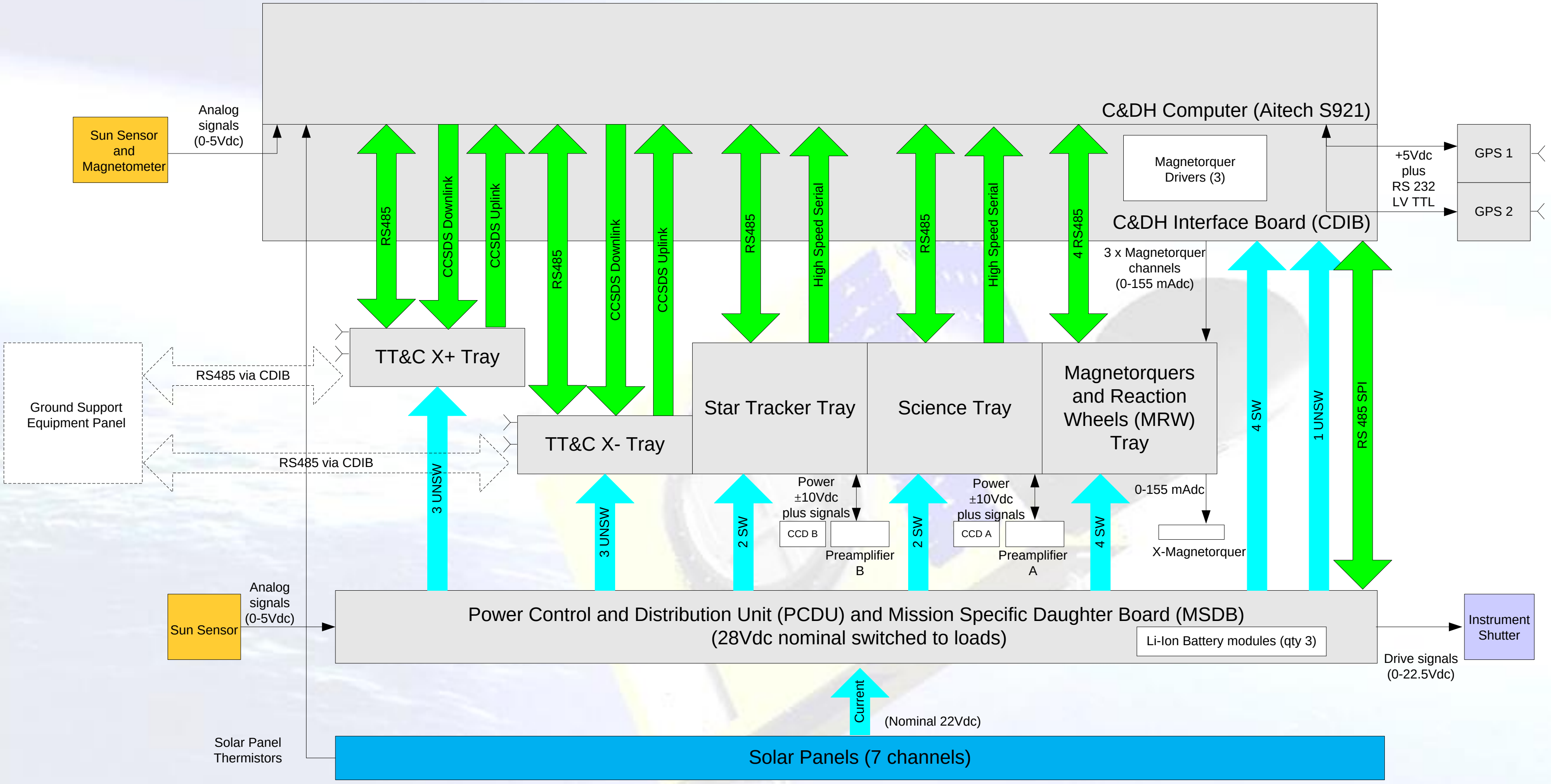
Orbital Express EFBD, as an example



NEOSSat EFBD, as an example



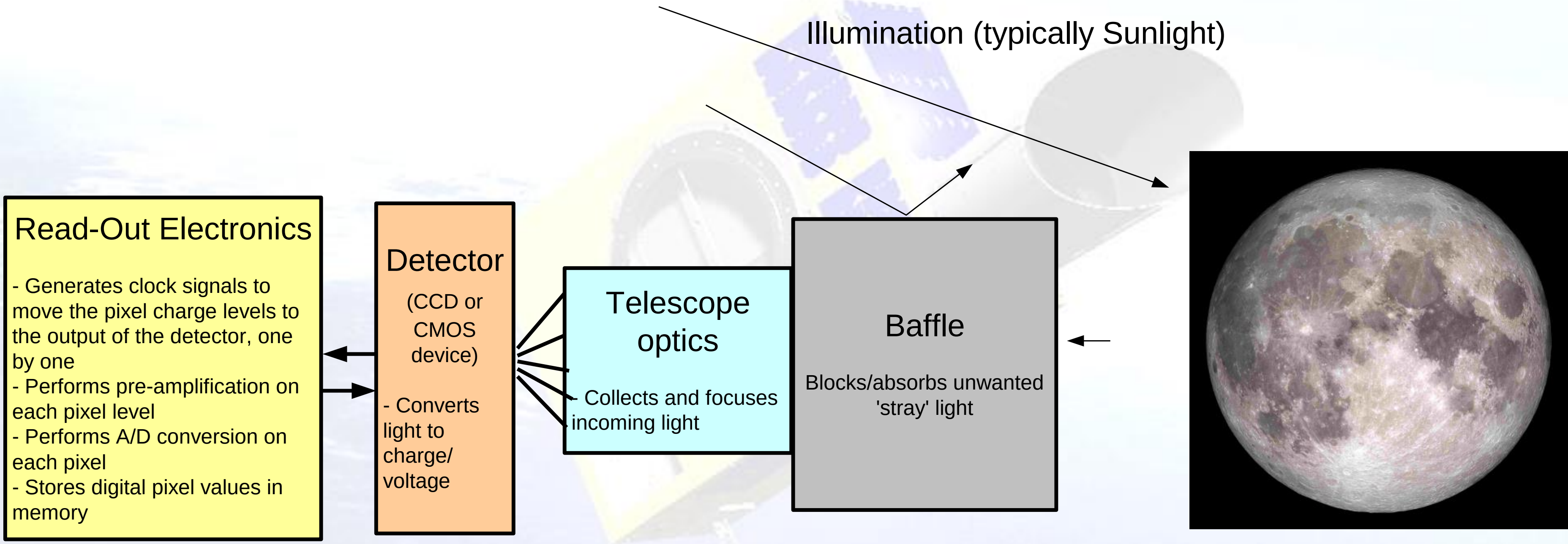
NEOSSat Electrical Functional Block Diagram

Optical Instruments

Optics/Optical Instruments

- Although not fully electrical, the performance of space-deployed optics is important for instrument specification for imagers
  - Space telescopes (space pointing, Earth pointing, …):
    - Optical portion to collect and focus light
    - Imaging portion (typically a CCD or CMOS device) onto which focused light is projected and electronically 'read out' as (digital) pixel values
    - Baffle portion as needed: prevent unwanted ('stray') light from reaching the imaging portion
  - Camera systems for robotic or other imaging applications:
    - Optics: FOV, aperture/optical resolution, controlled or fixed-focus
    - Detector: Resolution, sensitivity, dynamic range (intrascene and exposure controlled) for all lighting conditions
    - Artificial lighting versus sunlit
    - Pointing control on pan/tilt unit, or fixed mount
- Design involves balancing performance of all portions

Optics/Optical Instruments (cont)



Space telescope example

Optics/Optical Instruments (cont)

- Optical Performance:
  - Diffraction-limited performance is ideal (cannot be better than this)

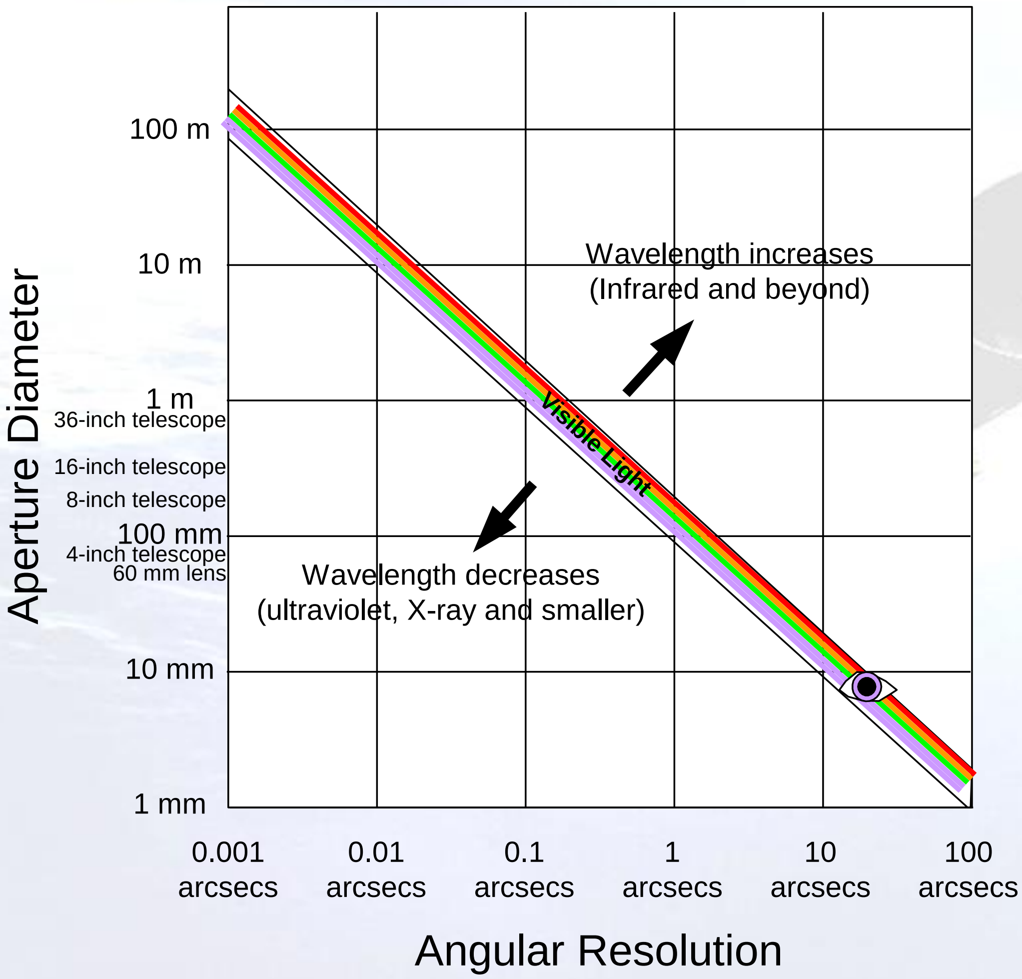
$$\theta = \text{Minimum angular separation of features that can be distinguished by telescope optics (radians)}$$

$$= \frac{1.22 \text{ x wavelength (mm)}}{\text{Aperture diameter of telescope (mm)}}$$

  - Stray light rejection can become an important parameter
- Imaging Performance
  - Pixel size (in microns, usually square). Together with optics determines image resolution – whichever is worse
  - Pixel sensitivity (well depth, dark current, noise. All in units of e-)
  - Analog to Digital resolution of pixel levels (i.e. 12-bit)
  - Readout electronics noise:
    - Random noise is ideal (best performance since it usually comes from the sensor alone). Expressed in electrons
    - Systemic noise (power supplies, interference, crosstalk …) is to be avoided or eliminated in the design

Optics/Optical Instruments (cont)

Diffraction Limited Performance drives the size of the instrument:



In turn, the resolution of the focused light onto the imager drives the pixel size requirement

(i.e. smaller pixels cease to improve image resolution)

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Electrical Power Subsystem

"Power is Everything"
– John Aaron, Apollo 13

Electrical Power Distribution

- **Electrical Power**: Single most important equipment and mission design driver
  - Most space systems are very tight on power budgets
- "Ambient temperature" does not exist as on earth.
  - Without heat energy, components can cool down to only a few Kelvin (-269C)
    - Well below survival limits of most equipment
    - A Venus-deployed subsystem faces the other extreme!
- "Power Positive": The guarantee that overall power usage (on average) will never exceed overall power generation capability.
- For a long term average, the only continuous source of power is usually sunlight or nuclear power generation.

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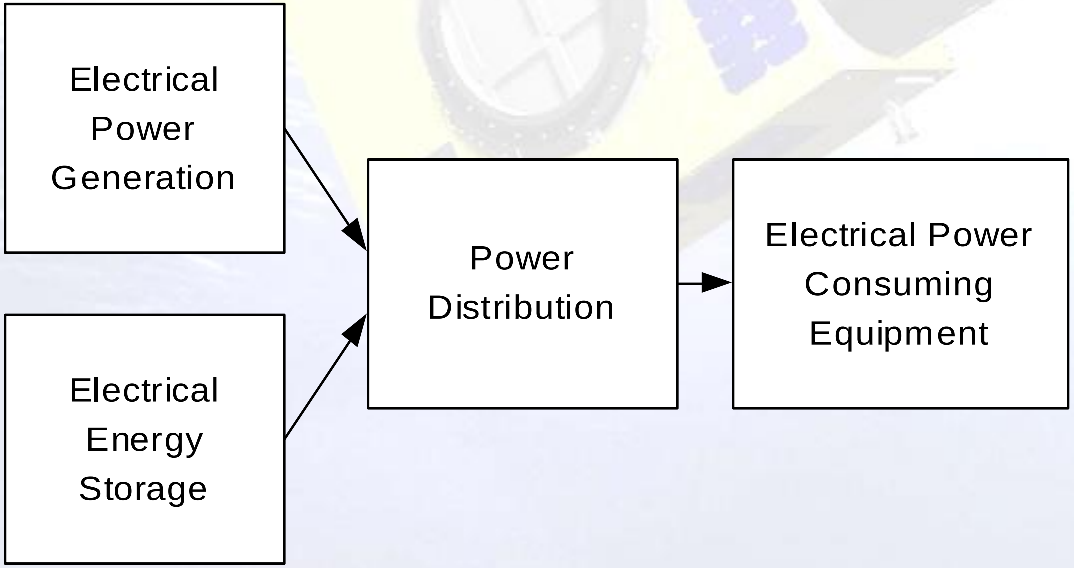
Electrical Power Subsystem

- Electrical Power Subsystem (EPS):
  - Power Source
  - Energy Storage
  - Power Distribution
  - Power Regulation and Control within EPCEs



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Power Source Examples

- Solar (Solar arrays, Solar Thermoelectric)
  - 'Unlimited' if power demands remain within EOL capacity
- Nuclear (Radioisotope Thermal Generators (RTGs), RHUs)
  - Uses heating from radioactive decay to generate electrical power
  - Heat/radiation often requires separation from electronics
  - Specific power is poorer than Solar panels (more mass for higher power applications)
- Fuel cells [e.g. hydrogen + oxygen $\rightarrow$ water + electrical energy,]
  - Limited energy or, like batteries, must be recharged
  - Regenerative Fuel Cells use (e.g.) solar array energy to perform electrolysis of water (byproduct) to create more fuel [water + solar energy $\rightarrow$ hydrogen + oxygen]

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Power Source (cont)

- Solar arrays
  - Efficiency has improved over past years
  - Power $\propto$ Solar Incident Energy x Area x cosine loss x η x other losses*

    *i.e. packing efficiency, degradation due to radiation, dust, temperature, et cetera
  - Some papers indicate $\eta \approx$ 30% at BOL
    - Many recent systems only achieve < 20% if Silicon cells.
    - Triple Junction GaAs cells alone achieve $\approx$ 26-28%
    - Remember that the above efficiencies DO NOT include power conversion losses, which can be highly variable depending on the system topology and detailed design

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Energy Storage

- Fuel cells
  - Hydrogen is more of an energy storage medium than a fuel, really, since its collection requires energy
- Batteries
  - NiCAD, Nickel-Metal Hydride (NiMH), **Lithium Ion**, Lithium Polymer (fairly new to space flight but showing promise)
  - Considerations: Capacity, Energy density, specific energy/power, life (charge/discharge cycles), depth of discharge, rate of discharge, time-dependent degradation
- Mechanical energy storage
  - Flywheels
  - Not very mature yet

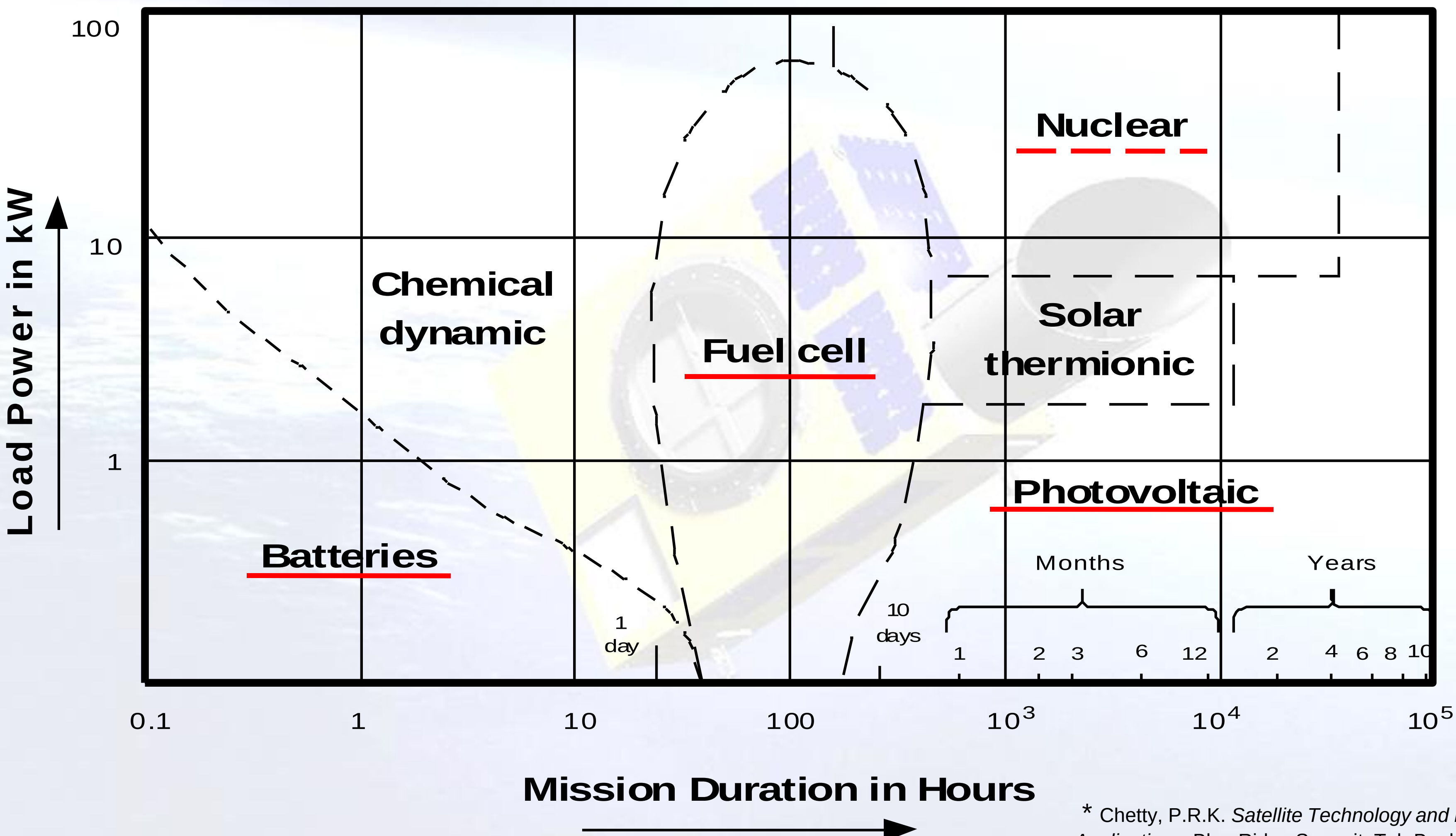
Energy Storage

- Batteries (cont):

Parameter	Lead-Acid, Advanced	Nickel-metal hydride	Lithium-Ion *	Lithium Polymer
Specific Energy, Wh/kg	33-42	60-120	100-265	>250
Energy Density, Wh/l	60-110	140-300	250-730	600
Specific Power, W/kg	180	250-1000	250-340	3000
Life, full-discharge cycles	500-800	500-2000	400-1200	no data
Cost, USD/Wh	$0.6 - $0.14	$0.36	$0.40	$0.06

* Tesla cars, most mobile devices use this type

Power/Energy Source vs Load/Duration*

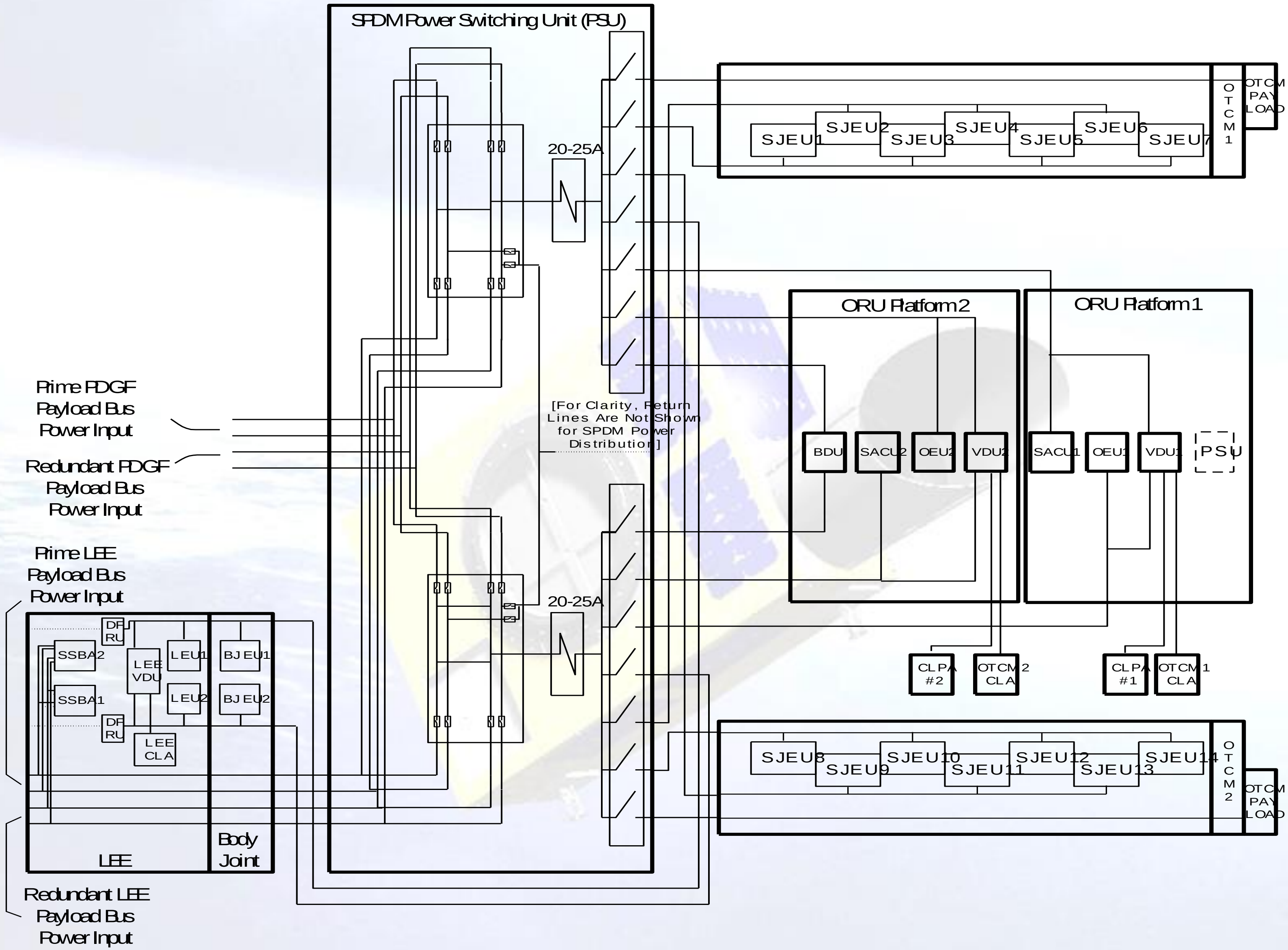


* Chetty, P.R.K. *Satellite Technology and its Applications*, Blue Ridge Summit: Tab Books, 1988

Power Distribution

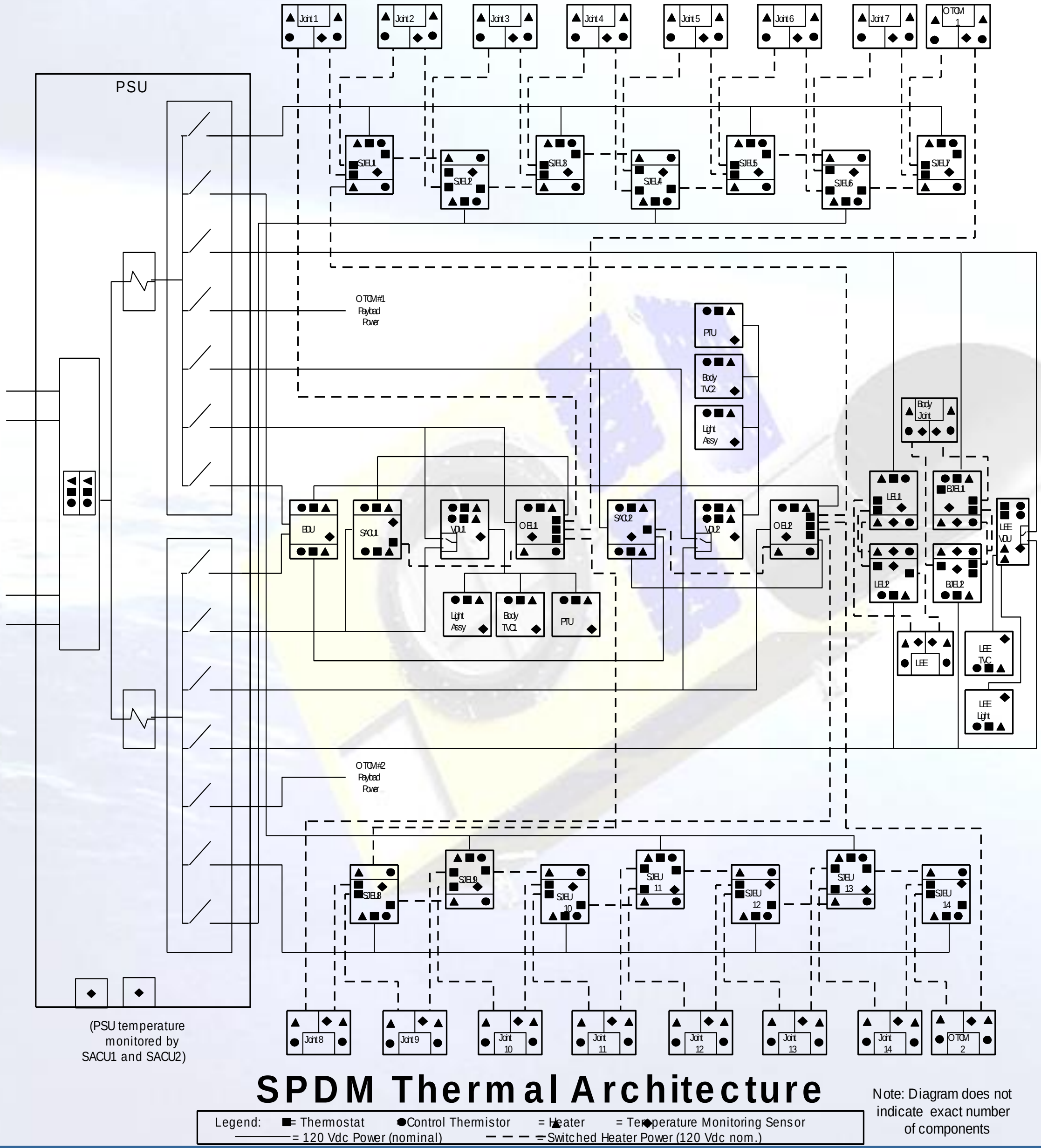
- Power Distribution Architecture
  - Indicates connections between:
    - power generation/energy storage equipment
    - power switching/overcurrent protection equipment
    - all power consuming equipment
  - Shows connectivity, but not details on the number or type of wire (unless for mass estimation purposes)
  - Shows how redundancy is implemented for failure tolerance
  - Return lines often omitted for clarity, but this <u>must</u> be stated

Power Distribution



SPDM Power Distribution

Power Distribution



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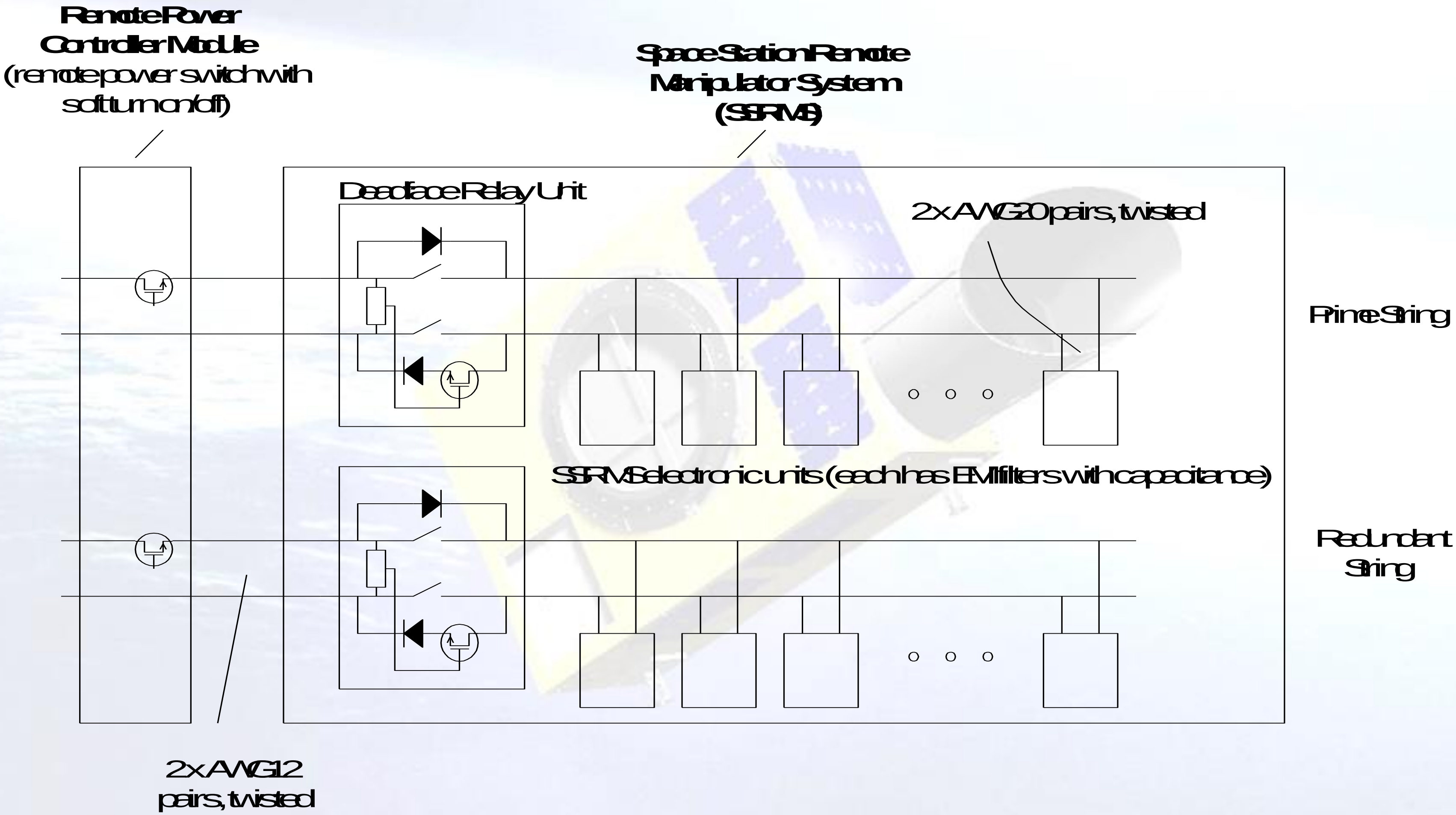
Power Distribution



Simplified SSRMS Power Distribution Diagram

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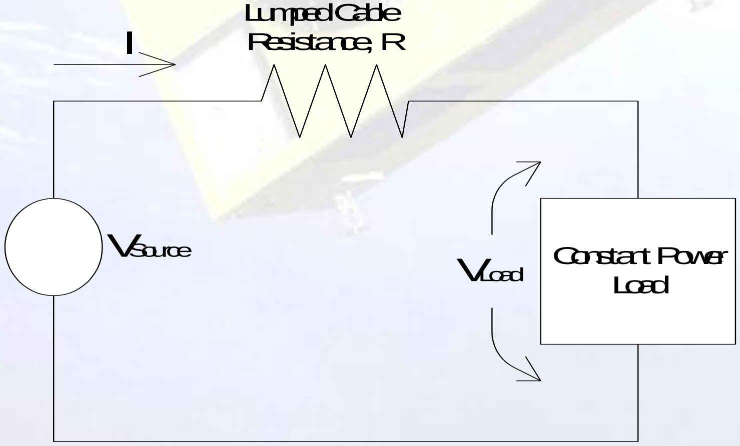
Power Distribution

- **Cable Sizing, Voltage Drop, Thermal Design Issues**

[Cable sizing is more sensitive for space systems due to the mass impact and the thermal environment]

- The SSRMS
  - linear multidrop power distribution architecture
  - sensitive due to the negative resistance effect of the power converters:



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Power Distribution

- **Cable Sizing, Voltage Drop, Thermal Design Issues** **(cont)**

  - Thermal design of the cables <u>can</u> become very sensitive
    - Possibility of overheating the cables in a 'thermal runaway' effect
    - The effect might only be a higher voltage range than originally expected for the equipment running on power carried by these cables

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Power Distribution

■ Cable Sizing, Voltage Drop, Thermal Design Issues (cont)

- **Thermal Design Issues:**
  - Possibility of destruction of equipment
  - Typical approach used for space systems:
    - – Passive radiator surfaces for heat rejection via radiation
    - – Resistive electrical heating for non-operating units and structure
  - Heat rejection for small system elements typically via conduction through structure, ultimately to radiators
    - – Drawback: Radiators never not stop removing heat
    - – ISS heaters are sized for an average power of roughly 80% of the operating unit power, suitably averaged over a time scale relevant to the unit's thermal inertia (louvres are an alternative)

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Power Budgets/Power Demand

- **Power Budgets**
  - Ongoing assessment:
    - Power demand *vs* Available power
  - Unlike mass (mostly) - power generation/demand changes over time:
    - Continuously throughout operations
    - Between identical units due to component variation
  - Requirements in power subsystems are often expressed as:
    - Ampere-hours (energy)
    - Average power (usually simple)
    - Peak power (never simple)
  - Initial budgets: Usually based on similarities with existing systems
  - As design matures, power demand is updated
  - Worst case, Average, Best case, RSS. Which is correct?

Power Budgets/Power Demand (cont)

- **Power Demand patterns**
  - Power demand is a time-varying value:
    - Know your Averaging window (key to assessing power system)
      - » Heaters are sized based on voltage range (minimum voltage while power consumption is at 'max. average')
      - » Electronic unit power converters are designed for a minimum voltage of a much shorter duration transient
  - Power generation and storage subsystems may have complex characteristics of load power demand
- **'Power Demand Characteristic Curve'**
  - A 'Power Demand Characteristic Curve' can be used for both a system and its corresponding power generation equipment.
  - Sheds light on compatibility and possible overdesign

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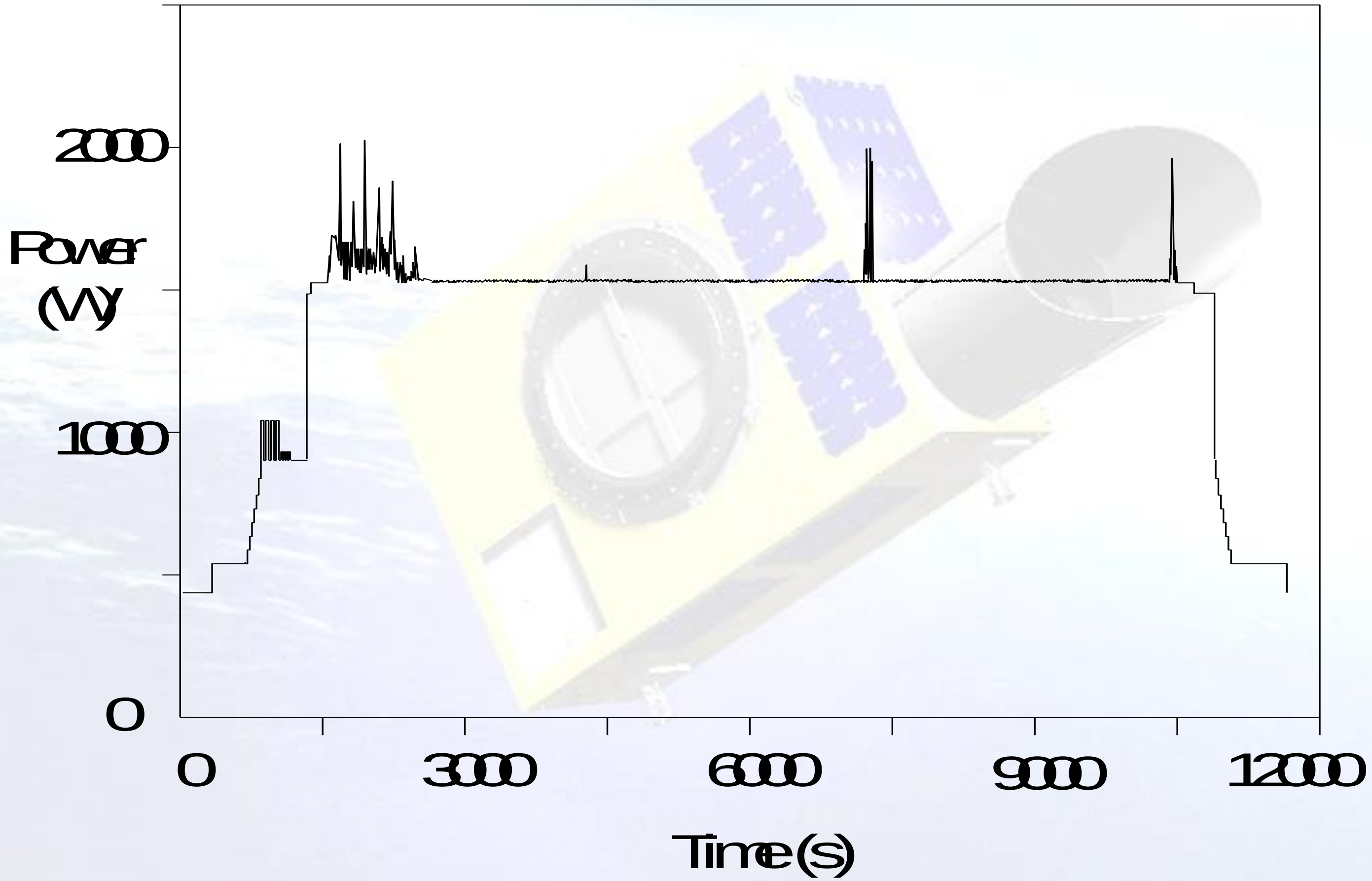
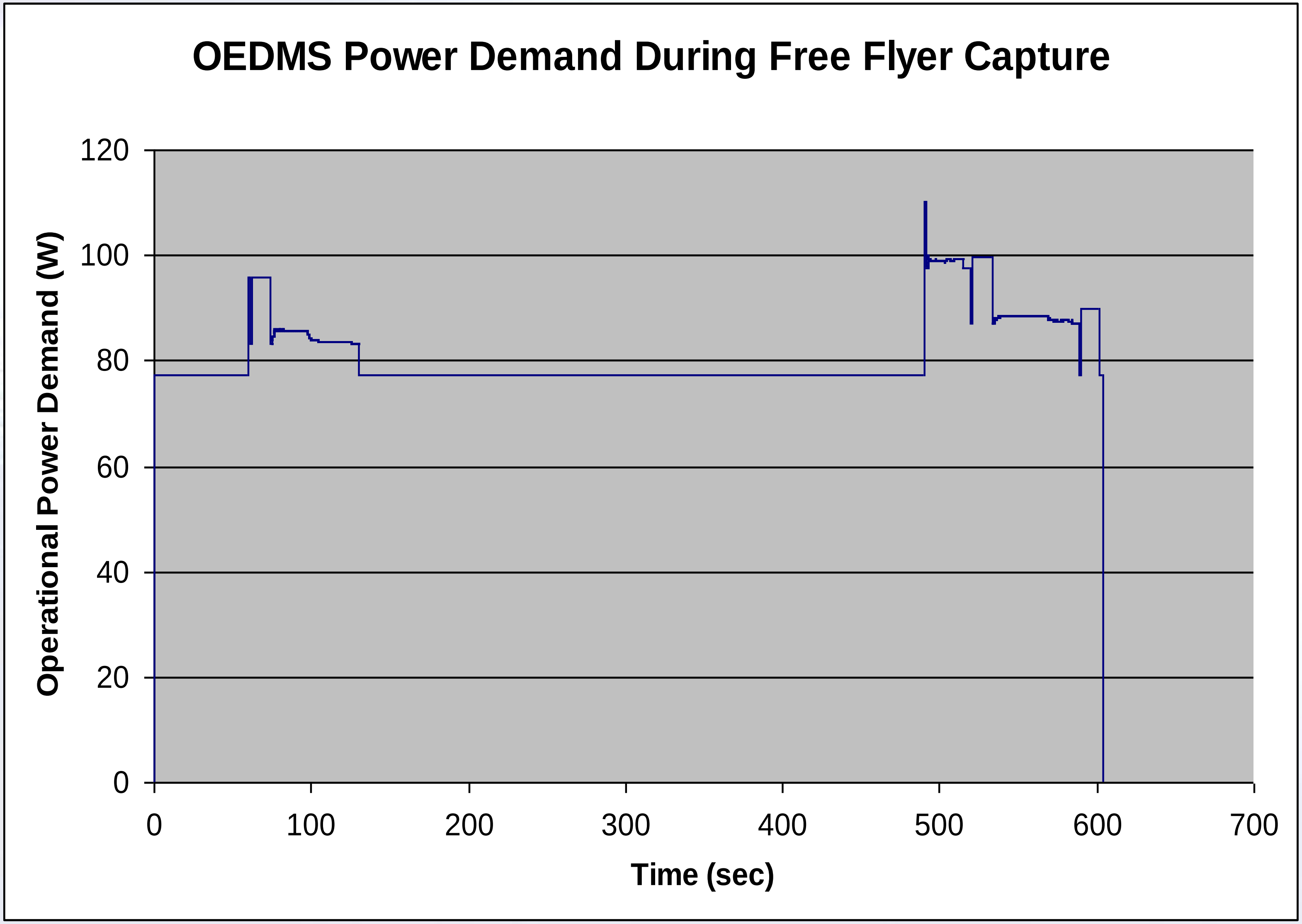
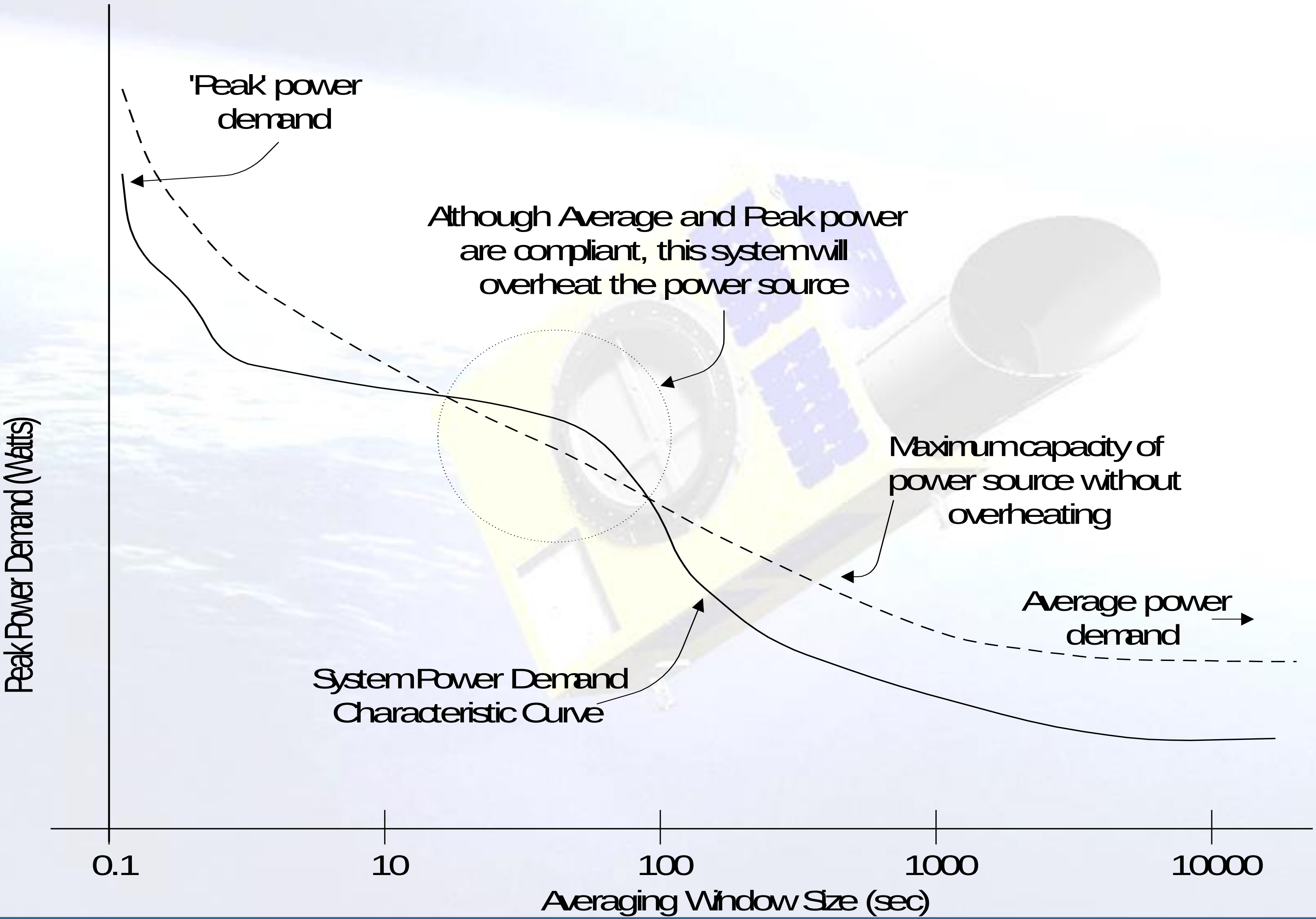
SSRMS (Canadarm2) Power Demand



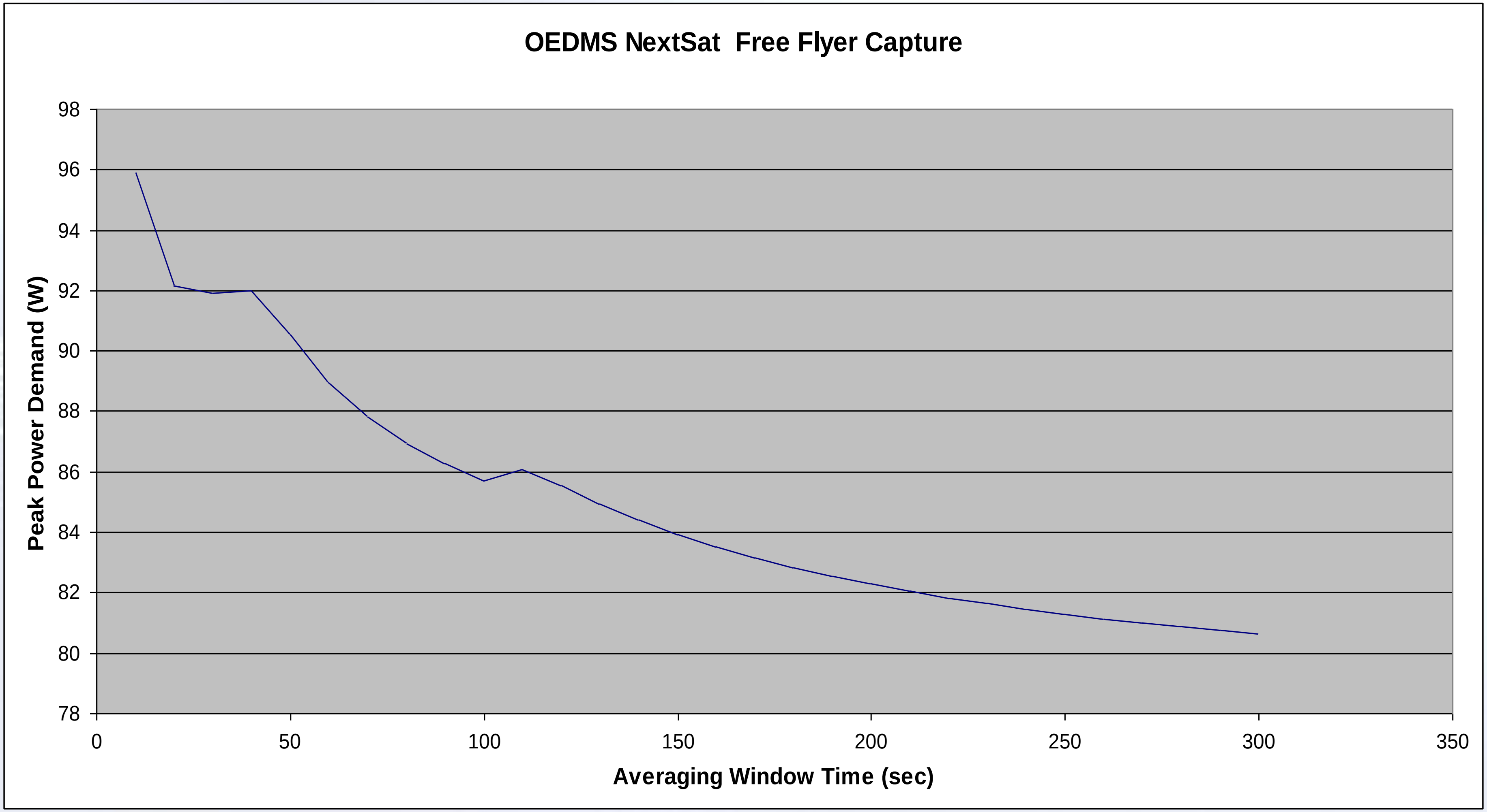
Orbital Express Manipulator Subsystem Power Demand



Power Demand Characteristic Curve



Power Demand Characteristic Curve



Power Budgets/Power Demand (cont)

- **Overcurrent Protection**
  - Cables are derated for current carrying in space
  - Further derating needed when included in a bundle
  - MIL-STD-975 contains current carrying capacity in vacuum

Data Communications and Distribution

Data Communications

- Ground/spacecraft communications require wireless (RF) data link
- Several infrastructures already exist (for non-Geostationary systems):
  - NASA Deep Space Network (DSN)
    - Three ground stations around the world for spacecraft data links
    - Data rates: uplink from 1.0 to 2000 bps, downlink from 8.0 to 6.6M bps (allocation/access time to be negotiated)
  - Air Force Satellite Control Network (AFSCN)
    - Ground stations around the world, line of sight communications (less than 10 min each) while spacecraft is overhead
    - Data rates: uplink from 1 kbps to 2 kbps, downlink from 125 bps to 1.024 Mbps
  - Tracking & Data Relay Satellite (TDRS)
    - 3 uplink channels (10k, 300k, 25M bps) 3 downlink (1.5M, 12M, 300M bps max)
  - Canadian Space Agency Mission Operations Centres (supporting multiple Canadian satellites)

Earth Orbiting Spacecraft Only

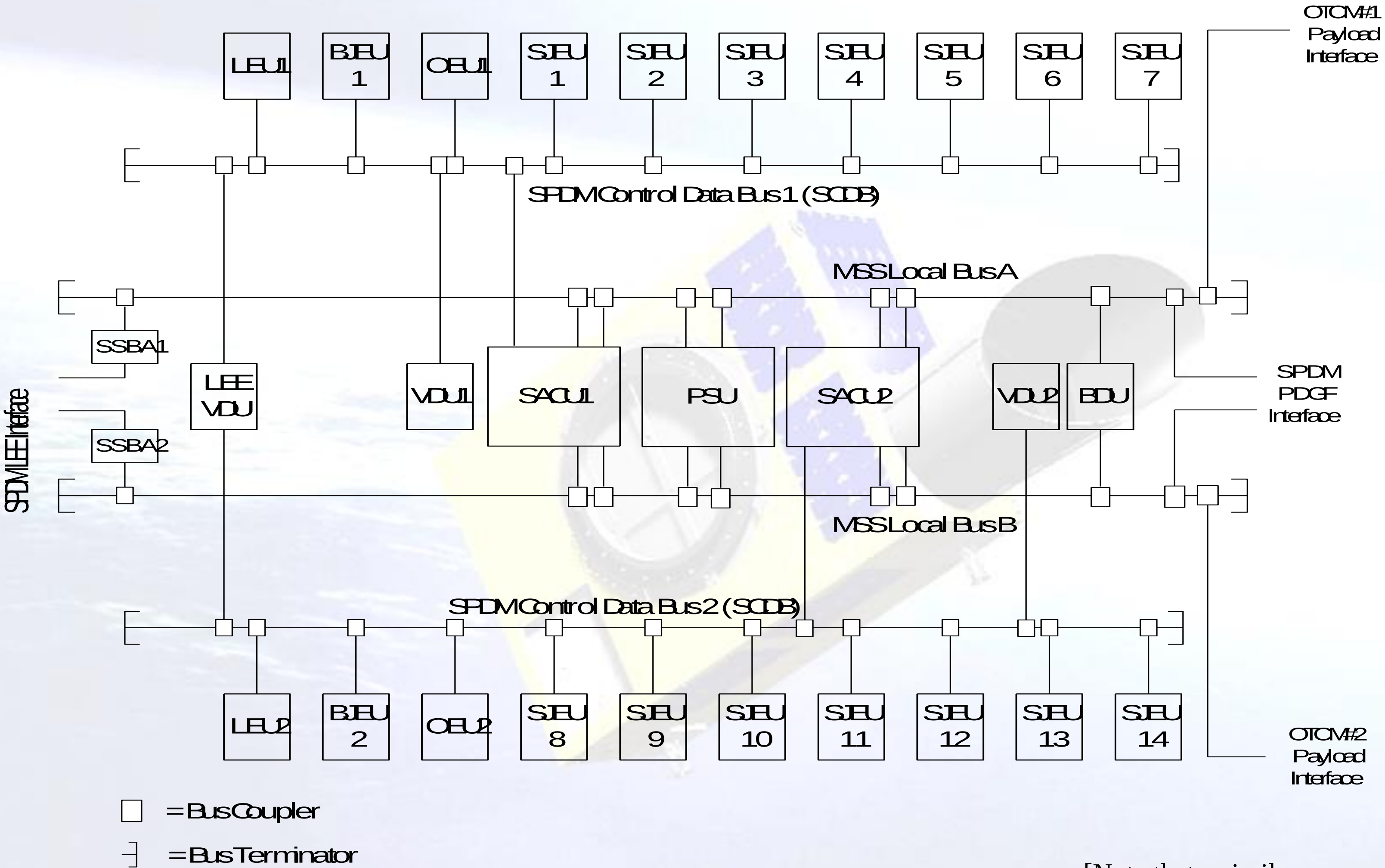
Data Distribution Networks

Data Distribution

- Digital data communication between blocks within the Electrical Functional Block Diagram
- Serial or parallel communications can be used
  - The need for high speed, low cable mass and high reliability generally requires serial data communications
- Serial data communication:
  - Hardwired, point to point (i.e. RS232, RS422, LVDS)
  - Hardwired, multidrop (i.e. RS485, MIL-STD-1553A or B)
  - Fibre-Optics (generally point to point due to light power attenuation and radiation effects in space)
  - Wireless (Infrared, RF)

RS-422 and RS-485 have become common in space. LVDS signaling has also, but has poorer Common mode performance in noisy environments

Data Distribution Networks (cont)

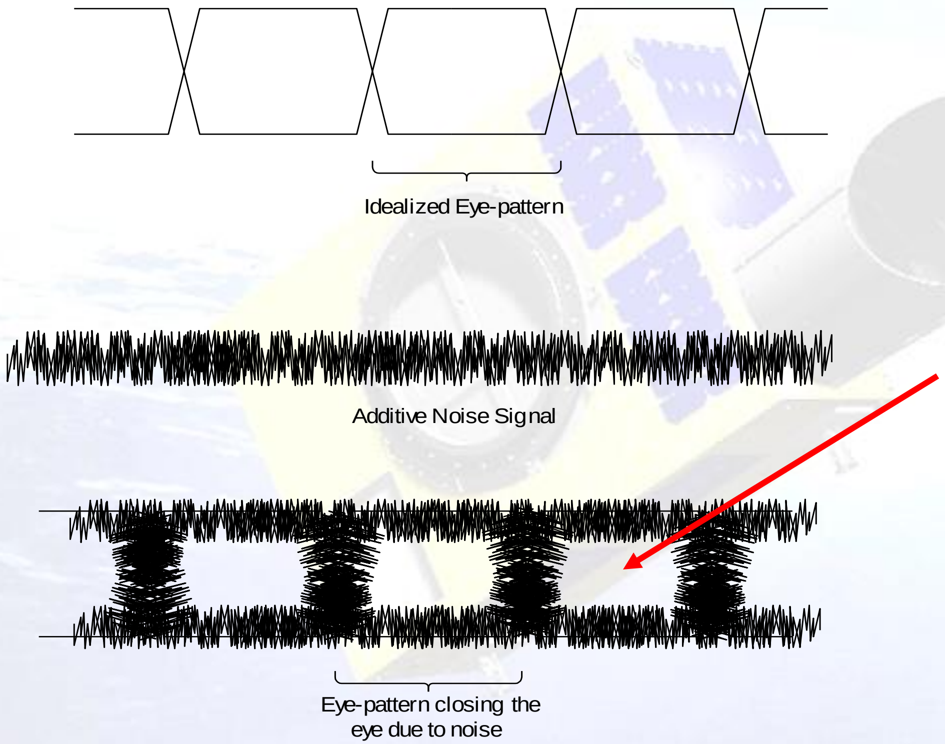


SPDM Data Buses Architecture

[Note that a similar topology could be implemented using RS-485]

Data Distribution Networks (cont)

All serial data transmission has transmission errors (expressed as “Bit Error Rate”, or BER)



When these ideal, noise-free data bits are clocked in to the receiving end circuitry there is never any confusion which are the “1”s and “0”s. The BER = 0

When these data bits are clocked in to the receiving end, some bits will be incorrect
(“1”s become “0”s and vice versa).

Bit errors, caused by any one of several sources of noise, is why we have TCP/IP protocols with error detection and correction, retransmission, et cetera, and occasional data corruption

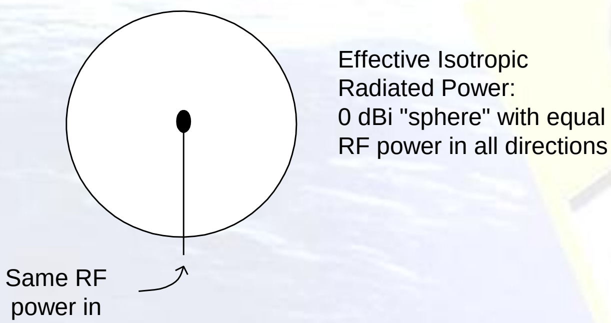
Typical raw BER values: 10e-5 (RF, hardwired), 10e-9 (fiberoptic)

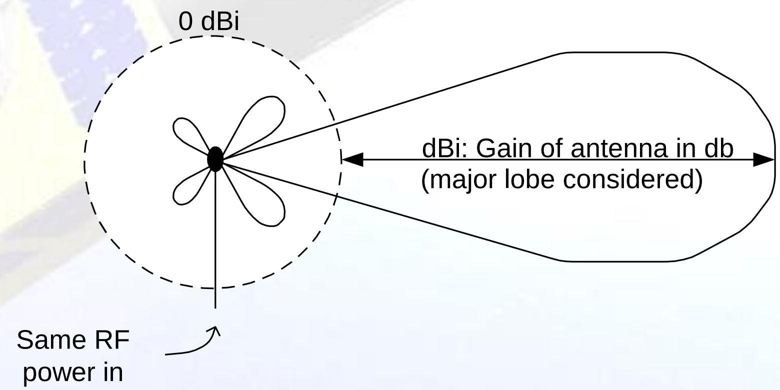
Data Distribution Networks (cont)

- Wireless Serial Communications: protocols such as CSMA/CD (i.e. ethernet)
  - This needs to be considered for RF modem communication, particularly if more than two subsystems communicate on a single channel
- Fibre-Optics in Space
  - Offers great potential for high data rates, much lower cable weight
  - Has been used in at least one satellite and ISS Video Distribution
  - Gamma radiation causes absorption centres, attenuating the signal
  - Solution: transmit much more light power to overcome the losses and to somewhat reverse the effect with the resulting local heating

Antennae

- Designed conductive structure to efficiently couple RF signals into radiated RF power, or vice versa (reciprocity)
- Directionality is a key attribute and influences sensitivity and signal strength, but is traded against need for highly-precise pointing accuracy
- Higher frequencies permit smaller physical size for the same directionality





<u>Omnidirectional (“isotropic”):</u>
- Theoretical idealization only (none are perfect)
- Does not matter which way it is pointed
- Wastes most of the power (nothing receives it)

<u>Directional (usually employs a dish or array):</u>
- Must be pointed at receiver (or vice versa)
- Wastes less power than omni
- Physical size inversely proportional to frequency

Video

(now usually part of the data distribution)

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Video Distribution Networks

- Video
  - Treated as a separate architecture when it is generated in analog format
  - Digital video brings it into the “Data” category
- Baseband Video Distribution
  - NTSC video, the signal which typically comes directly from a camera
  - Maximum bandwidth: 4 to 6 MHz depending on quality
  - Frequency response/phase linearity needed for good quality picture is challenging
  - Places a very tight requirement on distribution design due to inevitable need to select from more than one channel (the more views available to system operators the better)
- Modulated Analog Video Distribution
  - In the Space Station: modulated onto fibre optics using PFM (pulse frequency modulation, 'pseudo-digital’). Switchable onto one of three fibre optic channels

Discrete Circuits

Discrete Circuits

- **Discrete Circuits**
  - Literally, a circuit where a signal driver is separated from the receiver as opposed to being integrated together in some fashion
  - Usually a category referring to any wiring carrying anything other than power, data, or video
  - Can require a lot of individual analyses to demonstrate a workable design with suitable margins for worst case scenarios

Failure Tolerance and Redundancy

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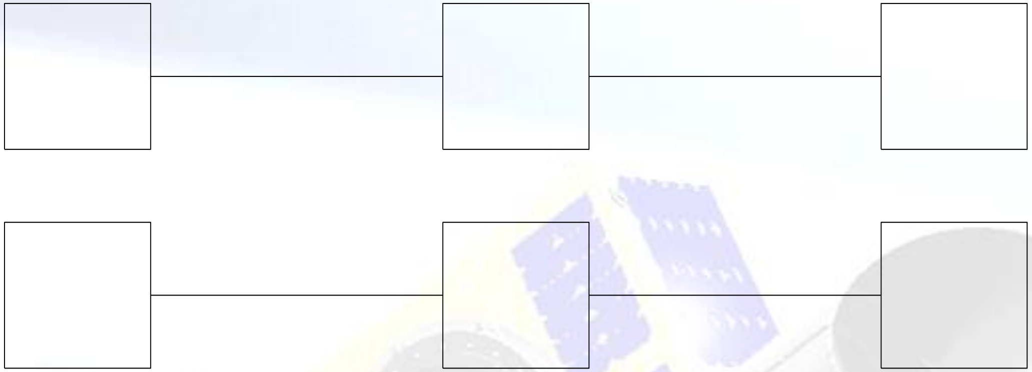
Failure Tolerance and Redundancy

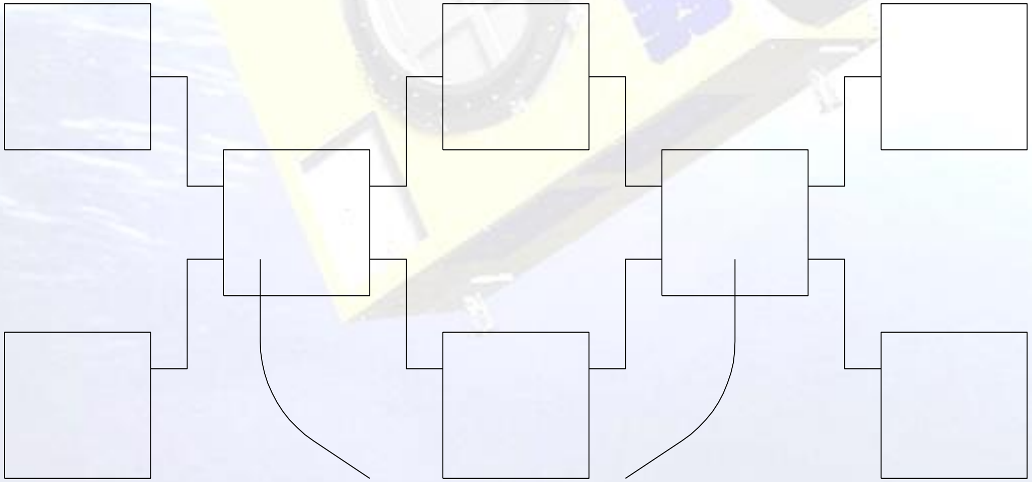
- ***Failure tolerance mostly impacts the electrical architecture***
- Good design won't eliminate failures - all components have finite life
- Failure Modes and Effects Analyses (FMEAs):
  - Detailed investigations
  - Done at component level for all failures effects on system
- Failure tolerance achieved only via ‘redundancy’.
- Redundancy for undetectable failures only increases ‘availability’
- Cross strapping allows more recovery options at the cost of lower MTTF

Failure Tolerance and Redundancy (cont)

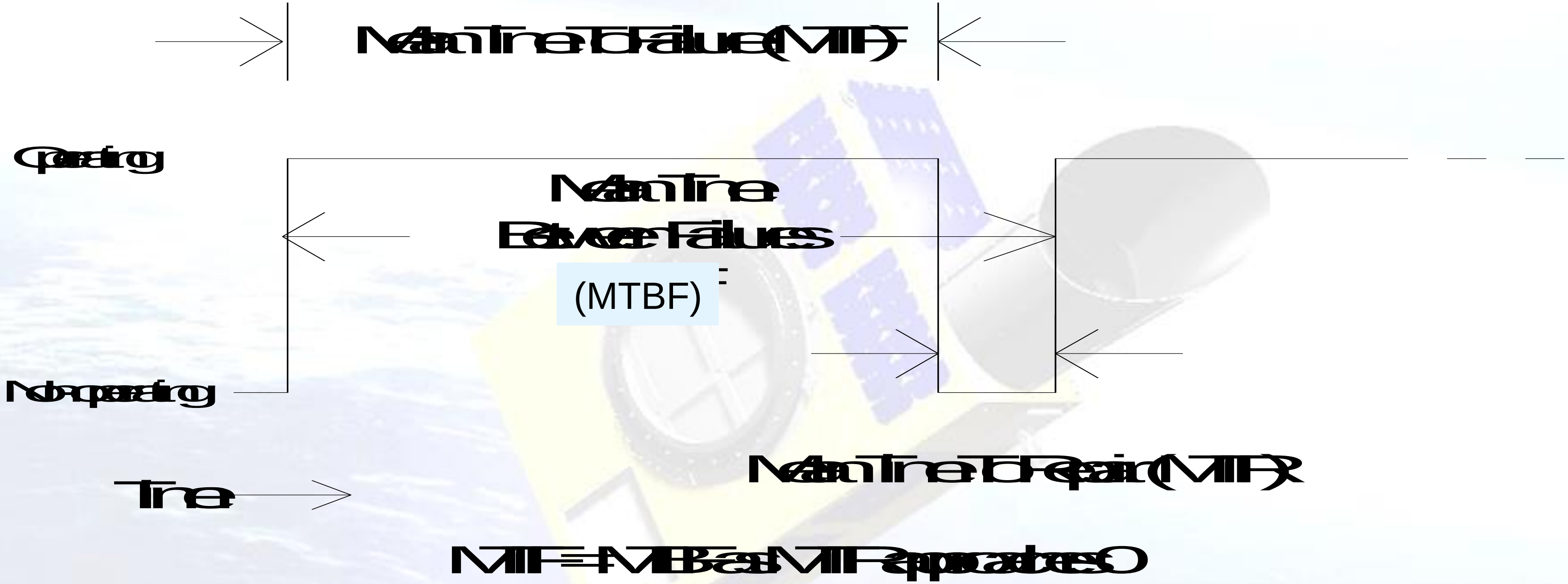
No Cross Strapping (like SSRMS)



Cross Strapping Function Added



Failure Tolerance and Redundancy (cont)



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Environmental Considerations

[…. but first, let's discuss how to protect electronics from damage due to electrostatic discharge ...]

Electrostatic Discharge

All electronics can be damaged by Electrostatic Discharge (ESD):

- High voltages (up to 2000 volts) are on all of our bodies, even in Summer's humid weather (far worse in dry winter weather)

- This is true **right now**, you likely cannot feel it (mostly felt when touching a metal object and causing a spark)

- These voltages are high enough to stress or damage electronic parts, and even circuits, unless sealed within a dissipative or conductive box/bag

- You can even cause damage without touching the hardware, from up to a metre away!

- To can only know when you did **not** damage/stress a part, by knowing you took precautions at all times. If you do not, you can never know the parts will work for their expected full life.

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Electrostatic Discharge (cont)

Whenever near or touching electronics, observe these rules:

- Always wear a grounded ESD wrist strap, and never let others walk up to you without themselves being grounded/wearing one.
- Eliminate non-dissipative plastic items from bench area (e.g. no styrofoam cups!!!!)
- Never leave electronic parts or assemblies exposed. Always enclose them in “dissipative” sealed enclosures/bags when you are not present/working on them.

Environmental Considerations

Key environmental design drivers for most space-deployed systems:

Temperature Extremes

- Thermal control required for most elements
- Heat rejection for cooling of active units:
  - conduction/radiation
  - this in turn causes heat loss while non-operational
- Warm up period if temperatures ever fall below operational temperature ranges
- ***For Mars lander subsystems***
  - Thermal environment is cold
  - [For hot environments, some SiC work done in recent years (i.e. NASA GRC)]
    - » Circuits operating continuously at 500C. Parametric drifting is significant. Interconnection corrosion is a major challenge, as is sealing of circuitry to prevent it

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Environmental Considerations (cont)

Key environmental design drivers for most space-deployed systems (cont):

Radiation

- Components shielded somewhat by metal housing
- Total dose can still be high (i.e. Van Allen belt, gamma)
- All components to be tested for Single Event Effects (SEL, SEU) and total dose depending on environment
- MOS devices most susceptible to gamma total dose, which causes threshold shifts: Digital ICs and power control devices such as MOSFETs (derating is needed)
- Proton radiation can cause ‘displacement damage’, affecting solar arrays, bipolar devices, camera CCDs

Environmental Considerations (cont)

Key environmental design drivers for most space-deployed systems (cont):

Vacuum

- Affects thermal control, as mentioned
- Not all materials used on earth can be used in space (i.e. Nylon outgasses)
- Vent holes
  - Prevent damage during rapid decompression (if applicable, i.e. airlocks on ISS)
- Lack of ambient temperature/convection creates gradients
  - Thermal distortions that can affect critical tolerances, such as camera lens calibration or even critical mechanical alignments
- Lubrication is tricky. Lack of oxidation can lead to welding
- ***No ground reference/no conduction to prevent static charge buildup between isolated system elements!!!***

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Autonomy,
and Risk

Autonomy

- Autonomous *vs* human judgment: a very important and complex trade-off
- Generally desirable to have humans make decisions *where the bandwidth and time/latency permit*

Where time critical the system must react as determined by rules or other event-driven responses (i.e. runaway joints, overcurrent conditions, or where communication is slow or delayed)

- Where autonomy makes sense:
  - Some Lunar Missions
  - Mars missions
  - Venus missions
  - Low-bandwidth or high latency data links to Earth-orbit systems

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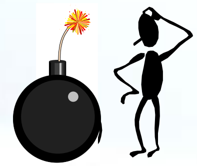
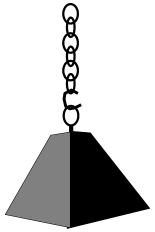
Risk Mitigation

- Risks are generally either
  - Technical ("we can't meet req'ts")
  - Cost/schedule ("it'll overrun").
  - The two are clearly linked.
- Risk Mitigation Plans are usually required ASAP once risks are identified
- Technical Risks:
  - Use of "proven" pre-existing flight-heritage subsystems or components is a common method of mitigating technical risks, as is 're-use'
  - Other approaches include early prototyping/testing, KISS rule
- Schedule Risks
  - Supply chain and subcontractor capabilities
  - Poor estimation (should be covered by 'management reserve')

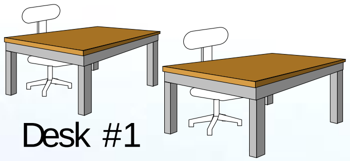
Risk Management



- How many of you:
  - Bring more than one pen/pencil to an exam?
  - Backup important computer files to CD/DVD?
  - Leave earlier for 9AM exams than for a 9AM lectures?
  - Drive a car with one spare tire? Two spares?
  - *Would <u>not</u> choose desk #2*
- Then you have considered <u>risk</u>



- Risk can impact technical, schedule, or both



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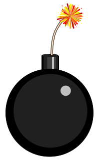
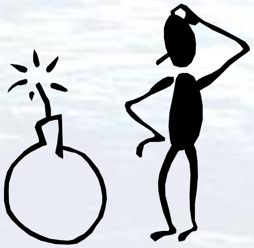
Risks Management Plan



- Businesses commit to provide products/services compliant with technical/cost/schedule requirements
- All businesses face *risk*: Any potential negative event over which there is no full control: i.e.



  - Supplier cannot provide parts within necessary time, or they do not meet advertised performance
  - Obsolescence of critical parts designated for re-use
  - Failure / breakage of system during testing
  - US dollar exchange rate changes during program
  - Market demand changes
  - Labour dispute or strike. Loss of key personnel (or contractors)
- Risks are generally categorized as either 'Technical' or 'Cost/Schedule'

Risk Management Plan (cont)

- Calculating the ***Expected Value*** of cost Risks

  - Risks in executing a job need to be considered in costing and in the budgeting process
    - Project budgets need risk money allocated as a separate cost account
    - Total Risk budget = $\sum_{i} (\text{cost of risk})_i \times (\text{probability of risk})_i$

- Monte Carlo techniques can determine ***Expected Duration*** of schedules to show known risks

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