

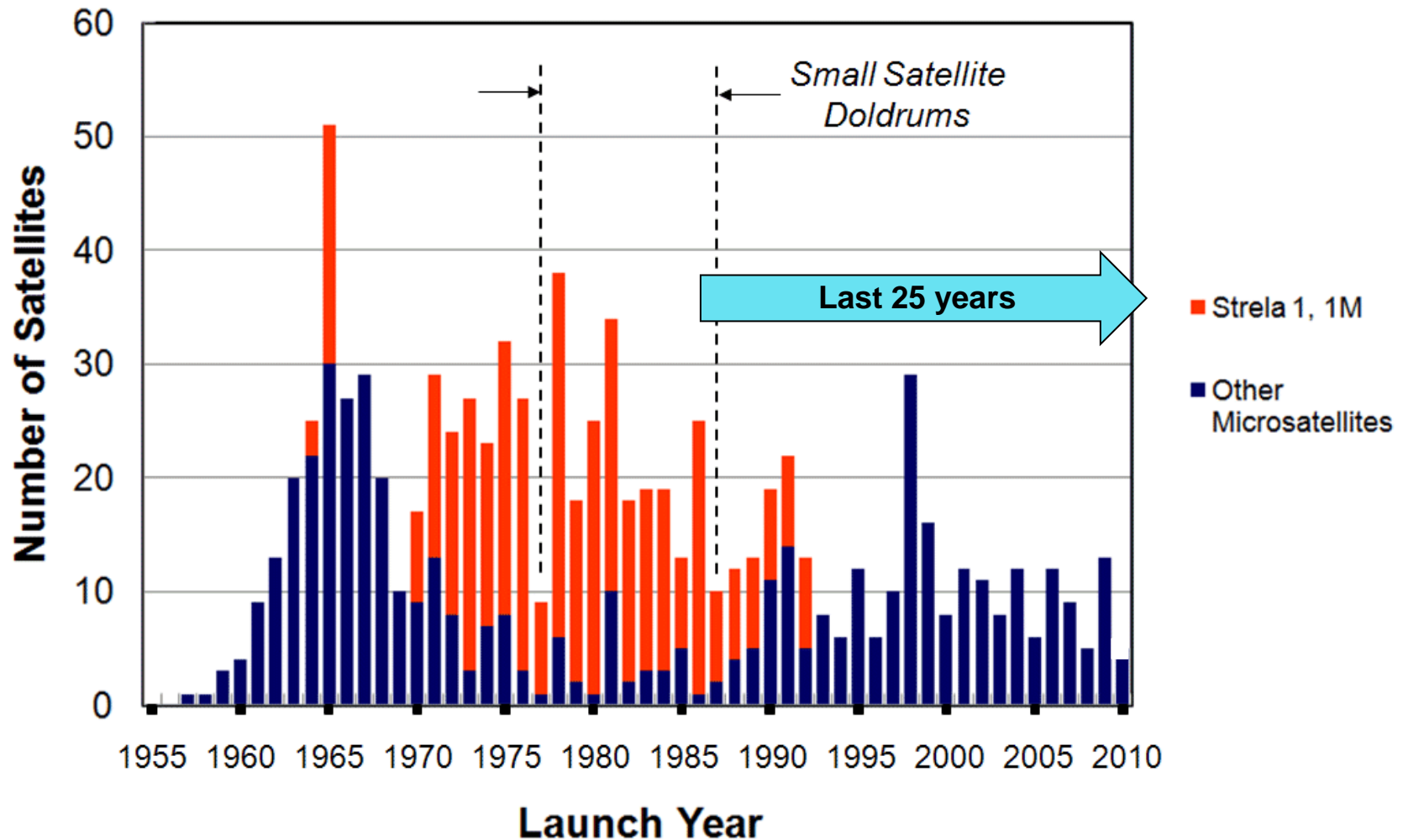
# 25 Years of Small Satellites



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**The Aerospace Corporation**

**Presented August 9, 2011**

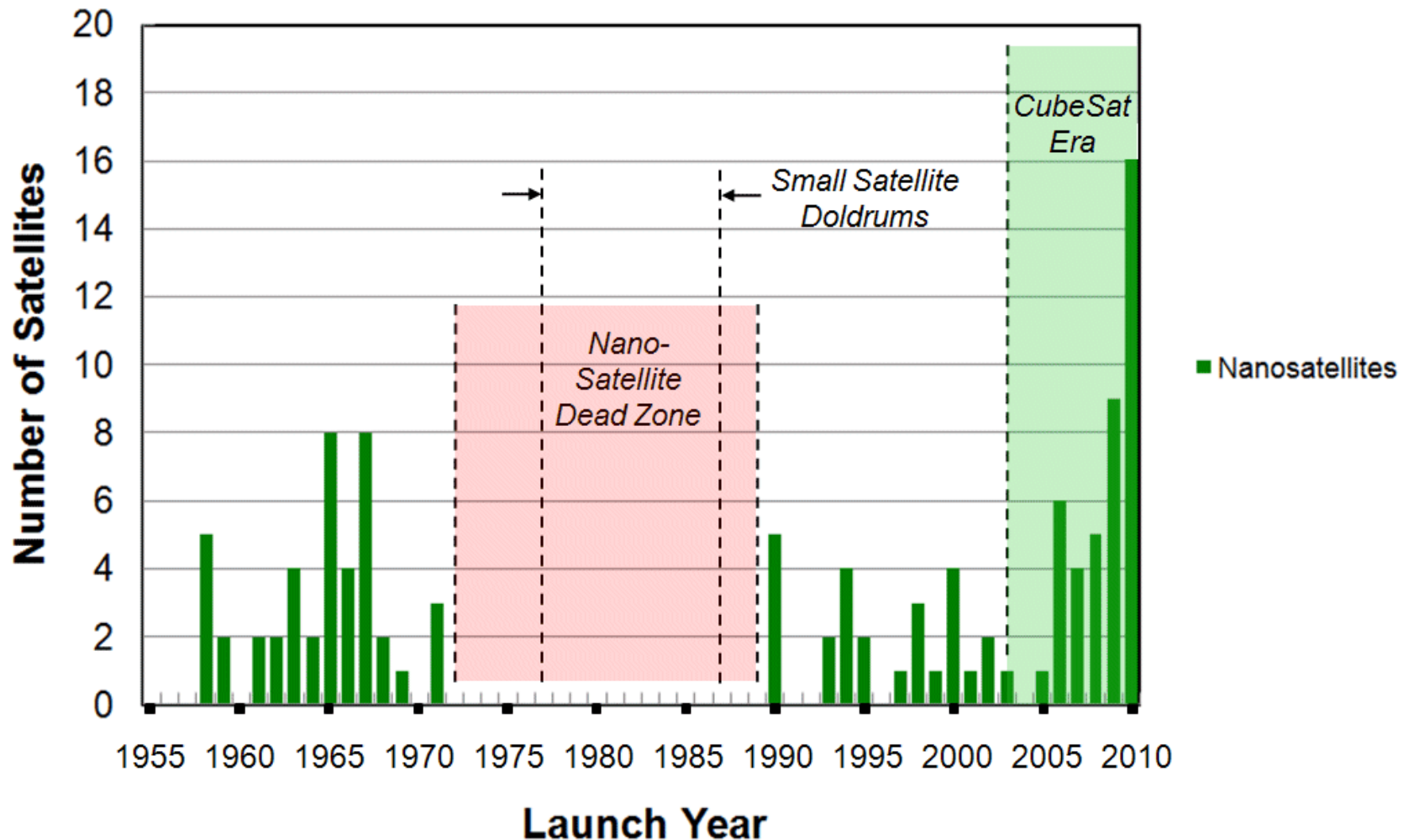
# Microsatellite Launch History:



***Microsatellite launch rates rose rapidly in the early 1960's, and peaked in 1965. Non-Strela microsatellite launch rates hit bottom from 1977 to 1987; the "Small Satellite Doldrums". They've recovered over the past 25 years.***



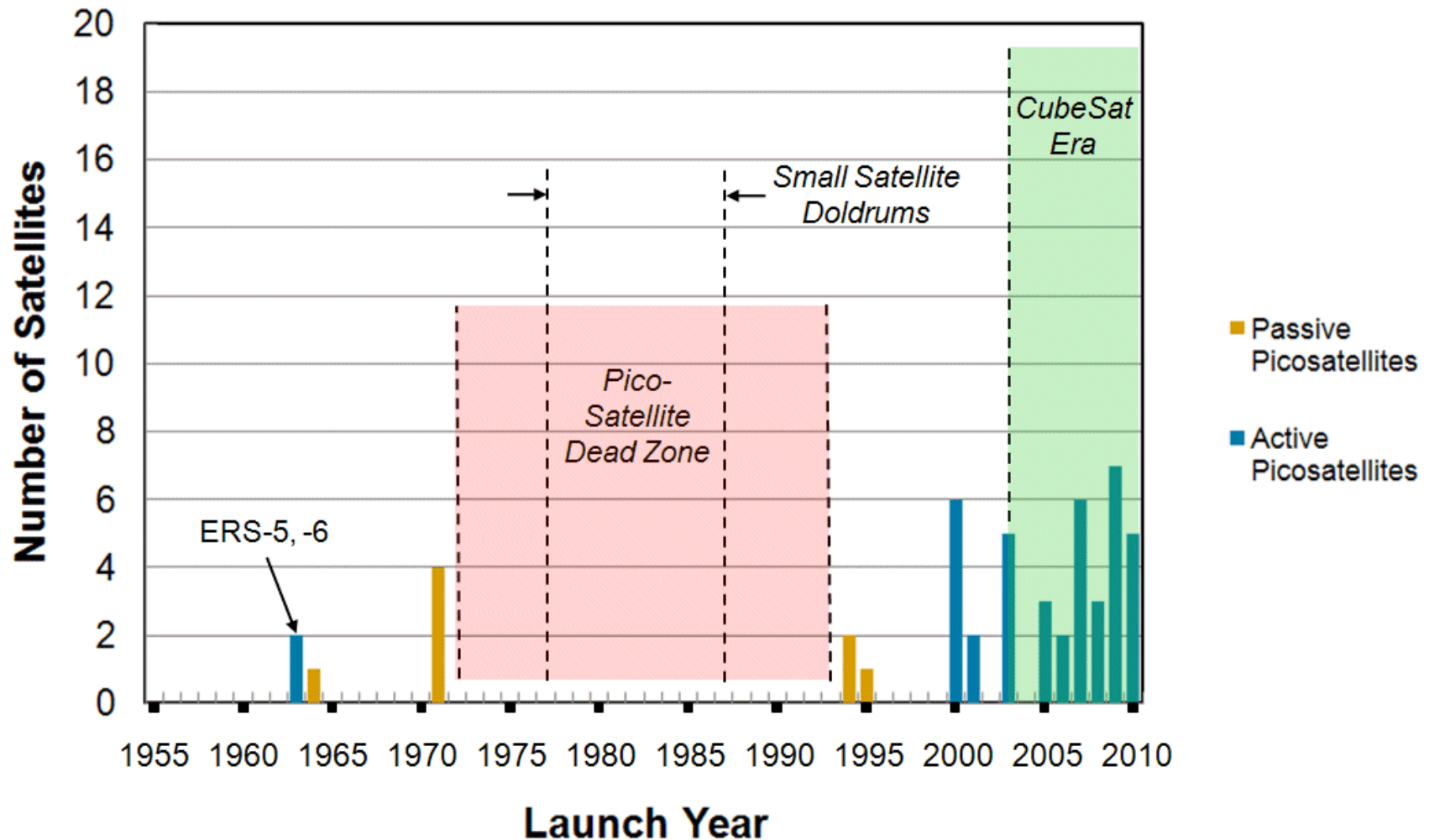
# Nanosatellite Launch History:



3 About 3 nanosatellites were launched per year during the first decade of space exploration. Launch rates hit zero between 1972 to 1989, but stabilized at ~2 per year through 2002. The CubeSat paradigm has enabled a rapid rise in launch rates.



# Picosatellite Launch History:



**Only two active picosatellites were flown before 2000. The Stanford Orbiting Picosatellite Automated Launcher (OPAL) ejected 6 picosatellites into orbit, kicking-off a 21<sup>st</sup> century return of picosatellites and the CubeSat Era.**



# Small Satellite Launch History: The First 30 years

- **The 1960's: Boom and Bust**

- *Small satellite launch rates rapidly increase in early 1960's as the Space Age unfolds*
- *Small satellite launch rates decrease in latter half of decade as launch vehicle throw weight capability increases and satellites get bigger (on average).*

- **The 1970's: Soviet Microsatellites Dominate**

- *Strela-1M constellation deployed; it eventually requires over 300 spacecraft*
- *Western small satellite launch rates continue to decline as satellites grow in size*

- **The 1980's: Small Satellite Doldrums (1977-1987)**

- *No nanosatellites or picosatellites launched*
- *Less than 5 Western microsatellites launched per year*
- *DARPA initiates LightSat program; holds workshop in 1987*
- *First AIAA/USU Small Satellite Conference in 1987*
- *"Doldrums" end in 1987*

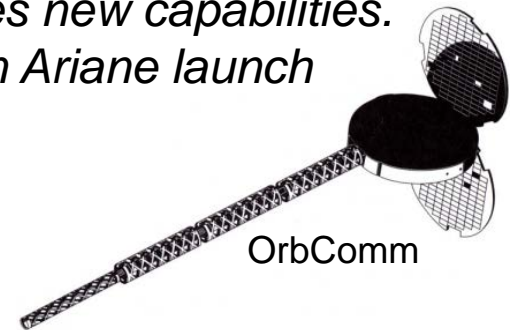
5 **By 1986, the Soviet Union was actively launching military communications microsatellites, but the rest of the world was experiencing a dearth of new small satellites. Fortunately, that changed over the next 25 years.**



# Small Satellite Launch History: The Last 25 Years

## • The 1990's

- *Microprocessors and microelectronics give small satellites new capabilities.*
- *ESA offers standardized secondary payload capability on Ariane launch vehicles; new flight opportunities become available*
- *OrbComm constellation launched*



OrbComm

## • The 2000's: Let's Get Smaller

- *Microsatellite space telescope (MOST)*
- *Nanosatellites with 3-axis attitude control and propulsion (SNAP-1)*
- *Active picosatellites return*
- *CubeSats offer standardized access to space; \$40,000 gets you a ride*



PicoSat-1

## • The 2010's: Expanding Mission Capabilities

- *Interplanetary missions (UNITEC-1, DCAM-1, -2)*
- *Formation-flying for distributed spacecraft (FASTRAC-1, -2)*
- *CubeSat ejectors on Indian, Russian, Japanese, European, and U.S. launchers*

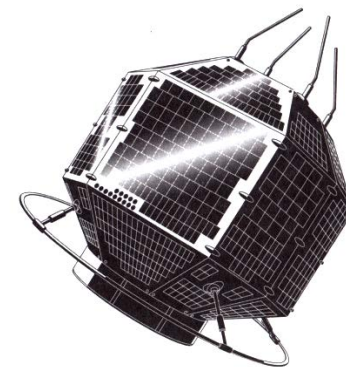
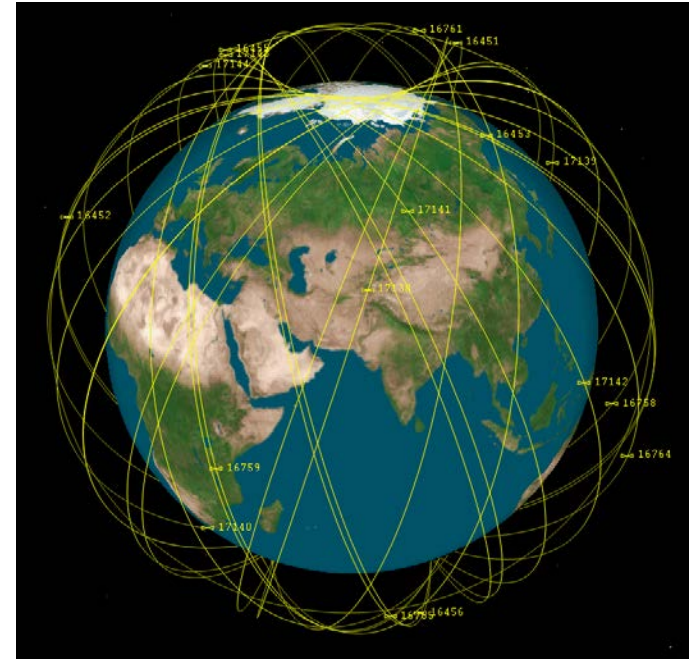
*The last 25 years have seen significant growth in small satellite launch rates, capabilities, and missions.*





# Small Satellites Launched in 1986 (25 years ago):

- 24 Strela-1M communications satellites →
  - *Launched by former Soviet Union*
  - *Record-and-forward communications*
  - *~50-kg mass*
  - *No attitude control*
  - *No station-keeping*
  - *2-year operational lifetime*
  - *360 were launched between 1970 and 1993*
  - *They are still up there at ~1470-km!*
- 1 Fuji-OSCAR-12 amateur radio satellite
  - *Launched by Japanese H-1 rocket*
  - *50-kg mass*
  - *Passive magnetic attitude control*
  - *No station-keeping*
  - *It's still up there at ~1500-km!*



***All of the small satellites launched in 1986 were communications microsattellites with passive or no attitude control. All of these satellites are still on-orbit.***



# Small Satellites Launched in 2010 (last year):

## • 4 Microsatellites

- UNITEC-1 (16-kg, interplanetary amateur comm.)
- Prisma-Tango (40-kg, rendezvous and formation-flying target)
- FASTRAC-1 and -2 (15-kg, formation-flying)

NanoSail-D



Image courtesy of NASA

## • 17 Nanosatellites

- Zheda Pixing 1A-1 and -2 (2.5-kg, MEMS testbeds)
- AISAT-1 (6.5-kg, ship tracking)
- 7 “3U” CubeSats (RAX-1, O/OREOS, Nanosail-D, SMDC One-1, Qb X-1 and -2, Mayflower-Caerus)
- 4 “1.5 U” CubeSats (Perseus 001, -002, -003 and -004)
- 2 “1U” CubeSats (Hyato at 1.5-kg, WasedaSat-2 at 1.2-kg)

O/OREOS

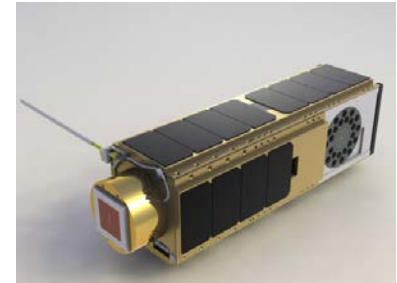


Image courtesy of NASA

## • 5 Picosatellites

- 3 “1U” CubeSats (Negai, STUDSAT, TISat, )
- DCAM-1, and -2 camera platforms (0.3-kg, interplanetary)

26 micro/nano/picosatellites were flown last year; 16 were CubeSats. There was a significantly greater variety of vehicles and missions than in 1986. Three micro-satellites and some of the nanosats have 3-axis attitude control and/or propulsion.





# Most Recent Small Satellite (as of July 21, 2011):

- **PSSCT-2**
- **Last satellite deployed by the U.S. Shuttle program**
- **5" x 5" x 10"**
- **3.6-kg mass**
- **3-axis attitude control**
- **24 microprocessors + 10 embedded processors**
- **Advanced solar cells**
- **Two GPS receivers**



*\* PSSCT-1 information can be found in paper SSC09-IV-5  
"Spin Dynamics of the Pico Satellite Solar Cell Testbed Spacecraft"*

***This spacecraft was ejected by the U.S. Space Shuttle Atlantis on July 19, 2011. It was the 180<sup>th</sup>, and last, spacecraft deployed by the U.S. Space Shuttle program.***



# Small Satellite Technology Drivers for the Past 25 Years:

- **Micro/Nanoelectronics**

- *Microprocessors you can barely see with the unaided eye*
- *Gigabytes of storage on your fingernail*
- *Multi-megapixel imagers on your fingernail*

- **Microelectromechanical Systems**

- *Rate gyros that can fit in a picosatellite with better than  $10^\circ/\text{hr}$  integrated error*
- *Smart thermal, magnetic, acceleration, and angular rate sensors*

- **Solar Cells**

- *Triple-junction solar cells with high sunlight to DC conversion efficiency*

- **Batteries**

- *Lithium-ion batteries*

- **Modeling and Simulation Software**

- *CAD/CAM for mechanical and electronic design*

- **The Global Positioning System**

- *Automatic position, velocity and time in a picosatellite or larger spacecraft*

- **The Internet**

- *Ordering parts and submitting designs for fabrication*
- *Remote control of distributed ground stations*

***Component, subsystem, system, and system-of-system technologies have driven small satellite development over the last 25 years.***



# The Evolution of Micro/Nanoelectronics:

## Example: The Intel 80286 microprocessor

- **Processor in IBM PC/AT (1984)**

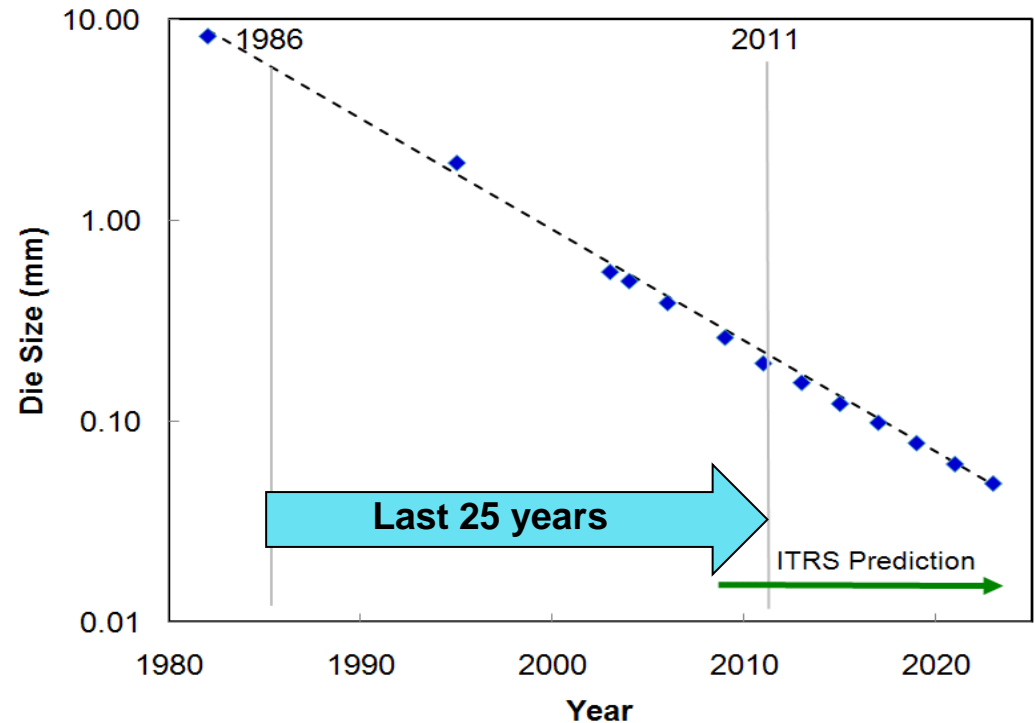
- *~1 million instructions per second*
- *134,000 transistors*

- **Moore's Law**

- *Doubling of transistor density every 2-2.5 years*
- *Valid over last 40 years*
- *Should last 10 more years*

- **Impact**

- *Microprocessors you can barely see*
- *Smart sensors*
- *Distributed processors*



\* ITRS: International Technology Roadmap for Semiconductors

**Digital processors once found in personal computers are now embedded in smart sensors.**

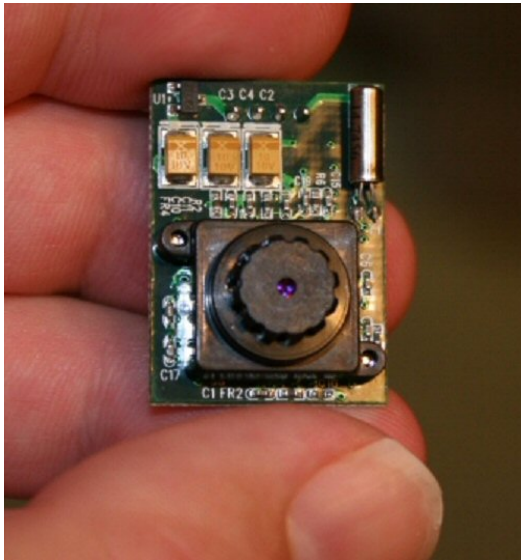


# The Evolution of Micro/Nanoelectronics:

## CMOS Image Sensors

- **Inexpensive, multi-megapixel imagers**
  - *Visible cameras*
  - *1-2 cm in size for imager*
  - *Some have built-in image compression*

2005-era 640 x 480 imager



AeroCube-3 Image of Earth



***Today, 2 to 10 megapixel visible imagers can be integrated into picosatellites and larger spacecraft.***





# The Evolution of MicroElectroMechanical Systems (MEMS):

- **Rate gyros**
  - *Now challenging fiber-optic gyro performance*
  - *Attitude accuracy of a few degrees over an hour*
- **Accelerometers**
  - *Better than 1-micro-g resolution is available*
- **Microbolometers**
  - *Optical thermometers with  $\sim 0.1$  K accuracy*
  - *Uncooled infrared focal plane arrays*

Melexis MLX90615 Thermometer



***The Melexis MLX90615 optical thermometer is one example of a MEMS sensor coupled with a mm-scale microprocessor in a small, sub-cm scale package.***

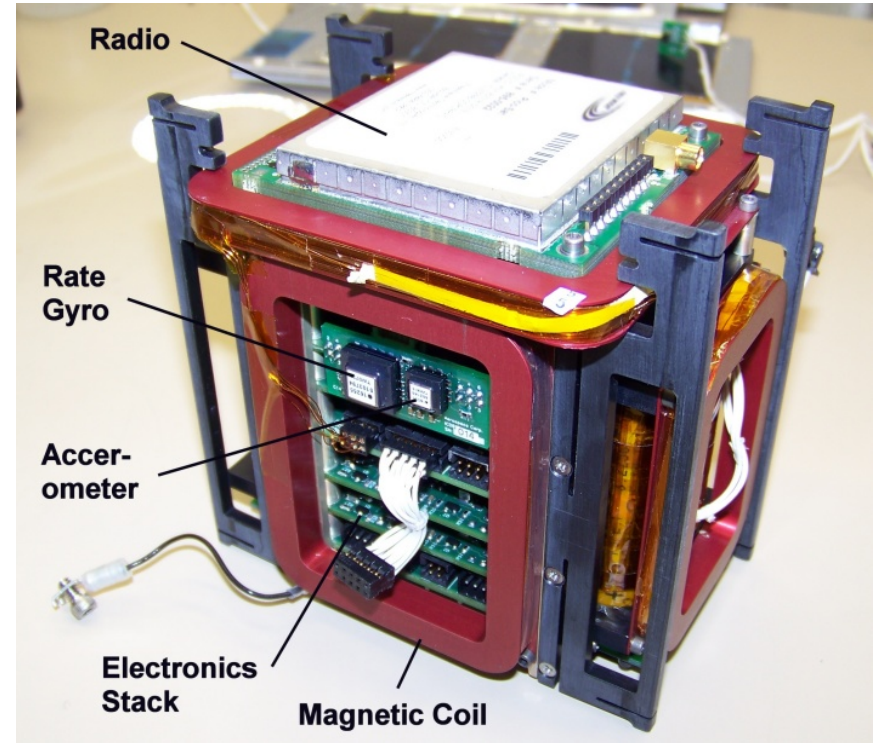
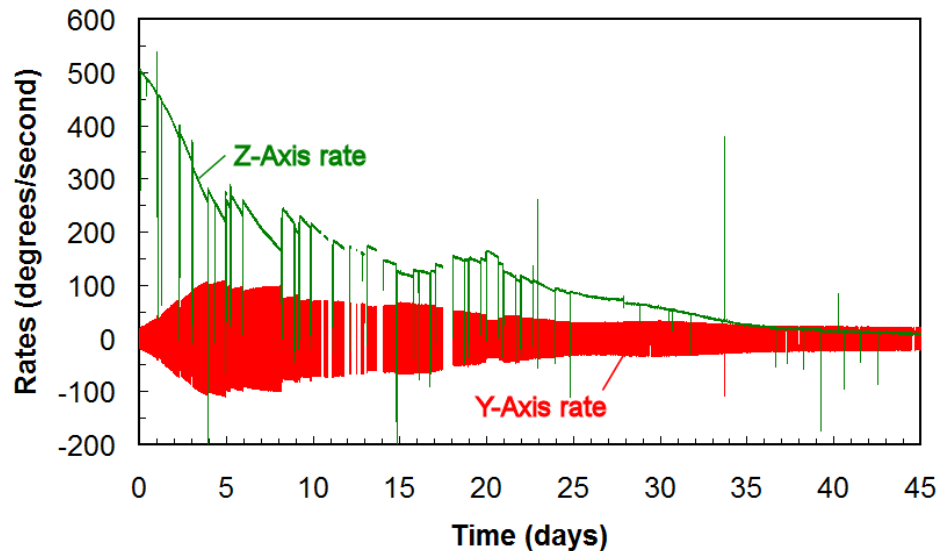




# On-Orbit Use of MEMS Rate Gyro:

- **PicoSatellite Solar Cell Testbed-1**

- *Spin-stabilized nanosatellite*
- *Rate gyros monitored spin dynamics*

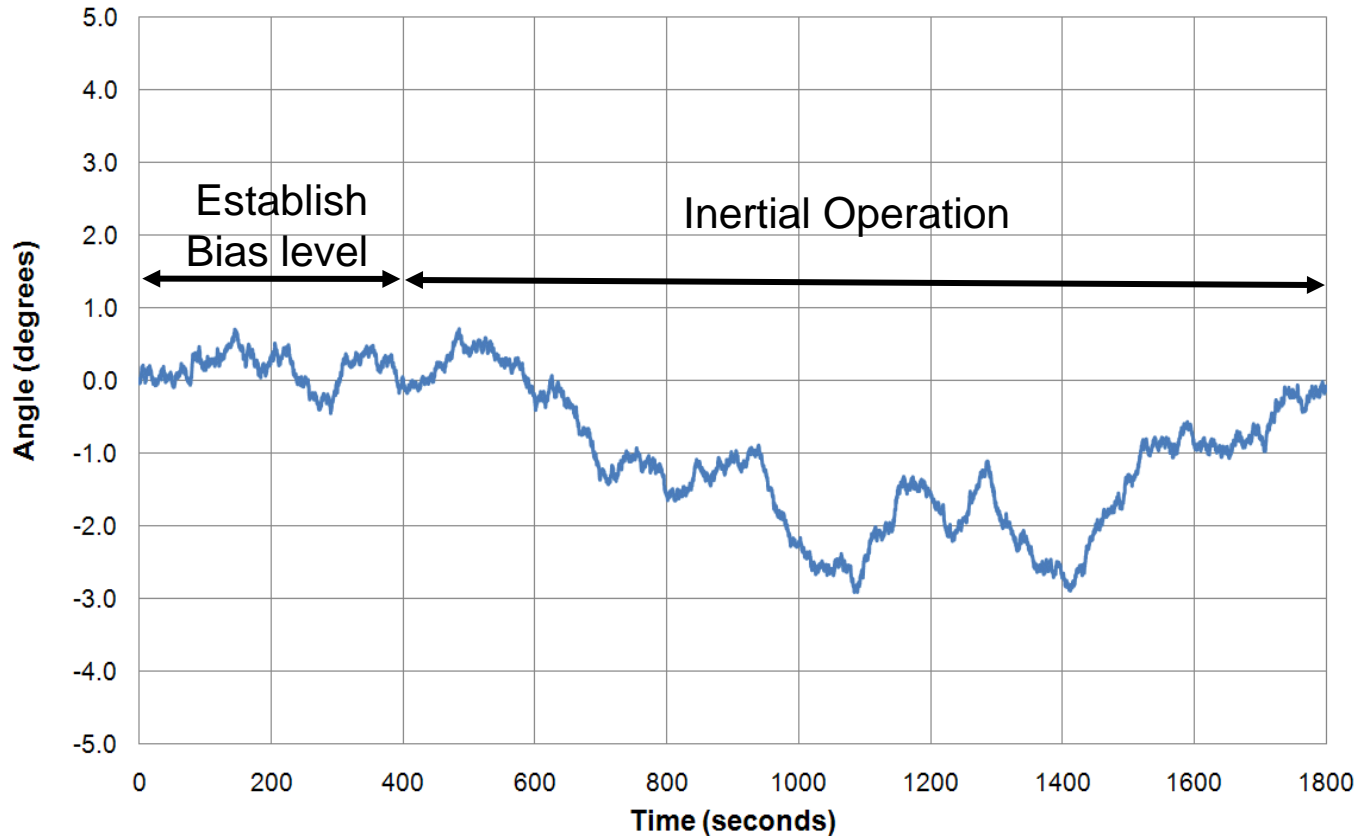


*From: "Spin Dynamics of the PicoSatellite Solar Cell Testbed Spacecraft," by Siegfried W. Janson and David A. Hinkley, paper SSC09-IV-5, 23<sup>rd</sup> Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 2009.*



# Improved MEMS Rate Gyro:

Laboratory test of VTI Technologies SCC1330-D02 Rate Gyro (single axis)

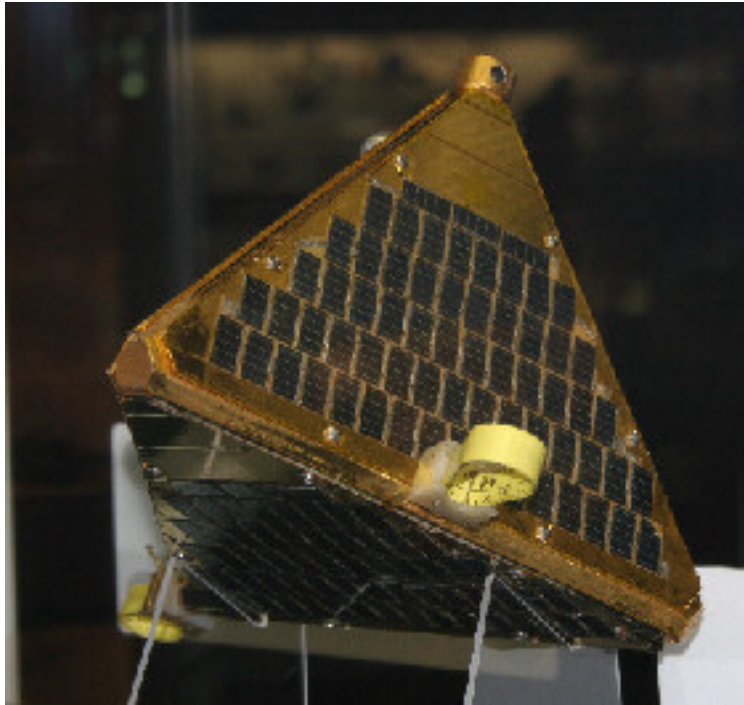


***This non-optimized laboratory test shows a maximum 3° error over 23 minutes of inertial operation. The first 6.7 minutes were used to determine the bias level offset.***



# The Evolution of Solar Cells:

**1963: ERS-12**



**2009: AeroCube-3**



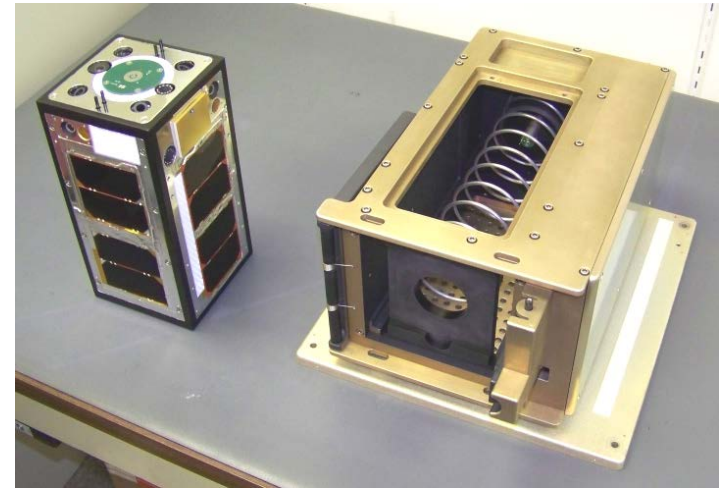
Early 1960's:	1-to-2 cm scale silicon cells	~8% efficiency	~0.5 V
Mid 1980's:	5-cm scale gallium arsenide cells	~18% efficiency	~0.9 V
Late 2000's:	5-to-10 cm scale triple-junction cells	>27% efficiency	~2.4V

***Today's solar cells are significantly more efficient than those available 25 years ago. Fewer cells are required per unit power. In addition, cell voltages have increased so that a single cell can drive spacecraft circuits.***



# CubeSats:

- **Containerized delivery of satellites**
  - *Orbital deployer provides physical containment of secondary satellites*
  - *Less risk for primary satellite*
  - *Container gets flight-qualified for a launch vehicle, not individual spacecraft*
- **Improved access to space**
  - *Wide variety of international launch options*



**A-POD for Space Shuttle**



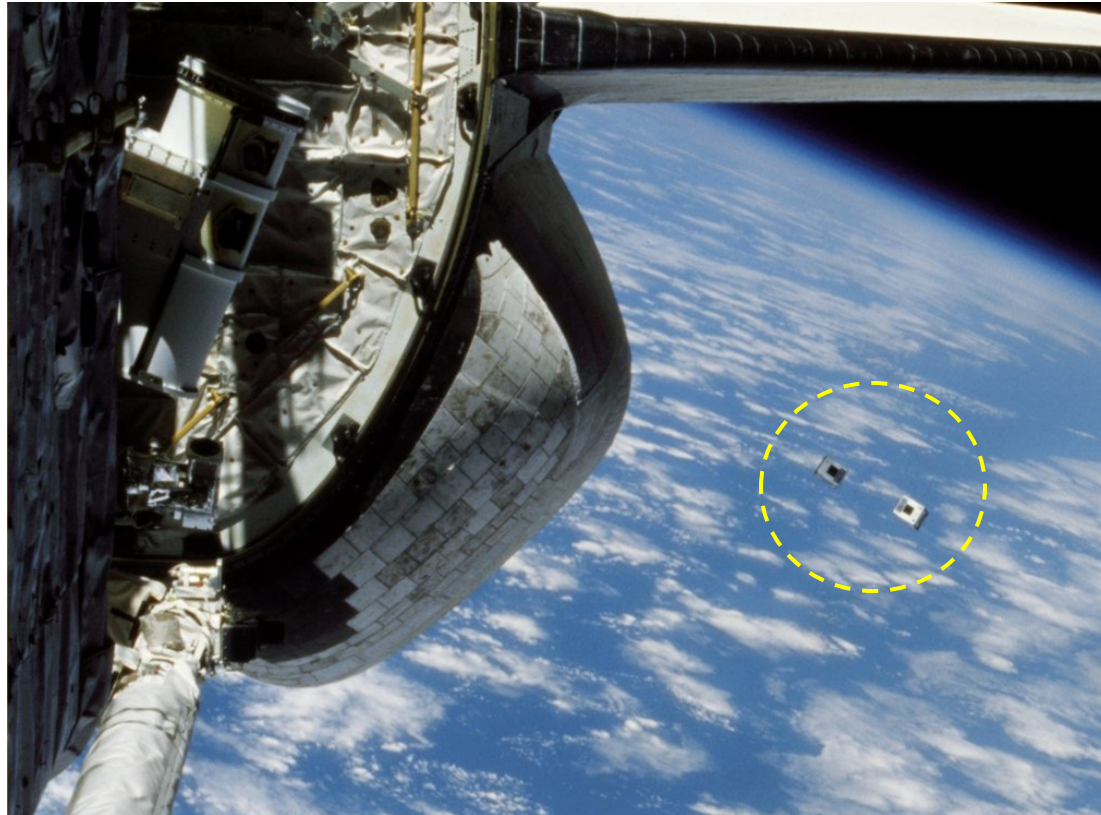
**Standard P-POD with three CubeSats**

*The California Polytechnic Institute “P-POD” is the standard orbital deployer. Other deployers (e.g., T-POD, X-POD, and A-POD) are also available.*





# A-POD Ejected Nanosatellites on STS-116 (2006):



*Photograph reprinted courtesy of NASA*

- Tethered pair of 4" x 4" x 5" spacecraft
- 1.3 and 1.6 kg
- Cameras and propulsion

***Two 4" x 4" x 5" tethered nanosatellites (MEPSI target and inspector) were ejected by STS-116 on Dec. 20 2006.***





# Small Satellite Missions:

Mission	Stabilization	Orbit	Examples
Radar calibration	NS	LEO	ODERACS
Atmospheric density measurements	NS	LEO	ODERACS
On-orbit radiation testing of components	NS	LEO, GTO,HEO	ERS-27
Space biology experiments	NS	LEO, GTO,HEO	O/OREOS
Laser ranging, general relativity experiments	NS, SS	LEO	LAGEOS
Local space plasma measurements	NS, PM, SS, GG	LEO, GTO,HEO	Munin
Low data rate communications relay	NS, PM, SS, GG	LEO	OrbComm
Low data rate store and forward communications	PM	LEO	UoSAT-2
Medium data rate communications	GG	LEO	MUBLCOM
Tether experiments	GG	LEO	MAST
Seismic monitoring via VLF wave reception	GG	LEO	QuakeSat
Ship tracking	3A	LEO	AISat-1
Solar cell testing	SS, AM, 3A	LEO, GTO,HEO	PSSC Testbed
Ionospheric mapping using GPS radio occultation	AM, 3A	LEO	PICOSAT
Medium to high resolution, targeted Earth imaging	AM, 3A	LEO	TOPSAT
Formation flying	3A	LEO	FASTRAC-1,2
Stellar magnitude monitoring	AM, 3A	LEO, GTO,HEO	MOST
Lunar and asteroid rovers		Interplanetary	MINERVA
Gravitational field mapping	AT	Lunar Orbit	RSTAR
Solar sail/ drag sail development	PM	LEO	NanoSail-D
Satellite inspector	3A	LEO	SNAP-1
Interplanetary vehicle inspector	NS	Interplanetary	DCAM-1, -2

***The small satellites launched in 1986 were communications satellites. The small satellites launched last year (green) had far more diversity.***



# Conclusions:

- **25 years ago, the small satellite world was stagnant**
  - *Small satellites were predominantly simple communications satellites.*
  - *A handful of small satellites were launched, on average, per year outside the Soviet Union.*
  - *Nanosatellites and picosatellites were not being launched.*
- **DARPA and Utah State University held pivotal conferences in 1987**
  - *DARPA announced LightSat program with significant investments.*
  - *The first AIAA/USU conference had more academic participation.*
- **Technology development over the last 25 years has enabled smaller, more capable spacecraft and new mission options**
  - *Micro/nanoelectronics, MEMS, Triple-junction solar cells and Li-ion batteries*
  - *GPS and the internet*
- **The CubeSat paradigm has improved small satellite access to space**
  - *Initial cost was ~\$40 K for a 1U CubeSat; universities could afford it.*
  - *Many international launch options now exist.*
- **Now, small satellite missions are more diverse and launch rates are up**
  - *Small satellites for space biology experiments, tracking ships, monitoring stellar magnitudes, inspecting other vehicles, space weather measurements, etc.*
  - *More nanosatellites are being launched than microsatellites.*



## ***Acknowledgment***

**I thank The Aerospace Corporation's Independent Research and Development program for supporting research in small satellites.**

