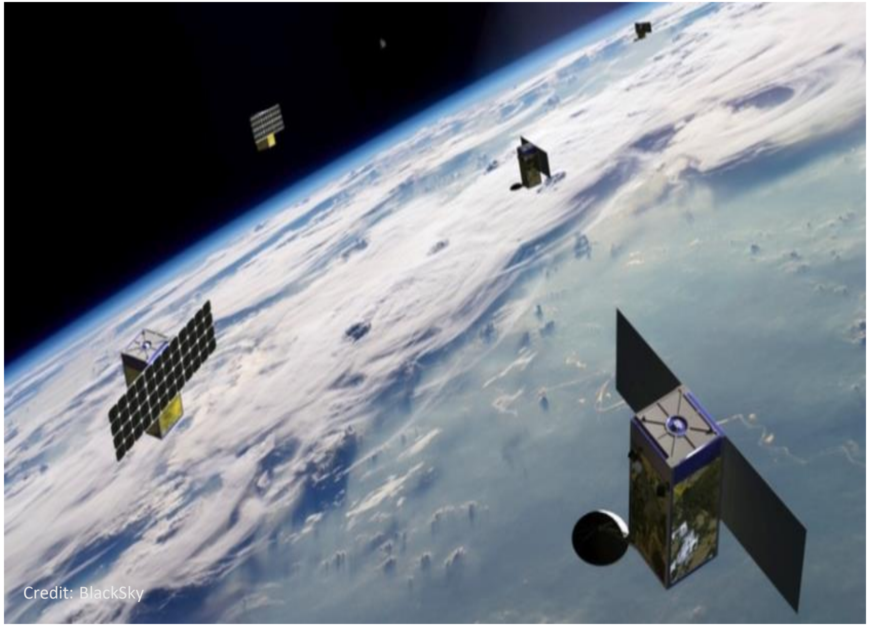
# Small Sat Constellation Assurance Considerations

*Dr. Douglas J. Sheldon*
Assurance Technology Program Office (ATPO) Manager
Office of Safety and Mission Success
Jet Propulsion Laboratory, California Institute of Technology





# Disclaimers

- Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.
- The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

# Constellation Assurance - Overview

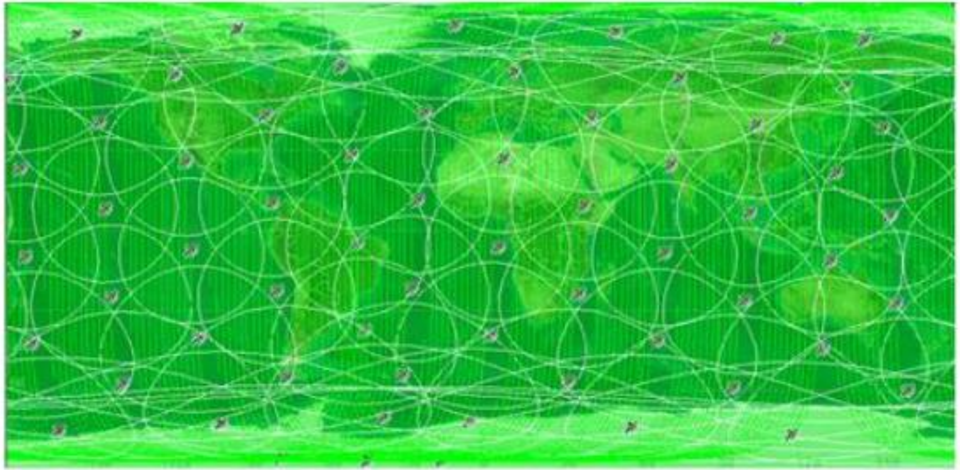
- Why Small Sat Constellations?
- Mathematical Preliminaries
- Market Information
- Small Sat Constellations
  - Constellation Comparisons and Case Study
- Vendors, Suppliers and Manufacturing 4.0
  - Quality Assurance vs. Information Assurance
  - Vendors and Suppliers are more critical than internal processes
- Assurance Concerns
  - Assurance role & deliverables scales super linearly with numbers
  - Space Debris
- Conclusions/Wrap-up

# Why Small Sat Constellations?

# Constellation Benefits

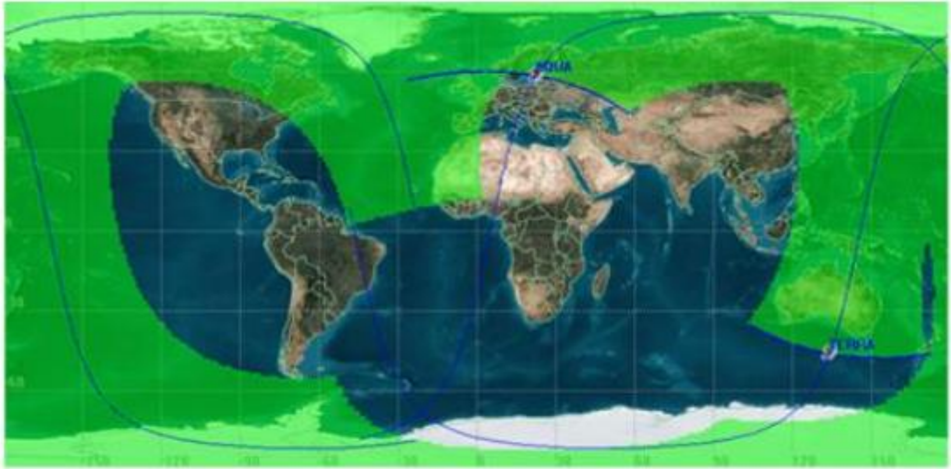
- Drive down costs by mass production
- Increased coverage of given area
- Cheap, simple instruments can be ‘stitched together’ to perform like a large, expensive instrument
- Continuous services and/or measurements can be obtained
- Different generations of design can be intermixed to allow for continuous improvements
- Robustness of architecture

# GEOScan



GEOScan

Dyrud et. al., Small Sat Conference, 2013

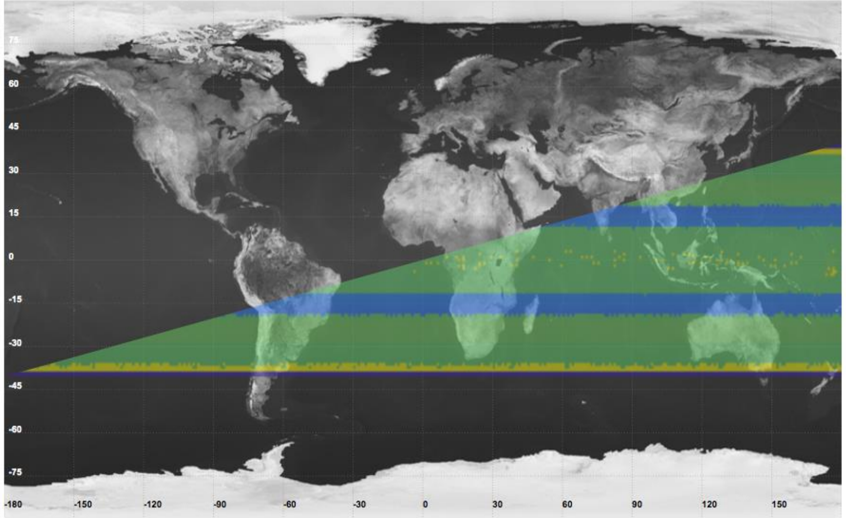


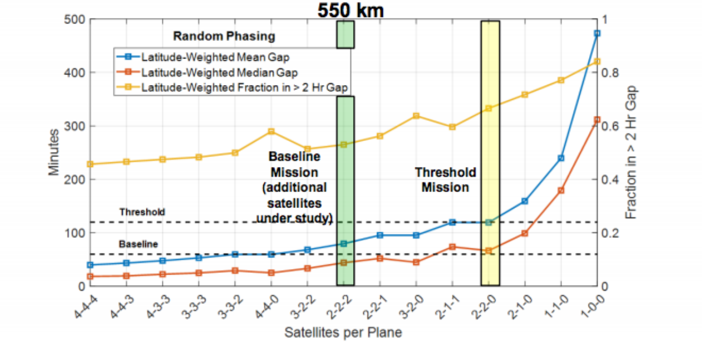
CERES on Terra and Aqua

- 6 instrument suite – 5kg & $20x20x14cm^3$
- Spatial coverage in 1 hour
- Constellation of <60 takes 3,600 samples
  - Noise reduction factor of 60/hour

# TROPICS – Time Resolved Observation of Precipitation and Storm Intensity with a Constellation of SmallSats

## TROPICS Revisit
## (6 sats, 3 planes, 30° inc., 550 km alt.)




| | | Average (min) | Median (min) | Frequency of gaps <2 hr |
|---|---|---|---|---|
| | 8 satellites | 60 | 30 | 55% |
| Current Baseline | 6 satellites | 75 | 40 | 45% |
| | 4 satellites | 120 | 70 | 25% |

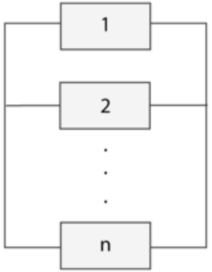
**Trade study underway to determine the optimal number of satellites (science, reliability, cost)**

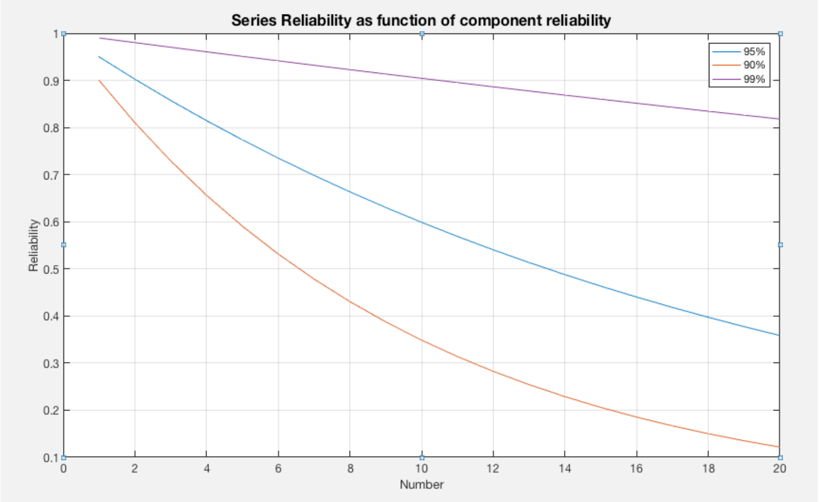
Blackwell, et. al, Small Sat Conference 2017

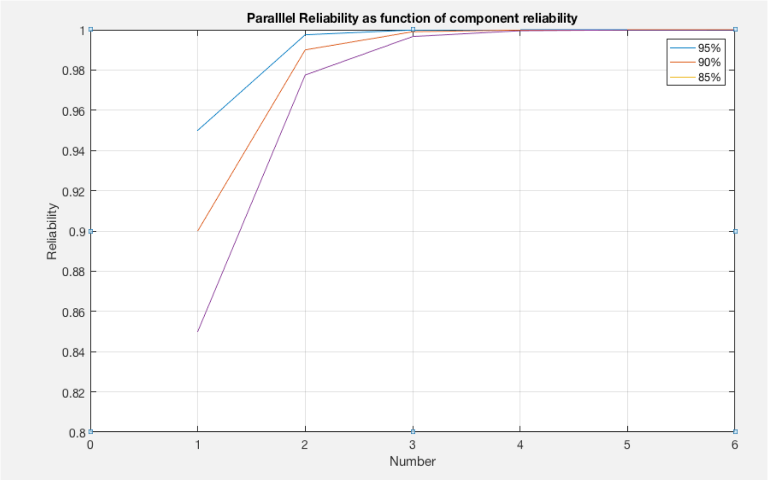
- 3U CubeSats with 60, 183, and 206 GHz radiometers and GPS radio occultation
- Microwave sensor amenable to miniaturization (10 cm aperture) • Broad footprints (~50 km)

# Mathematical Preliminaries

# Mathematical Preliminaries - 1/4

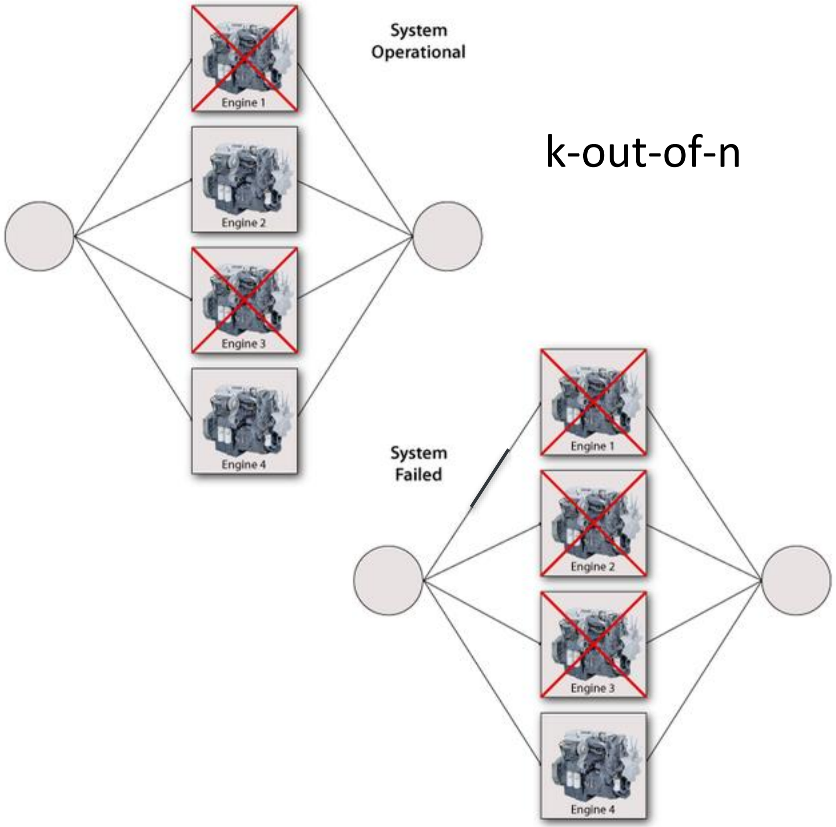




- Series Reliability systems have very low reliability, even with high reliability components

- Parallel Reliability systems have very high reliability for random failures, even with low reliability components

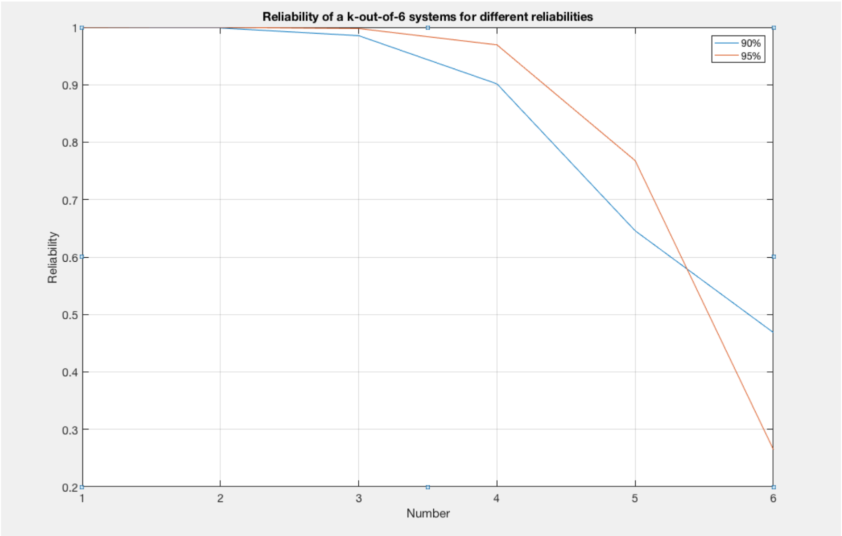
# Mathematical Preliminaries - 2/4




k-out-of-n

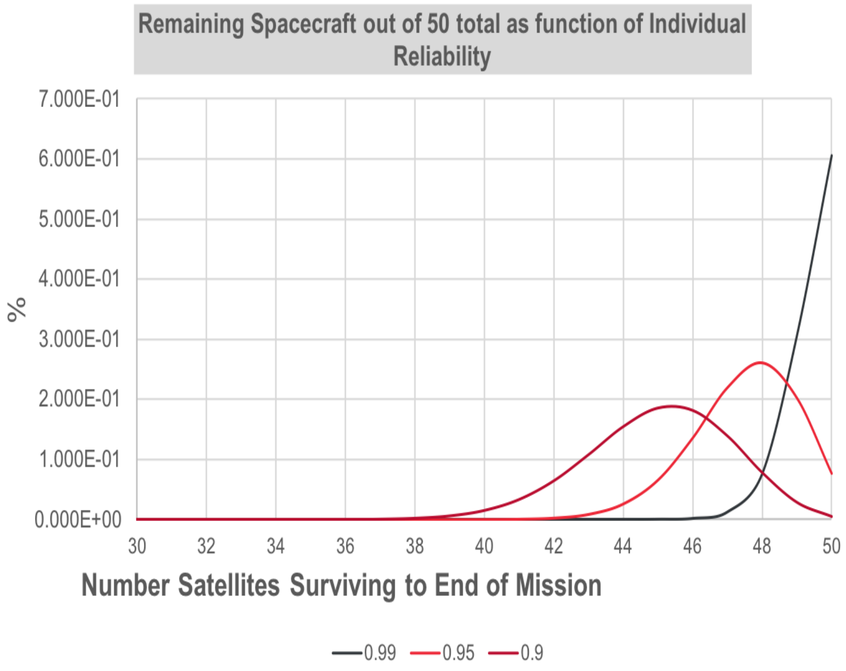
$$R_s(k, n, R) = \sum_{r=k}^{n} \binom{n}{r} R^r (1 - R)^{n-r}$$

- All the components have the same failure distribution and whenever a failure occurs, the remaining components are not affected
- Closer to reality



# Mathematical Preliminaries - 3/4

## Reliability of Individual Spacecraft drives Architecture

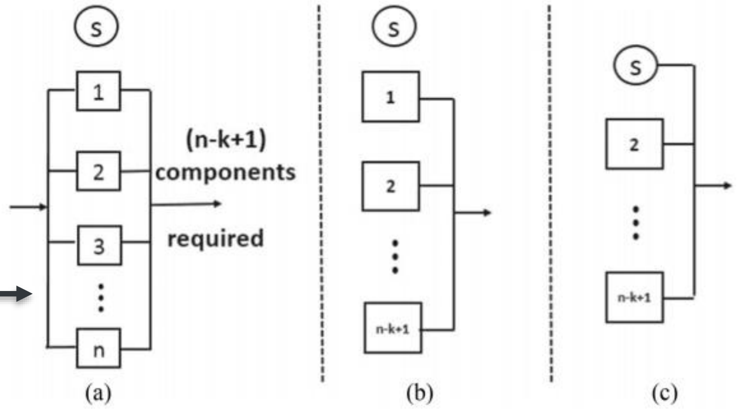


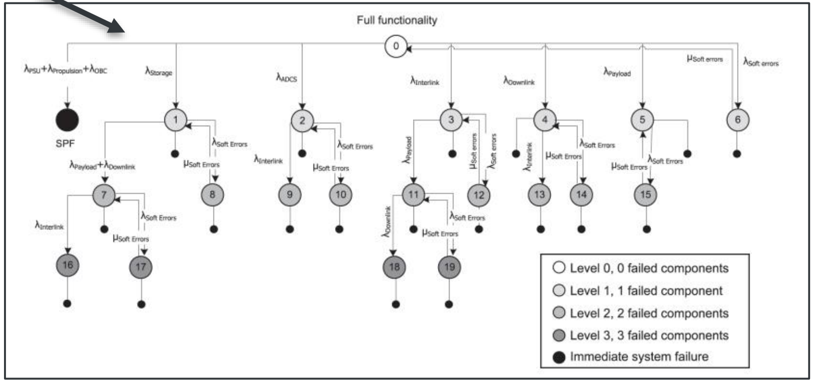

- Even with 99% reliable individual spacecraft, the chance of the entire fleet working till the end of mission life is very small
- With less than 99% reliability, there is no chance for the entire original constellation to be operational at the end of mission
- Flexible and adaptable fault tolerant architectures must be designed in from the earliest stages of the process
- ***Repair, replacement and replenishment must be considered as prime mission requirements***

# Mathematical Preliminaries - 4/4

- *k-out-of-N*:G
  - requires the survival of at least *k* components for the survival of the entire system
- *k-out-of-N*:F
  - system that fails if and only if at least *k* components have failed
  - Ability to include cold spares
- *Markov Chains*
  - Probability of transitions between operation and failure
- ***Mathematical modeling is a fundamental and key tool to understanding risk in constellation systems***

$$\frac{d}{dt}\vec{x} = \frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{n,1} & \cdots & a_{n,n} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = A \cdot \vec{x}$$



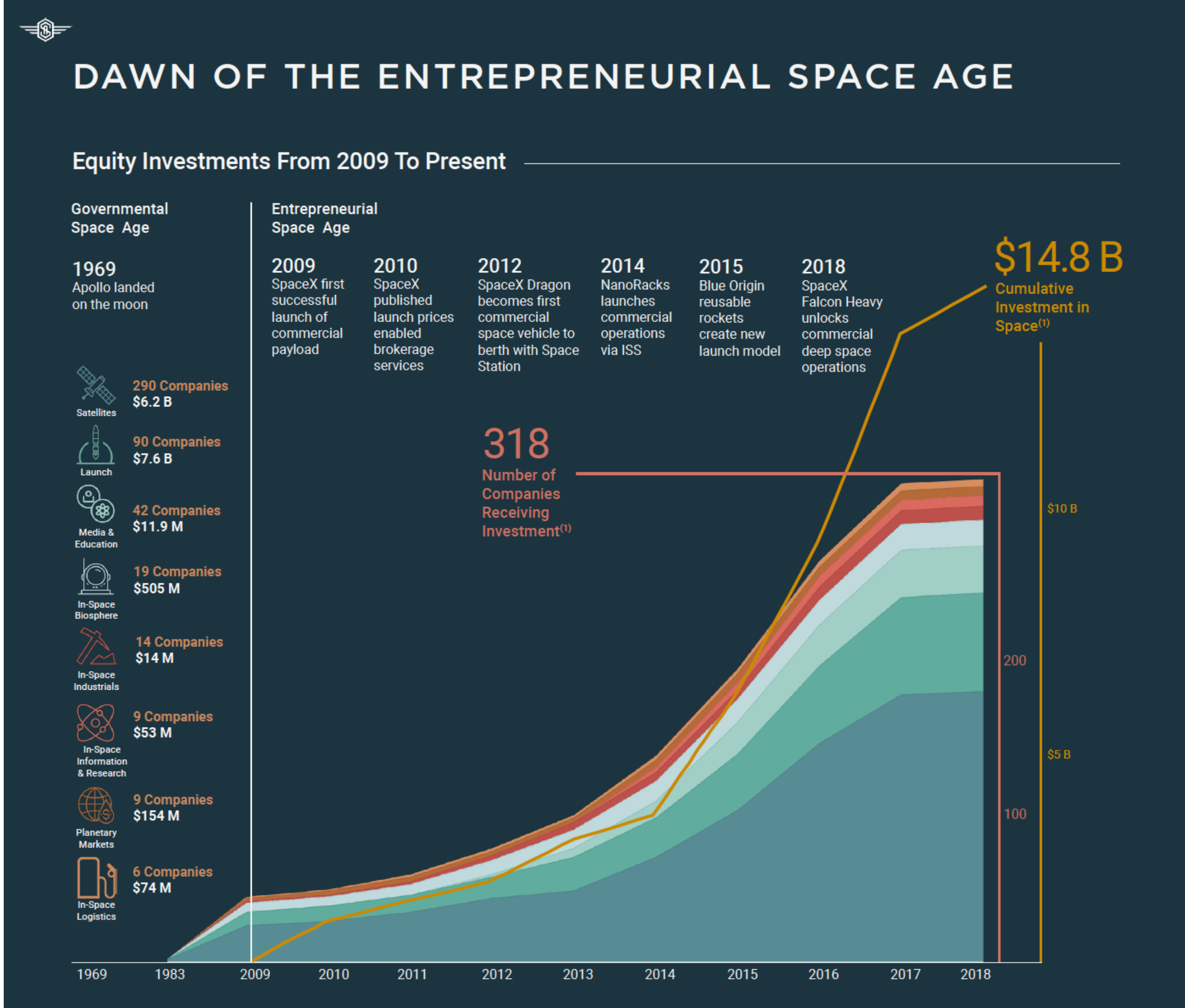




S. Engelen, IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS VOL. 50, NO. 2 APRIL 2014

# Small Sat Market Information

# The Entrepreneurial Space Age

- 2014 was the ”inflection point” year
- Rate of funding for commercial space increased 2.5X (250%) 2014-2018 compared to previous four years



# Highlights of SmallSat in 2017

## 2017 Highlights

- The global launch vehicle market demonstrated its ability to meet the growing demands of the nano/microsatellite segment **without the presence of dedicated small satellite launch vehicles**
- **PSLV C37 launched a record 104 satellites** in a single launch in February, the vast majority of which were nano/microsatellites
- 2017 was also a record setting year for Planet, who **acquired Terra Bella**, **launched 146 satellites**, and finally **achieved their goal of daily revisit coverage**
- The **QB50 academic constellation officially launched**, marking a major milestone for international cooperation in the nano/ microsatellite arena; in all **36 QB50 satellites** were deployed

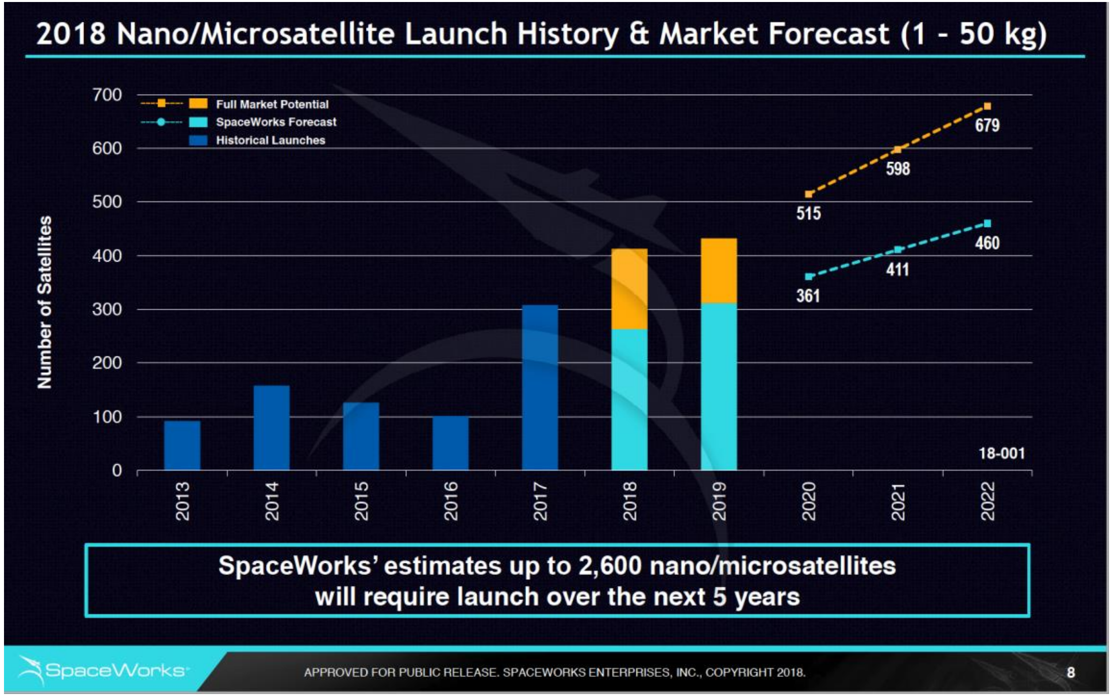
PSLV-C37 launches a record-breaking 104 satellites

QB50 satellites after deployment from the ISS

Image Credits: ISRO, NASA

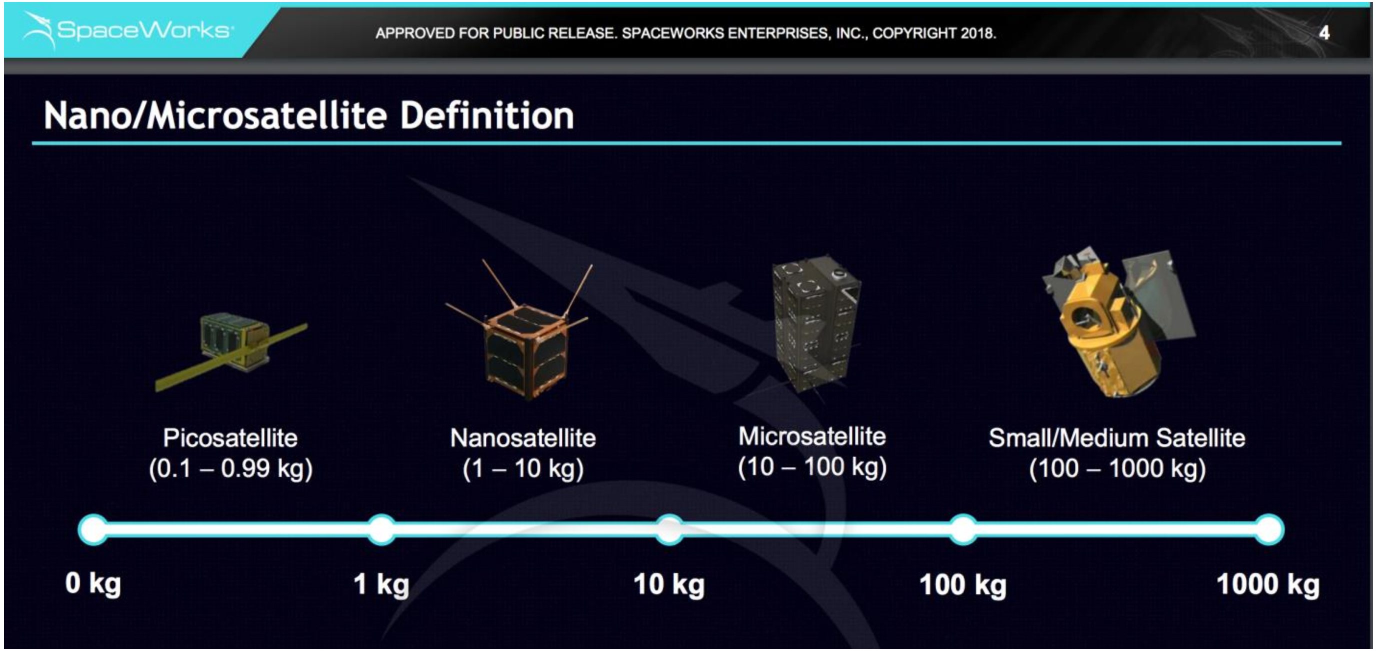
SpaceWorks

# Thousands of SmallSats expected to be launched in 5 years




- >30% growth/year
- The supplier base will have to grow in capability and capacity to meet this demand
- ***Supplier Quality will have a significant impact on this forecast being realized***

# Basic Definitions of SmallSats

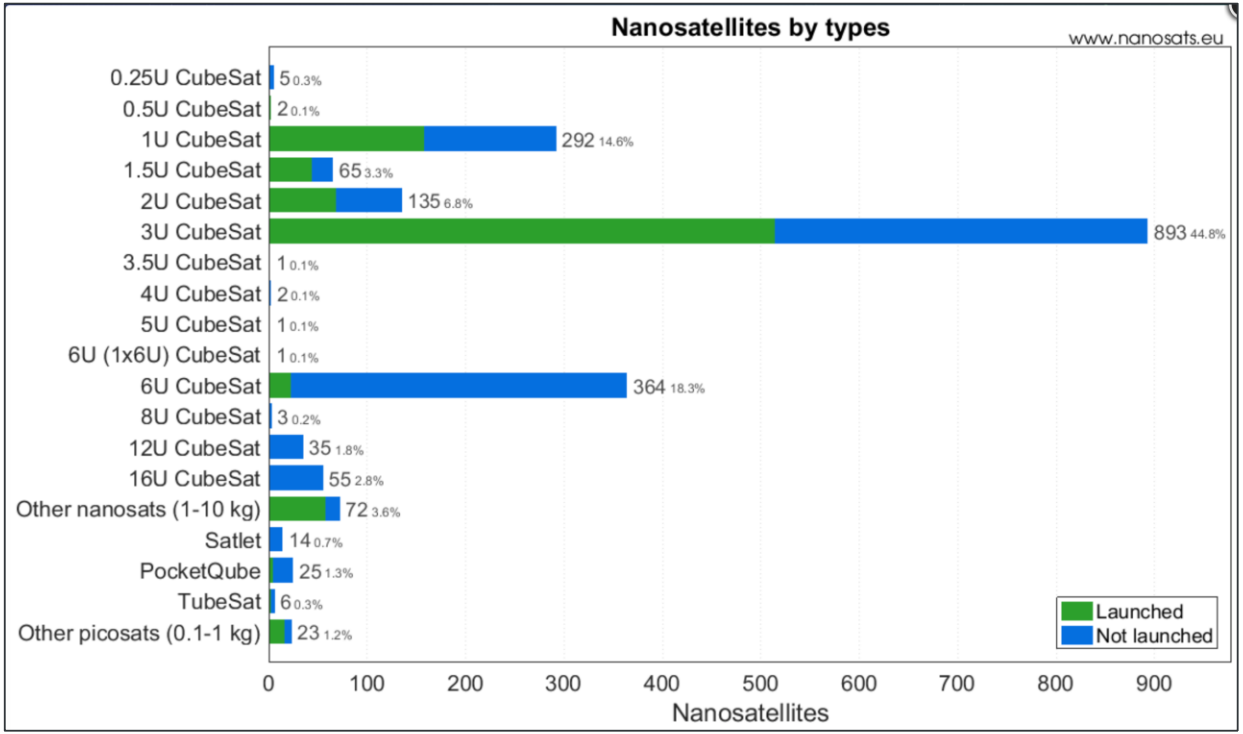



- ***Mass difference have significant impact on systems architectures, parts and materials selection***

# SmallSat Operators/Supplier Base


- The Supplier/Operator base has naturally divided up by mass of satellite
- ***Smallsats DO NOT easily scale across size and mass***
- Solutions and sub-systems that work for one mass size often do not work for the next larger (smaller) size mission
- JPL experience has re-enforced this lesson

# Size comparisons of Small Sats

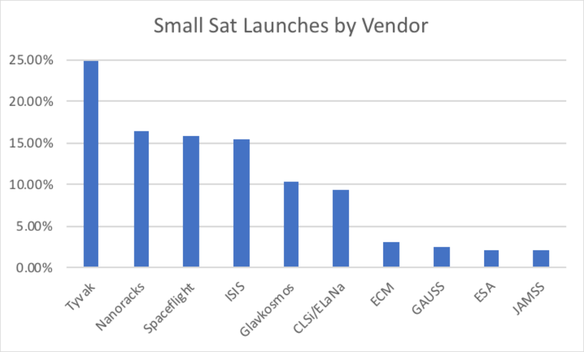



- ***Overall reliability is improved by adopting the most prevalent configuration (3U or 6U)***
- More vendors will be providing more mature designs and products for these two sizes

# Small Sat Launch Providers

## 4 companies have 70% of the market

| Provider | CubeSats launched | First launch | Cost | Additional information |
|---|---|---|---|---|
| Terran Orbital / Tyvak | 121+ (40+ planned) | 2003 | | CubeSat integrator for most US Gov. missions. Launches include organized by Cal Poly. |
| ISIS (Innovative Solutions In Space) | 75+ | 2009 | $210,000 - 270,000 for 3U LEO | |
| NASA CSLI and ELaNa | 46+ (120 selected) | 2011 | Free | For US educational, NASA and non-profit CubeSats. Different rockets used. |
| ESA Fly your Satellite! | 10 | 2012 | Free | European educational CubeSats. Used to be with Vega. ISS orbit from now on. |
| JAMSS / JAXA | 10+ | 2012 | | |
| Nanoracks | 80+ | 2012 | $85,000 for 1U | Only deployed from ISS. Now up to 1x6U and soon up to 12U. |
| Spaceflight | 77+ | 2013 | $295,000 for 3U LEO<br>$545,000 for 6U LEO<br>$995,000 for 12U LEO<br>GTO and Lunar also listed | |
| G.A.U.S.S. | 12+ | 2013 | | Only available launches for PocketQubes from UniSat microsatellites. |
| ECM Space | 15+ | 2017 | ? | Have their own 12U and 16U deployers. |
| Glavkosmos | 50+ | 2017 | ? | |
| TriSept | 0 | 2018 | ? | One of the NASA ELaNa launch integrators. |
| ULA (United Launch Alliance) | 0 | 2018 | Free | 6 units planned for now. Only for U.S. colleges and universities. |
| Rocket Lab | 0 (178 booked on website) | 2018 | $70,000 - 80,000 for 1U LEO<br>$200,000 - 250,000 for 3U LEO | |
| Virgin Orbit | 0 | 2018 | Assuming $10 million and 40 CubeSats gives $250,000 per 3U. | Sky and Space has contract for 4 launches. |
| KiboCUBE (UNOOSA, JAXA) | 0 | 2018 | Free | Provide ISS launches for educational or research institutions from developing countries. |
| Vector Space | 0 | 2018 | | Integrated CubeSat dispensers. ICEYE has booked 21 launches from them. |
| bSpace | 0 | 2019 | $80,000 for 1U<br>$220,000 for 3U<br>$450,000 for 6U<br>$945,000 for 12U | Up to 27U with a 200U capacity on each launch from ISS. Captured in 4k 360 degree virtual reality. |
| PT Scientists | 0 | 2019 | $0.9M per kg to Lunar orbit | |
| Goonhilly / SSTL | 0 | 2019 | Lunar orbit | |
| Astrobotic | 0 | 2019 | $1.2M per kg to Lunar orbit or surface | |
| Precious Payload | 0 | ? | | Global launch reservation system for small satellites. |




- ~$250K/3U to LEO
- ~$1M/kg to Lunar Orbit

# Merger and Acquisitions in the Small Sat Market

- With any dynamic and evolving market, the vendor base is expected to change quickly as well.

- ***This has significant impact on NASA's ability to manage risk***:
  - Product portfolios are constantly changing
  - Organization emphasis can shift
  - Development efforts can be left incomplete

- Examples:
  - December 2017 - ÅAC Microtec acquired Clyde Space
  - November 2017 - General Atomics acquired the U.S. assets of Surrey Satellite Technology
  - November 2016 - end-to-end manufacturer GomSpace acquire NanoSpace, a propulsion subsystem provider

# Small Sat Constellations

# Commercial SmallSat Constellations Currently – nanosats.edu

| Organization | Launched / Planned | First Launch | Form factor | Field | Funding | Technical and comments |
|---|---|---|---|---|---|---|
| Planet | 322 / 150+ | 2013 | 3U | Earth observation | $183 million | 29 MP sensor taking images with 3.7 m ground resolution and swath of 24.6 km × 16.4 km from 475 km altitude. |
| Spire | 71 / 100+ | 2013 | 3U | Weather / AIS / ADS-B | $149.5 million | Measure change in GPS signal after passing atmosphere to calculate precise profiles for temperature, pressure, humidity. |
| GeoOptics | 4 / 6 | 2017 | 6U | Weather | $5.15 million | Satellites outsourced from Tyvak. |
| Astrodigital | 4 / 10+20 | 2014 | 6U / 16U | Earth observation | $16.7+ million | 6U has 22 m resolution in RGB and NIR. 16U has 2.5 m resolution in RGB, red edge, and NIR using one 70 MP sensor. |
| Sky and Space Global | 3 / 200 | 2017 | 3U | IoT / M2M / Voice | $11.5 million | Plans to use inter-satellite links. Satellites outsourced from GomSpace. |
| Planetary Resources | 2 / 10 | 2014 | 12U | Earth observation | $50+ million | Visible-NIR 40 channel hyperspectral imager with 10 m resolution. Midwave infrared imager (MWIR) in 3-5 µm with 15 m resolution. Has been deprioritized for asteroid missions. |

- ***$415M investment to launch 406 Smallsats in constellations ~ $1M/SmallSat***
- 27 additional constellations are planned and listed at nanosats.edu
- Represents an additional $70M of existing funding to support these upcoming missions

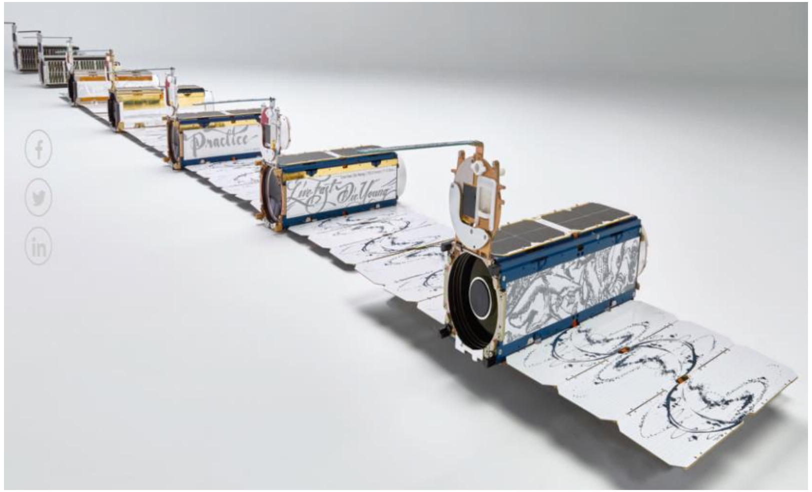
# Comparison of Small Sat Constellation Performance/Capabilities

| | Planet – Dove | Rapideye | Skybox |
|---|---|---|---|
| Total Area Covered | 300M $km^2$ | 6.5M $km^2$ | 0.185M $km^2$ |
| Number of Satellites | 175 | 5 | 13 |
| Area/satellite | 1.75M $km^2$ | 1.3M $km^2$ | 0.014M $km^2$ |
| Native Resolution per picture | 5m X 5m | 6.5m X 6.5m | 1.1m X 1.1m |
| Picture per Area/satellite | 70Gpictures | 30Gpicture | 12Gpictures |
| Download Tx | 220Mb/sec | 80Mb/sec | 470Mb/sec |
| Investment | $180M | $140M | $500M |
| $/Area/Satellite | $102/km$^2$ | $108/km$^2$ | $35,700/km$^2$ |

Final Business Goal = $1/km$^2$ at End of Mission

# Small Sat Constellation Case Study - Planet Labs

| Doves | Builds 1-5 | Builds 6-10 | Builds 11-13 |
|---|---|---|---|
| Operational Period | 2011-2012 | 2013-2014 | 2015-2016 |
| Optics | Off-the-shelf optics, narrow field of view | Custom telescope, focus mechanism | Second generation telescope with twice the field of view |
| Communications | Off-the-shelf S-band radio downlink | Custom X-brand radio downlink | Optimized comms system to gain – 500% increase in download rate, new antennas |
| Power | Lithium ion 7/5 AA cells, limited-efficiency solar cells | Custom pack with fuel gauge, solar charge controller, silicon solar cells | 100% battery capacity increase, high efficiency solar cells |
| Spectral Bands | Red, Green, Blue | Red, Green, Blue | Red, Green, Blue, NIR |
| Image Quality | Image vignetting, low SNR, suboptimal optical quality | Improved optical quality | Vignetting removed, good SNR, quality optical alignment |
| Capacity (km2/sat/day) | 3,000 | 500,000 | 2,500,000 |




https://www.planet.com/pulse/firehose/

- 1000X improvement in Capacity in 4 years

# Case Study - Planet Labs Constellation Improvement Process

- New generation every year
- *COTS evolves to become custom to improve capability*

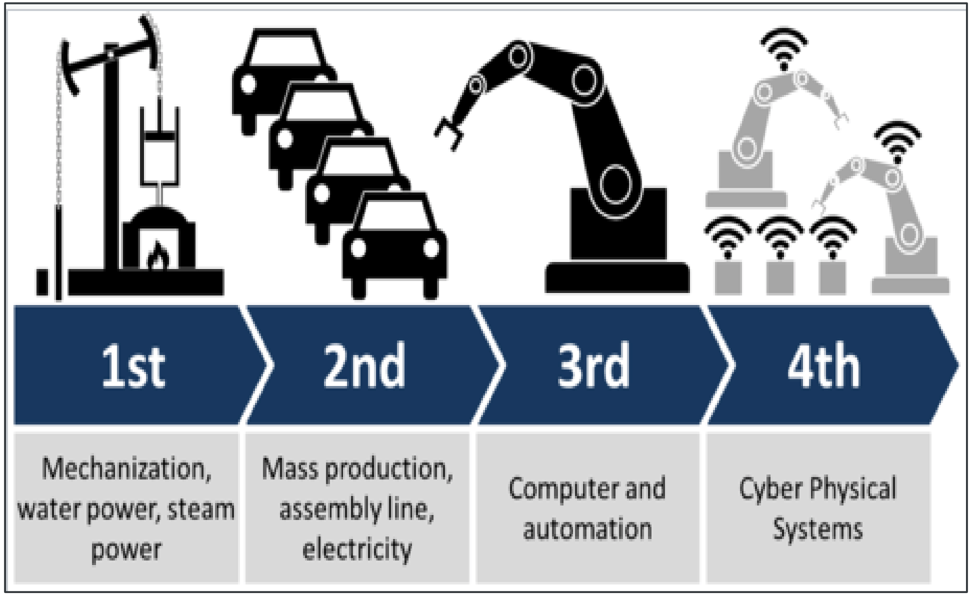

Build 7—launched after just 2 years of development—was Planet's first mass-produced satellite. It consisted of a custom telescope mated to an 11-megapixel CCD camera.


Build 10 introduced an improved carbon-fiber telescope and horizon sensors for more precise attitude control. These innovations resulted in a sharper image, increased signal to noise, and more usable pixels.

# Vendors, Suppliers and Manufacturing 4.0

# Manufacturing is evolving – Manufacturing 4.0

This is the modern world that will design, manufacture and test next generation small sat constellations




- Interoperability: The ability of machines, devices, sensors, and people to connect and communicate with each other via the Internet of Things (IoT) or the Internet of People (IoP)

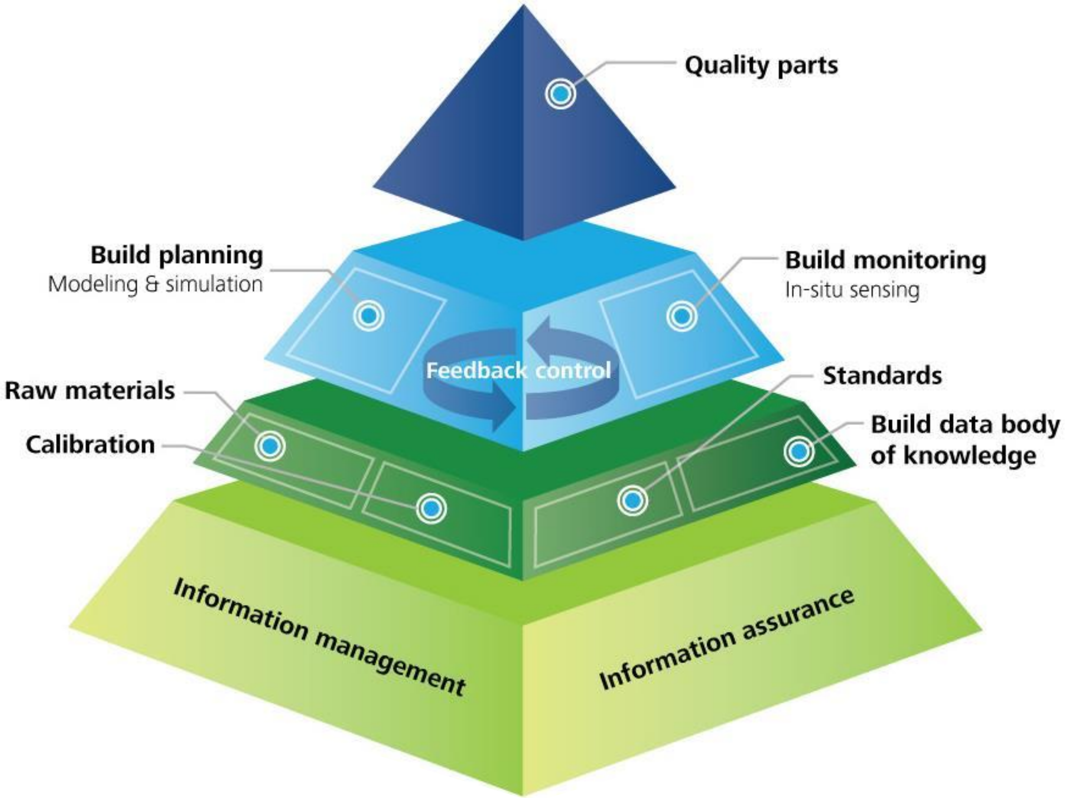
- Information transparency: The ability of information systems to create a virtual copy of the physical world by enriching digital plant models with sensor data.

- ***Changes in manufacturing imply changes are required in Assurance.***

- ***These are the Small Sat Manufacturing conditions***

# Quality Assurance Evolves into Information Assurance

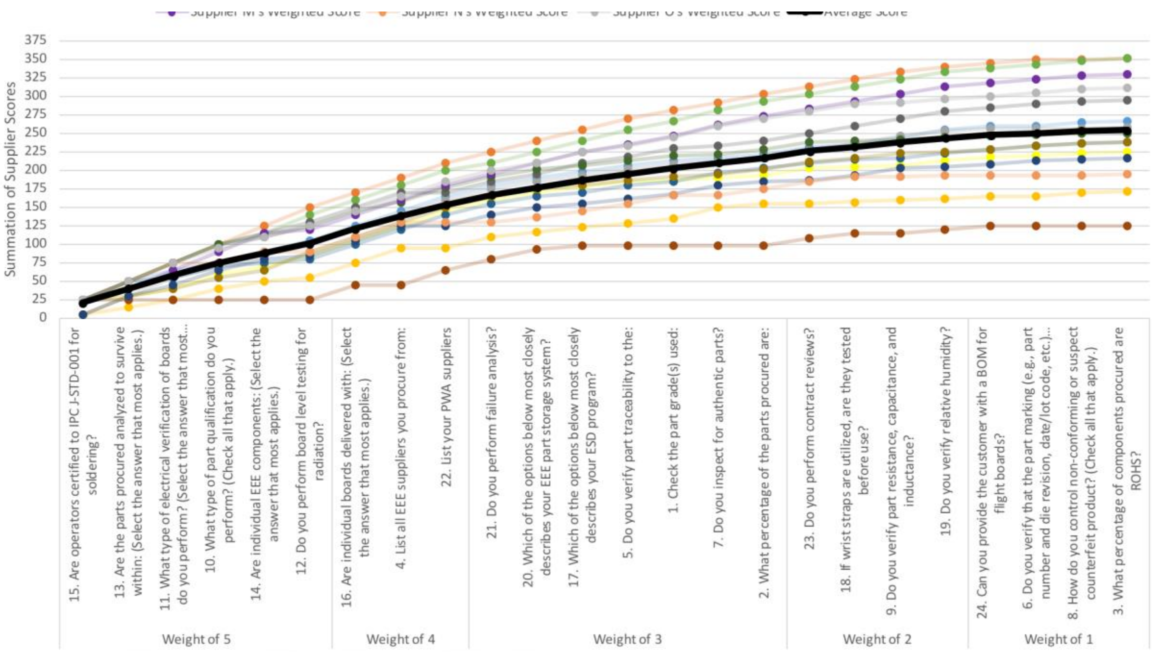
Assurance needs to evolve to keep pace with Manufacturing evolution and changes




- Assurance focus is now on qualifying the combination of design, material, process, rather than end items
- ***Constellations assurance is based on architecture qualification***
- Assurance must embrace and modern 21st century low cost design-build-test infrastructure

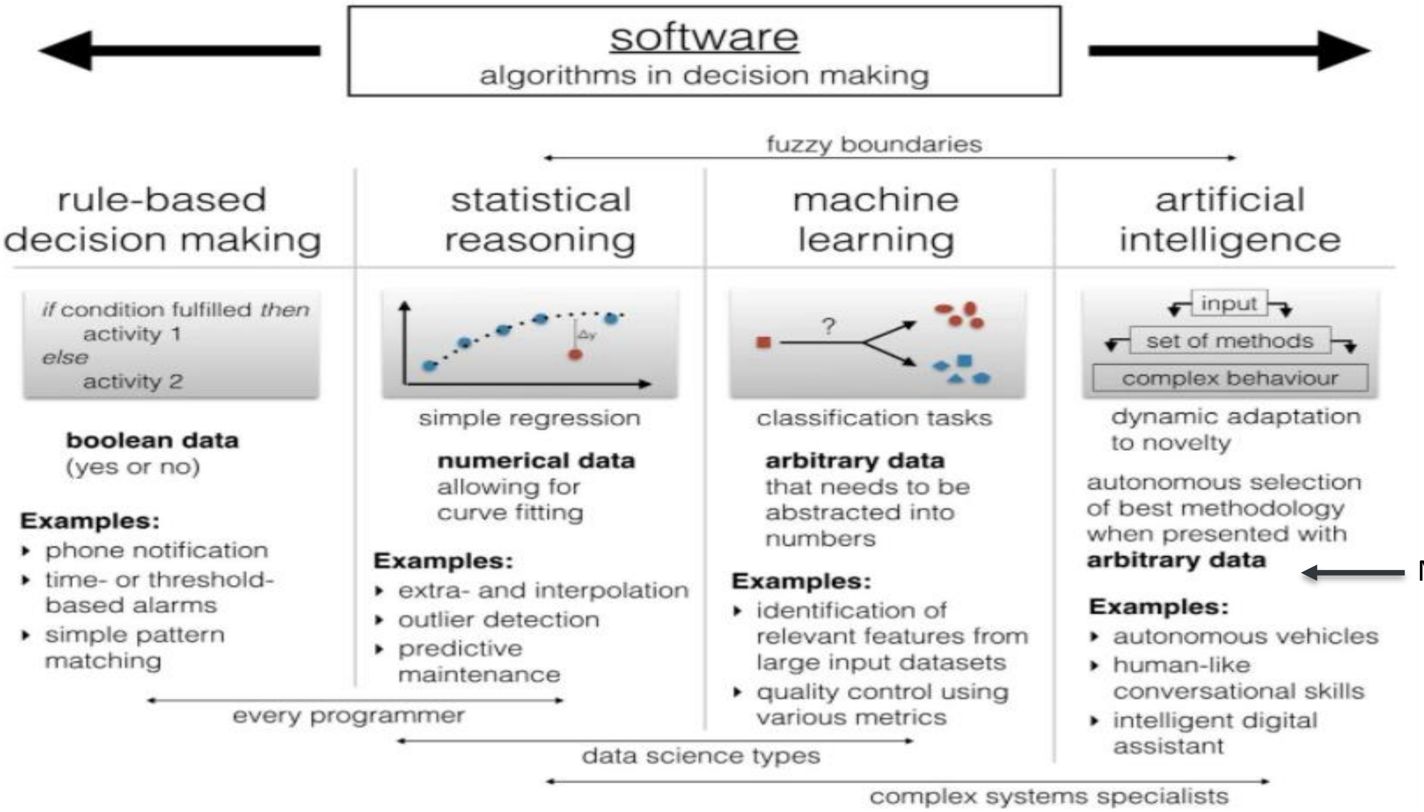
- ***Quality = Information***

# SmallSat Supplier Evaluation/Questionnaire - NEPP




- NEPP Program conducted an in-depth survey of various SmallSat providers and vendors
- Significant variation (3X) across supplier base
- Wide range of responses indicative of wide range in quality

# Overview of decision making tools and concepts




Model Based Mission Assurance

# Data mining techniques – Assurance tools 1/3

## Apply Cosine Similarity to EEE Parts Data

**Raw Data**

| Part Number | Height | Length | Width | Operating Temp Min | Operating Temp Max | Output Voltage Min | Output Voltage Max | Input Voltage Min | Input Voltage Max |
|---|---|---|---|---|---|---|---|---|---|
| LT1965EDD-3.3#PBF | 0.8 mm | 3.0 mm | 3.0 mm | -40.0 Cel | 125.0 Cel | 3.201 V | 3.399 V | 4.3 V | 20.0 V |
| LT3090HDD#PBF-ND | 0.8 mm | 3.0 mm | 3.0 mm | -40.0 Cel | 150.0 Cel | 0.0 V | 32.0 V | 1.5 V | 36.0 V |

**Vectorized Data**

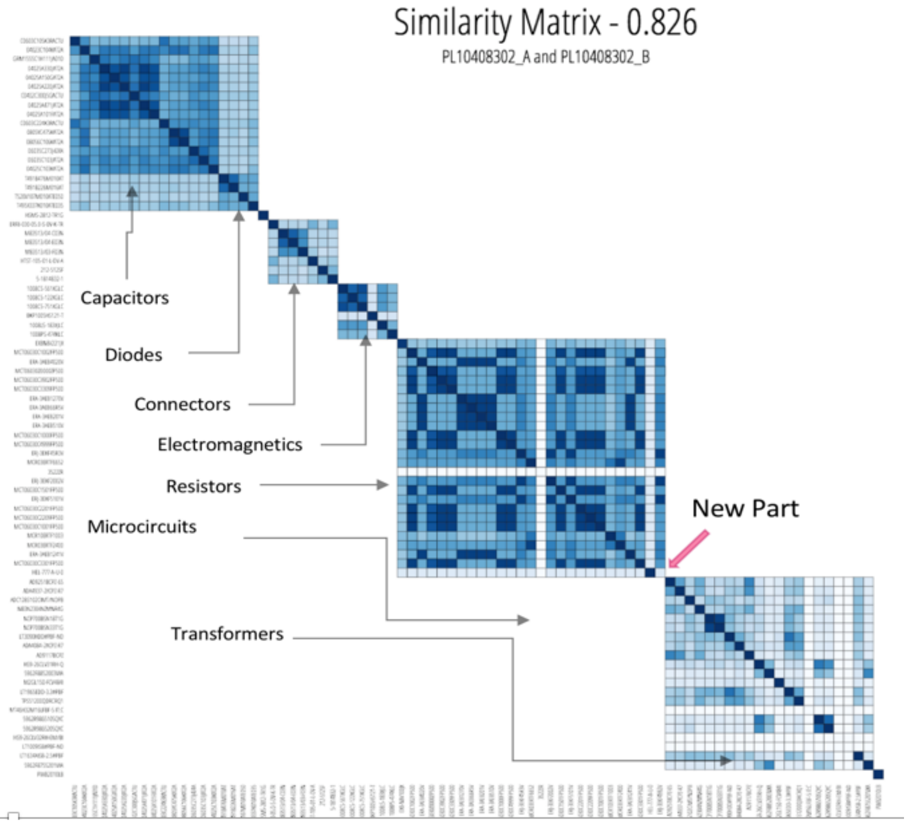
| Part Number | Height 0.8 mm | Length 3.0 mm | Width 3.0 mm | Operating Temp Min -40.0 Cel | Operating Temp Max 125.0 Cel | Operating Temp Max 150.0 Cel | Output Voltage Min 3.201 V | Output Voltage Min 0.0 V | Output Voltage Max 3.399 V | Output Voltage Max 32.0 V | Input Voltage Min 4.3 V | Input Voltage Min 1.5 V | Input Voltage Max 20.0 V | Input Voltage Max 36.0 V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LT1965EDD-3.3#PBF | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| LT3090HDD#PBF-ND | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |

**Cosine Similarity = 0.44**

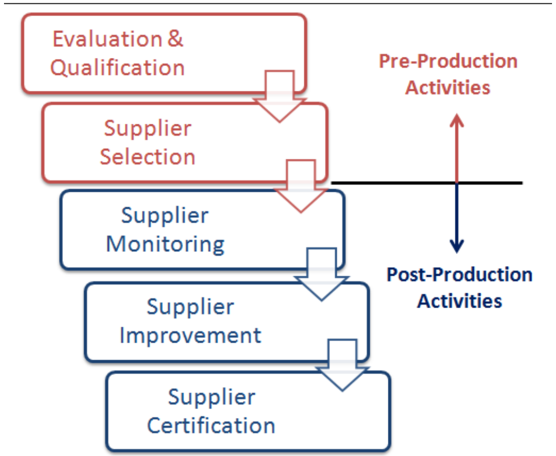
- **Data from IEEE datasheets360.com via web scrapper**
- *Not hand entered*
- **Using Python API (including Beautiful Soup and pandas)**

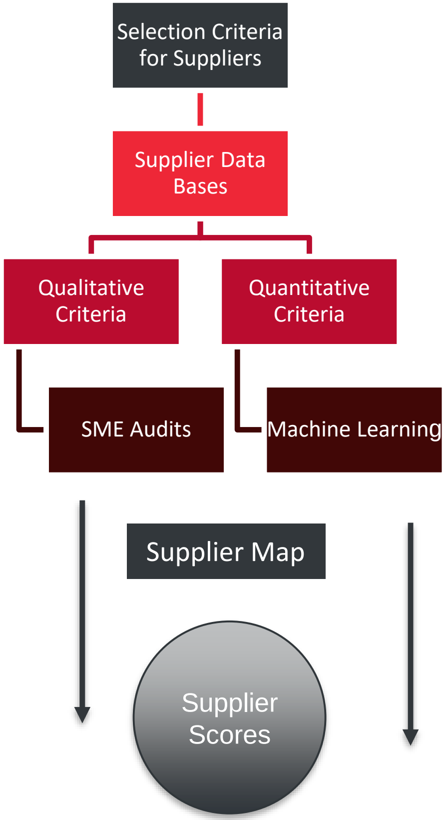
# Data Analytics – Assurance Tools 2/3

- **Similarity matrix for two part lists**
- **Coloring indicates strength of similarity:**
  - 0 – white (no similarity)
  - 1 – dark blue (identical)
- **Diagonal of 1's is an artifact of comparing different revisions of the same part list**
  - One-off in diagonal indicates addition of a **new part**
- **Distinct regions correspond to part types**
  - Part comparisons are not made between different part types
- **Manage subtle changes in part type, provide an precise definition of "Heritage" as way to reduce risk**



# Machine learning/Rule based decision making – Assurance Tools 3/3

# Constellation Assurance Concerns

# Assurance concerns scale super linearly with numbers

- Reliability goes down with decreasing size
  - Redundant parts within the platform are excluded to keep costs low and due to size limitations and energy supply limitations
- The life expectancy is less
  - Due to less fuel, or even the lack of, stable orbits cannot be maintained as long
  - Energy generation is limited due to smaller solar panels.
- Operation of large constellations becomes too complex for manual operation and automated processes have to be implemented.
  - Ground operating systems need to evolve as fast as satellite systems
  - More autonomy both on the ground and in the constellation

# Space debris = Assurance Task

- **SpaceX:**
  - Designing its satellites to make thousands of maneuvers during their lifetimes in order to avoid hitting other objects and to deorbit.
- **OneWeb:**
  - Deorbit out-of-use satellites within five years
  - Intentionally distanced its constellation from others to reduce the risk of inter-constellation debris creation
  - Ability to maneuver the satellites throughout reentry
  - Redundant GPS receivers to ensure position knowledge
  - *"The subsystems on the spacecraft that are required to do that deorbiting operation are spec'd as the highest-reliability functions on the entire spacecraft — even above that of the revenue-generating payload"* - OneWeb's director of mission systems engineering

- Opportunity for increased coordination between agencies that handle orbital safety and additional investments in the space situational awareness tracking systems.

# Conclusions and Recommendations

# Conclusions for Small Sat Constellation Assurance

- Mathematical analysis of constellations configurations is required to correctly comprehend reliability risks
- Small Sat constellations use is growning more and more every year
- Small Sat constellations also offer new scienctific breakthroughs with much lower cost
- The Small Sat market is evolving quickly with short learning cycles – the vendor base is becoming more sophisticated and experienced
- Assurance concepts and practices need to evolve to fully comprehend modern manufacturing concepts

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov