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Small Sat at 30: Trends, Patterns, and Discoveries

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ABSTRACT

Thirty years of the SmallSat Conference have produced a wealth of papers spanning technical, business, and market topics relevant to small satellites. Thanks to the online availability of every paper going back to the first SmallSat Conference in 1987, it is possible to analyze the proceedings of the conference to ascertain industry trends, development patterns, and technical discoveries. How has the focus of technology and mission paper topics changed over three decades? How has the participation of organizations, and the ratio of education, commercial, military, civil, and domestic/international involvement evolved? In this paper we provide the results of our analysis, ranging from the expected (Sir Martin Sweeting holds the record for most papers authored) to the surprising (Utah State University is the only organization to have published a paper in all 29 previous conferences). Through the data we can discern the era of “Faster, Cheaper, Better”, the introduction of “Operationally Responsive Space”, the advent of CubeSats, and the ongoing search for the holy grail of modularity. We see great successes like Orbital's Pegasus and Surrey's DMC, and the heartbreaking demise of industry pioneers like AeroAstro.

Reviewing this storied history, it is clear that some topics continue to be of interest three decades later even as technology has evolved and the world has changed. Through this historical analysis, we hope the reader will be able to draw from the lessons learned, avoid the failures of the past, and enable new and exciting successes in the next thirty years of small satellite development.

INTRODUCTION

This work tests a hypothesis: Given the rich dataset in the online historical proceedings, can we discern the key trends and events that have driven the evolution of smallsats over the last 30 years? By looking solely at the papers, authors, organizations, and session categories of each conference, can we perceive waves of technical innovation driving each other, the impact of industry economics and government decisions, and smallsat evolution in the context of the larger technical ecosystem it inhabits? The question came up in discussion at the 2014 conference, motivated by a perceived evolution in the focus of the technical papers being presented. The authors realized that the evolution of the conference proceedings to digital media opened up new avenues of discovery. Where previously testing the hypothesis would require the daunting task of going through decades of CD’s and paper proceedings, could data mining of the online proceedings be automated efficiently enough to make the problem tractable?

In fact, it could. Many trends are clearly visible in the data, and subtler patterns can be teased out as well. Presented here are the results, organized into three general sections:

- Approach: An explanation of the features available in the online data, how it was extracted, the tools developed for analysis, and ground rules and limitations affecting the results
- Analyses: Discussion of several historical trends through the lens of the conference proceedings, as well as the evolution of the conference
- Statistics: General statistics on the conference, including attendance, the most prolific authors and organizations, changing involvement by industry sector, and trends in paper collaboration.

APPROACH

To test this hypothesis, the necessary groundwork prior to analysis was to assess the features available in the database, develop tools to extract and organize the data, and develop the tools for specific analyses. In the course of the analysis, we developed ground rules: assumptions about the data and, based on limitations in the dataset, questions we would not attempt to address.

Database Features

The online proceedings contain information from all conferences since the first in 1987:

- Conference title and abstract, reflecting themes and focus (1998 on)
- Keynote speaker and bio since first keynote in 2003.
- Exhibitor information (2007 on)
- Pre-conference CubeSat workshop papers (began 2005, but only 2013 on linked from conference)
- Technical sessions and titles

For each paper, available data includes the year, session, title, abstract, authors and their organizations, and number of times it has been downloaded.

Database Extraction Tool

To gather this information, we wrote a web-scraping program in *Matlab*. The program begins at the root URL for the conference and traverses each conference year, gathering conference level information and paper level information into separate data structures with fields for all the information described above.

The structures are saved and available for a variety of analyses. At the same time, the software generates a spreadsheet allowing easy search and data sorting for all 2000+ papers.

Analysis Tools

We developed a wide variety of tools for analyzing different aspects of the data, falling broadly into statistical analyses and search and organization tools.

Statistical analyses served as an entry point for posing some of the more detailed questions, and are documented in a separate section below. These included basic metrics like number of papers per year and more detailed results like ranking author occurrences by total number and time history over conference years.

Search and organization tools facilitated sorting the data and testing hypotheses. These included functions for Boolean keyword searches in the data (e.g. “ELANA” & “educational launch”), outputting statistics on occurrences in papers vs year and spreadsheets gathering year, title, author, organization, session and abstract information for easier analysis. Organization tools let us sort papers into different categories and build tables and charts.

Ground Rules

The ground rules of the analysis are to restrict results to what can be found in the dataset described above: what is the world seen through the lens of the online proceedings? Although we anticipate a correlation between conference publication and smallsat related activity by individuals and organizations, it is clearly possible for activity to go undocumented (indeed, mandated in the case of classified work). And despite international involvement in the conference, it will be US focused.

Additionally, we present an analysis of the information available in the aggregated paper meta-data, not a review of the content in every paper. Thus it is only as smart as the data available and can be fooled by the misuse of keywords in titles and abstracts, by unanticipated synonyms for keywords, and by inconsistent data entry or naming.

One significant challenge for some of the analyses is the lack of naming consistency for organizations in the dataset. For example, the U.S. Air Force may be referred to as “USAF”, “US Air Force”, “United States Air Force”, etc, but must be distinguished from the “Air Force Research Labs”, “Air Force Institute of Technology”, etc. NASA centers must be distinguished from each other and NASA HQ. There are frequent acronyms, occasional misspellings, name changes, and acquisitions and mergers further complicating tracking organizational involvement. Our approach was to develop a set of rules for renaming organizations which included a primary org name and a list of synonyms or keywords unique to that org. A list of 275 rules consolidated the initial number of unique organization names from 1708 to 961.

A parallel issue occurs in the author data. Although there are 5908 unique author names, many authors have multiple names and misspellings. For example, Sir Martin Sweeting appears as “Sweeting, Martin”, “Sweeting, M.”, “Sweeting., M.”, “Sweeting, M N”, “Sweeting, M.N.”, “Sweeting, M. N.”, and “Sweeting, Sir Martin”. Synonym rules were developed only for the most prolific authors.

Another effect on statistical results is the inclusion of the pre-conference CubeSat workshop papers in the Digital Commons database in 2013, 2014, 2015. This throws off the statistical trending for those years by introducing additional organizations and papers beyond those in the regular sessions. Also, because abstracts are inconsistently available for these papers, it affects word counts.

ANALYSES

The following analyses illustrate some of the trends and phenomena statistically visible in the 30 year of collected proceedings. We have chosen to provide illustrative examples of trends related to the jargon of the conference, advances in technology, and several key industry events visible in the data.

Industry Trends, Timeline, Events

<u>The Naming of Things</u>

As in any industry, smallsat related buzzwords come and go. Although often a rebranding of existing concepts, as the new term gains momentum (typically when adopted by a funding agency) it is used more and more in programs, proposals, and papers. At some point, as the funding bubble pops, new funded efforts adopt new language to distinguish themselves, the term becomes stale or meaningless from overuse, and the appearance in paper titles and abstracts tapers off.

Faster, Better, Cheaper

In 1992 NASA Administrator Dan Goldin introduced a new approached to NASA missions which he termed "Faster, Better, Cheaper (FBC)". FBC was a departure from the philosophy of massive flagship projects consuming agency resources with almost uncapped overruns.

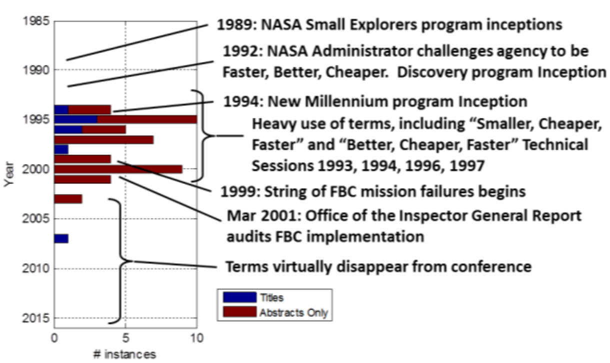

Figure 1: Timeline of industry events and paper instances with the terms "faster", "better", and "cheaper"

Well aligned with the philosophy of smallsats, and with the potential to generate funding for many smaller satellite projects, the concept was embraced by the smallsat community, and as shown in Figure 1 it quickly slipped into common usage both in session titles and papers. By the year 2001, however a string of embarrassing failures led to the questioning of FBC and ultimately the departure of Administrator Goldin.

Although FBC fell out of favor, and references to it quickly disappeared from the language of the conference (with the widely quoted maxim becoming "Faster, Better, Cheaper: Choose Two"), key precepts of the effort remain important to the smallsat philosophy of focused, small *programs* (not, naively, just small mass and size) to maximize efficiency and keep unit costs (or individual program costs in a portfolio) low enough to afford the risk of first adoption of technologies and process improvements. Better performance than larger missions is a worthy goal (and sometime realizable through earlier adoption of new technology or achitectures), but the idea that *value*/$ by avoiding the cost overrun spirals that plague large programs would continue in acquisition reform efforts under different names.

Responsive Space

Conference attendee from the mid to late 2000's will recall the prominence of Responsive Space. However, the critical military need for availability of space assets, and the concept of small satellites as a tactical approach for responsively filling an operational need via rapid, low cost replacement, augmentation, or survivability through overwhelming numbers has been around since the beginning of the conference. As illustrated in Figure 2, in 1989 there are two papers that specifically call out this need, using virtually identical language as the later surge of papers.[1,2]

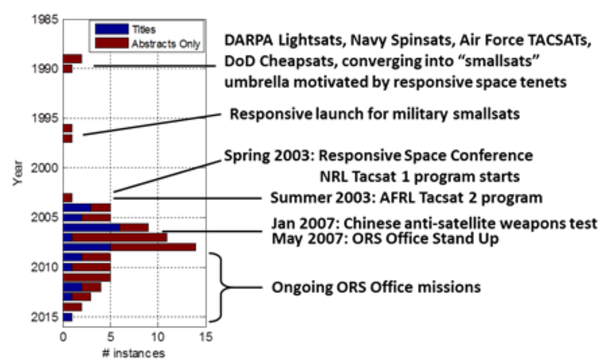

Figure 2: Timeline of industry events and paper instances with any of the terms "responsive space", "operationally responsive", "tactically responsive", "tactical satellites", "tacsat", "responsive launch", or "ORS"

In 2004, the bow shock of papers arrives, instigated by 1) the creation of a parallel Responsive Space

Conference featuring many of the usual suspects from the Smallsat Conference and 2) the inception of similar programs at AFRL and NRL. Momentum built up, spurred by the 2007 Chinese anti-satellite demonstration, which hastened the formation of a DoD Operationally Responsive Space office. During this time we see a growth of papers from the organizations directly involved in these efforts, but amplified by the use of the term in academic and commercial papers.

After the initial recognition that smallsats are one part of an overall strategy for responsiveness, the focus expands in other directions, including small, low-cost launch vehicles, standards development, and tactically taskable satellites. These new focus areas develop new terminology as the original terms become associated with earlier administrations, problems on particular programs, or are simply not specific enough. The use of the terms continues to wane, being used more and more for ORS office projects only.

What Are We Talking About?

Over the past 30 years the language we use to describe small satellites has evolved as well. Figure 3 illustrates the gradual trend toward more papers referencing "small satellite" in the title (blue) or abstract only (red). A trend exists towards increased use of the abbreviation "smallsat" as well). Also evident is the gradual adoption of the term "micro satellite" and it's synonyms, peaking in early 2000's, followed by the adoption of "nanosatellite" and it's synonyms, paralleling the rise of cubesats. Pico satellites (as well as femto satellites) are also referenced, and may have their day in the future.

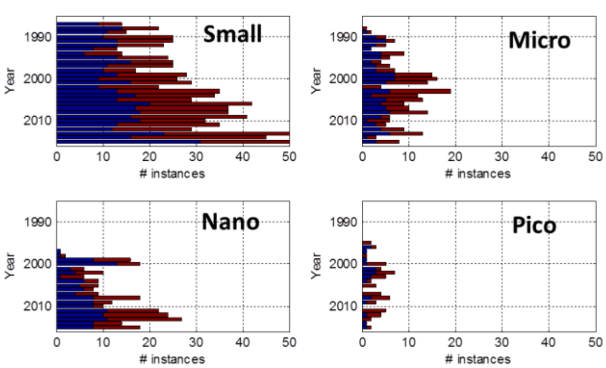

Figure 3: Comparison of number of papers using the terms small, micro, nano, and pico satellite

Notable Trends

CubeSats

The ubiquity of CubeSat related papers at the conference is no secret. Examining papers with titles or abstracts mentioning CubeSat and distinguishing them from papers including nanosats but not CubeSats illustrates how we got here.

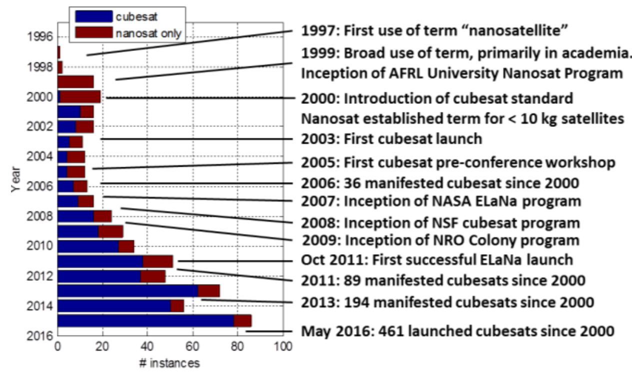

Figure 4: Timeline of industry events and paper instances with "cubesat" (blue) and with "nanosat" but not "cubesat" (red)

The first use of the term nanosat at the conference appears in 1997[3], followed by two the next year. It is no coincidence that in 1999, when the University Nanosatellite Program was started (its educational mission incidentally justified as pathfinder tech demos for the AFRL TechSat 21 formation flying effort[4]), there was an explosion of 16 papers, almost all from academia. By 2000 the term is well established and generally accepted as meaning < 10 kg.

In 2000 the CubeSat standard is first introduced to the conference as well[5]. CubeSats enjoy a dedicated technical session in 2001 and rapidly begin to dominate the discussion of nanosats. After the first CubeSat launch in 2003, momentum begins to build. In 2005 the pre-conference workshop begins, although workshop papers won't be captured in the proceedings, and hence the analysis, until 2013.

With the inception of the NASA ELaNa program in 2007[6] there are is a well-documented proliferation of academic programs[7,8]. Shortly thereafter we see the introduction of the NSF CubeSat, NRO Colony, and other programs. A variety of military, civil, and commercial efforts soon follow.

As more and more launches occur, a CubeSat sub-industry forms around the platform and related technologies within the smallsat industry, already itself a subset of the larger global space industry.

NASA Involvement

Another interesting trend to examine is the level of involvement of NASA and its various centers (including the closely affiliated FFRDC, the Jet Propulsion Laboratory). Figure 5 illustrates the number of unique papers with author credits from each organization each year (note that collaboration between organizations makes actual number of unique papers less than the sum shown). Not surprisingly, NASA Goddard Space Flight Center, JPL, and NASA Ames Research Center are the highest contributors. But perhaps surprising to attendees since 2001 is the high level of participation of the first two in the first half of the conference. By examining the papers, we can better understand the numbers.

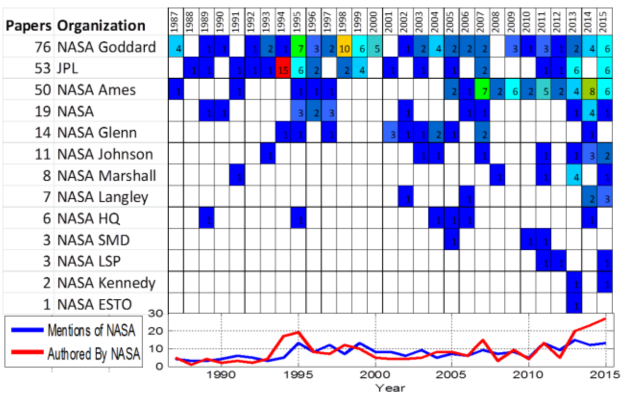

Figure 5: Heat plot of papers authored by NASA organizations versus time, including total number of papers mentioning NASA and papers authored by NASA

In 1995 four of the seven GSFC papers were derived from Small Explorers work, and discussion of SMEX missions and technologies appears to make up at least half of the GSFC contributions. The dramatic reduction in 2001 may be attributable to the end of the faster, better, cheaper era, or the closure of the GSFC SMEX office and transition to management by PI's.

The JPL anomalous domination of 25% of the 1995 conference papers is not easily explainable (they were indeed covering a wide range of topics), and neither is their near disappearance from the conference in 2000, although these dates roughly match the era of FBC. Recently JPL has returned with a roadmap for incorporation of CubeSats in deep space missions and a portfolio of technology development to support it.

The reemergence of NASA Ames within the conference from 2007 *is* explainable, however. Pete Worden started as center director at Ames in April 2006 with the specific objective of being disruptive through a focus on small satellites, which ultimately kick-started NASA's re-involvement in smallsats. Whereas Ames' papers in 2005 and 2006 were strictly about GeneSat (the first CubeSat-based biology mission), the newly formed Small Spacecraft Division emerged in force at the 2007 conference pursuing a variety of mission areas and focusing on low cost material and programmatic approaches[9]. From the 2007 conference on we see an increase in Ames papers reflecting an increase in projects and missions. Work at Ames helped influence funding priorities in the rest of NASA, including current Space Technology Mission Directorate programs.

Coupled with success leveraging the CubeSat platform, we see ELaNa emerge from the Launch Service Program and other NASA center involvement increase in recent years, to the point where NASA authors were involved in 13% of the 2015 conference papers.

Session Evolution

One way to see how the conference has reached its present form is to follow the evolution of the conference sessions. What topics have received more and less emphasis over time? What topics are enduring and have found a permanent place on the agenda? To do this we examined and categorized each session in every year, and arranged them on the matrix presented in Figure 6. As indicated by color changes and separation on the grid, sessions are categorized broadly, into thematic sessions, mission related, payloads and busses, subsystem technologies, launch and operations, education, cubesats, and posters and panels. Throughout its history the conference has remained steadfastly single track, maintaining its characteristic sense of a single community by resisting the temptation to cater to accept more papers and split into specialized parallel sessions. Studying how the finite resource of sessions has been allocated across these areas and the subcategories within them yields insight into both trends in the industry and the difficult decisions faced by the conference organizers.

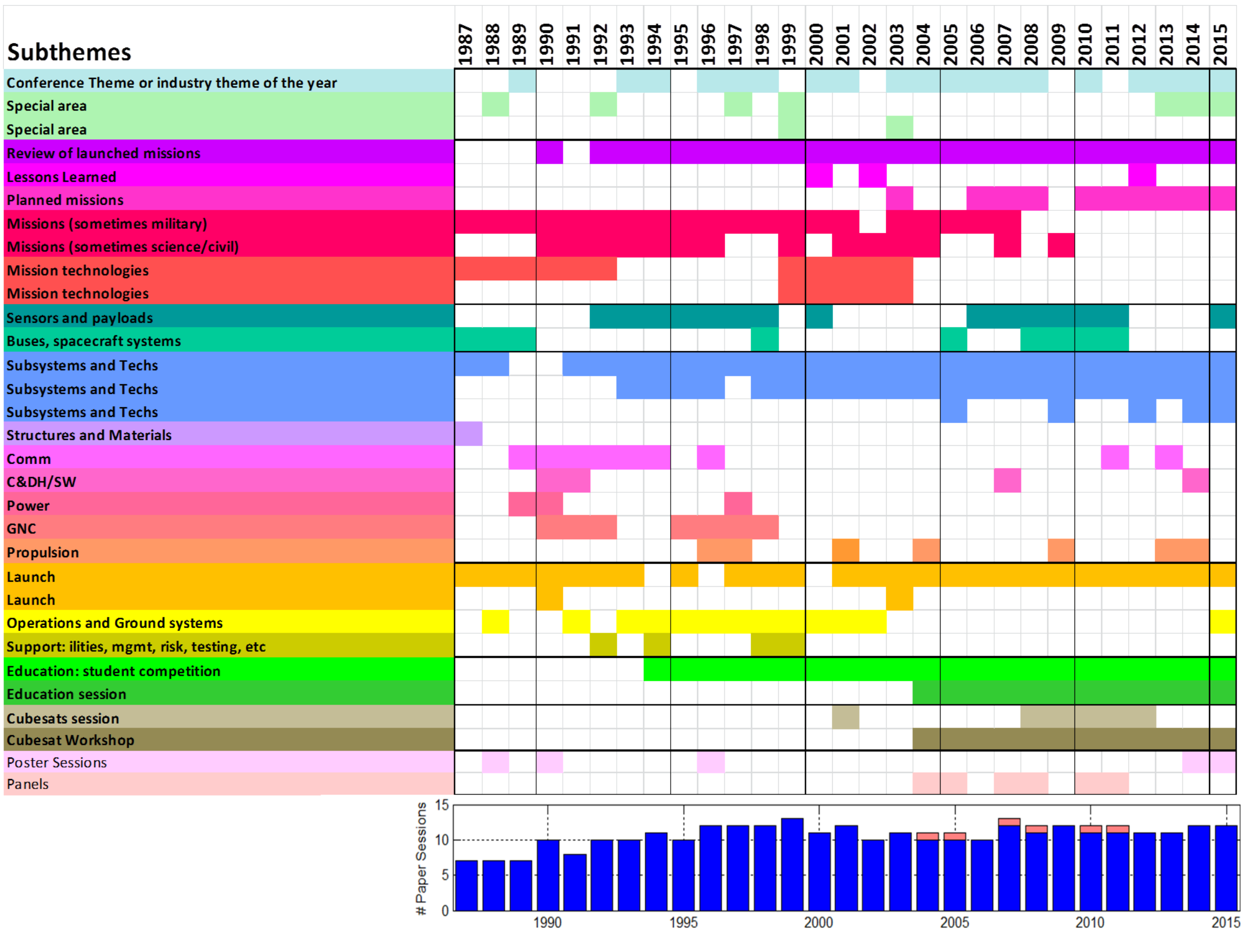

Figure 6: Evolution of the conference sessions: Sessions each year are categorized and color coded by topic area. Number of paper sessions per year tracked on bottom bar graph in blue, with panel sessions in pink.

The initial years of the conference see more flux in session types, but as the conference grows and settles to its typically 11 or 12 session duration by 1996. We can examine the evolution by considering first the changes in each major category, then by looking at trades between the categories during the last 30 years.

- Thematic: Typically 1 to 2 sessions are allocated to the annual theme of the conference and/or special topic areas such as international programs, specific mission areas

- Missions: Includes a consistent review of missions launched during the year. For a long time there were typically several sessions dedicated to military and scientific missions concepts, mission enabling technologies, and planned missions, but that tapered in the mid-2000's to two regular tracks on launched missions and missions to be launched soon.

- Sensors, Payloads, Busses: Dedicated sessions for these have come in about 6-7 year waves

- Subsystem Technologies: By 1990 the conference was attempting to group technology sessions by subsystem, which resulted in year to year changes depending on the batch of accepted papers, and shoehorning mismatched papers into sessions. In 1999 organizers began the practice just having "Advanced Technologies" sessions, generally grouping similar topics and creating specific subsystem sessions when there are sufficient papers to warrant them.

- Launch and Operations: Launch opportunities have and remain an enduring focus area for the smallsat community. Sessions dedicated to operations and ground systems, as well as programmatics and AI&T, faded around 2003, with those topics dispersed among the other sessions

- Education: The student competition has been a mainstay of the conference since 1994, and separate session dedicated to discussion of educational and workforce development programs was added on 2004.

- Cubesats: The first conference session dedicated to cubesats was in 2001. The pre-conference cubesat workshop began 2004, was extended to 2 days in 2007, and papers were included in the proceedings starting in 2013. Cubesat sessions in the main were included 2008 – 2012.

Stepping back from the details of sessions, there are industry patterns discernable within the context of conference pressures. From the latter we see the decision to add the education track and give up a dedicated operations and ground systems track, and the decision to focus the mission sessions into a regular past and future approach. But within that context we see cycles of technical maturity. Through 1991 there is an initial focus on desired missions and on bus concepts and technologies on the table. Through 1998 we see a focus on payloads and sensors that could be supported by smallsats and leveraged against those missions. Through 2005 we see a huge emphasis on mission applications, especially constellations and formation not addressable with traditional approaches, followed by another cycle of sensor and payload then bus development spawned from the attempt to address them.

STATISTICS

Conference Evolution

A fundamental measure of the conference's evolving role and the significance of smallsats to the industry is the annual conference attendance.

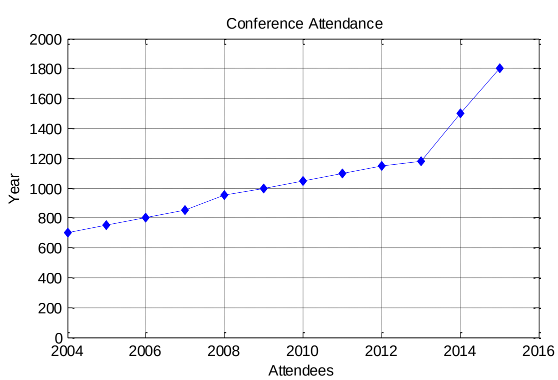

Figure 7: Smallsat Conference Attendence

In the figure we can clearly see the steady growth of interest from 2004 to 2013, attributable to the increasing utility of small platforms, and the proliferation of cubesat programs and associated sub-industry. 2013 attendance was tempered by US government budget sequestration impacting travel budgets, but followed by a dramatic increase driven by government seeking low cost mission solutions and the growing new space movement fueled by an influx of venture capital and other investments.

Authors

<u>Number of Papers</u>

Who authors SmallSat Conference papers? Out of 2194 papers with 8241 total author credits, there are 5908 unique authors. In the histogram below it is clear that, although there are almost 5000 authors who have authored only a single paper, the number drops dramatically as the number of papers increases, with only 25 contributing 9 or more papers.

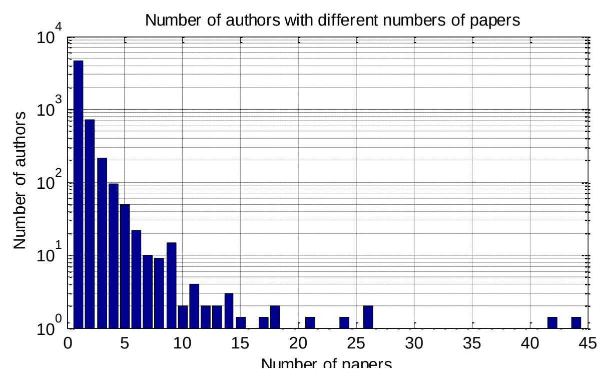

Figure 8: # authors binned by # of credited papers

The most author credits are held by Sir Martin Sweeting of Surrey Satellite Technology Ltd., with an astounding 44 papers spanning from the first 1987 conference. He is followed closely by Dr. Robert Zee of University of Toronto Institute for Aerospace Studies, with an equally remarkable stream of 42. A more detailed "heat map" visualization below (cut off at 10 or more papers) reveals the texture of author contributions: when they entered the conference and when they were most active.

Papers	Author	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
44	Sweeting, Martin	1	1						1			1		4	4	2	6	6	2	2	3	6					2	2	1	
42	Zee, Robert												1			1		3	3	3	2	4	3	4	3	5	2	4	1	3
26	Kitts, Christopher								2	1	1		1	2	3		1	1		2	1	3	3	2	1	2				
26	da Silva Curiel, Alex											1		2	3	1	2	3	3	3	3	1	1			1	1	1		
24	Twiggs, Robert			1					1	1	2		1	3	3	3	2	1	1			2			2	1				
21	Ward, Jeff		2		1	3				1	1	2	3	2	4				1	1										
18	Underwood, Craig				1	1						1	1	1	2	2	1		1	1			2	1				3		
18	Cutler, James														2				1		1		1		1	3	1	4	1	3
17	Swenson, Charles						1							1		1	3				1				1	2	2	1	2	2
15	Swartwout, Michael									1	1				1	1	1	1	1	1	1	2		1		1	1	1		
14	Klumpar, David															1	1	1		1			1		2	1	2	1		3
14	Sinclair, Doug																	2			1	2		1	1	1	2	2	1	1
14	Agasid, Elwood																			1	1	1	1	2	1	2		2	2	1
13	Fish, Chad																1								1	2	3	2	2	2
13	Young, Quinn																		1	2	2	1	4					1	2	
12	Palmer, Phil													1	3	2	2		1		1			1		1				
12	Bonin, Grant																							1	1	1	2	4		3
11	Puig-Suari, Jordi														1	1		1	1		1	1		1		2		1	1	
11	Lightsey, Glenn																	1		1		1	2		1	1	2	1	1	
11	Ricco, Antonio																			1	1	2	1	1	1	1			2	1
11	Clark, Craig																				1	1	1	1	2	1	1	1		2
10	Buckley, Steven												1		1		2	2	1	1		1						1		
10	Palo, Scott																				3			1	1			2	1	2

Figure 9: Authors with 10 or more papers, ordered by total number of papers then first contribution year

Organizational Involvement

Although individual author activity is interesting, more insight into industry trends is gained by examining organizational involvement as seen through credits in SmallSat Conference papers. Out of 8241 total author credits, 8192 have associated organizations. Although there are1708 unique org names from that list, many of them are multiple ways of referring to the same organization. By applying rules to consolidate an organization's synonyms to a single name, that list is reduced to 961. Although an organization, through multiple authors, might receive multiple paper credits for the same paper, we can process the data to determine the number of *unique* papers each organization was associated with each year.

Number of Papers

Restricting the visualization to just the 28 organizations with 20 or more unique papers, a similar heat map approach reveals a variety of organization types and textures of involvement. Presented in isolation here, this information was used to develop hypotheses and support conclusions presented in the industry analysis section of this paper.

Papers	Organization	Type	Sub	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
100	Utah State University	EDU	US	2	2	2	1	1	4	1	2	1	1	2	1	3	3	4	5	1	5	1	5	4	8	6	7	4	6	3	8	7
91	Air Force Research Laboratory	MIL	AF							4	4	2	2	3	1	7	4	5	7	5	4	3	4	8	7	2	10	5	1	1	1	1
81	University of Surrey	EDU	Europe	1	2		2					1	1	2	3	10	12	11	5	4	6	2	3	2	2	2	1	2		5	1	1
76	NASA Goddard	CIV	NASA	4		1	1		1	2	1	7	3	2	10	6	5		1	2	4	2	2	2		3	1	3	1	2	4	6
65	JHU APL	FFRDC	CIV	3	2	1	3	1	5	1	3	3	7	4	3	5	1	3	1	3	1	1	1	3	1			1	1	4	1	2
62	Surrey Satellite	COM	EDU		2			3		1		1	2	3	1	1	3	3	4	4	3	4	4	6	3	4	1	2	3	3	1	
60	Aerospace Corporation	FFRDC	MIL			1	2		2		1	2	3	1		5	2	1	1	3	2	1	1	2	3	2	1	2	3	5	3	11
59	Stanford University	EDU	US		5			2			2	4	6	2	4	5	5	3	2	2	2	1	1	3	2				4	2		2
54	Orbital Sciences Corporation	COM	US		1	1	4	1		3		3	6	7	6	6	1	1		1	1	1		3	4	2			1		1	
53	Jet Propulsion Laboratory	FFRDC	CIV		1	1		1	1	1	15	6	2		2	4		1		1		1		2				1	1	6		6
50	NASA Ames	CIV	NASA	1				1				1	1	1								2	1	7	2	6	2	5	2	4	8	6
50	United States Air Force	MIL	AF	2	2	3	2			2	2	1	3	7		3		2	1	3	3		1	4			4		1	1	2	1
49	Space Dynamics Laboratory	COM	EDU						1	1		1		1			1	1	1		1	3	4	2	4	1	6	4	4	5	6	2
48	University of Colorado	EDU	US	2					1	1	2	4	4	2	3	5			1	1		2	3	1	1	2	3	2	1	3	2	2
46	UTIAS	COM	EDU												1			2	1	3	3	4	2	4	3	3	3	5	4	4	1	3
44	AeroAstro, LLC	COM	US				1		2	2					1	1	4	6	9	7	3	3	2	1	1		1					
40	Naval Research Laboratory	MIL	NAVY		1	1		1		1	9	1		1		1		2		1	1	1		1	4	1		3	3	2		5
35	MIT	EDU	US				1		2		1		3	2				2	1	1		1	1	1	1			1	4	5	4	4
34	University of Toronto	EDU	Americas												1			1		3	4	4	2	3	2	2	3	3	2	2	1	1
30	Lockheed Martin	COM	US		2	1	3		1	1		2	1	2					3		1	1	4	1	1		1		2	1	1	1
29	University of Michigan	EDU	US					1										1	1					1			1	4	2	7	5	6
26	United States Air Force: Space Test Program	MIL	DOD				1		1				1			1		1		2	3	3	2	1			3	2		1	2	2
24	Naval Postgraduate School	MIL	NAVY	1	4	2	2	1								1		1	2	2				3	1	2					1	1
23	Los Alamos National Laboratory	CIV	DOE					1	1	2	3	1		6	1						1					2						5
22	Santa Clara University	EDU	US												1	3	2		1	1		2	1	4	2	2	1	2				
21	European Space Agency	CIV	Europe		1												1	2	2			2	2	2	1	2		1		2	1	2
19	NASA	CIV	NASA			1	1					3	2	3					1				1	1						1	4	1
19	Microcosm	COM	US					2				1	4	2		3		2	1	1				1		1			1			
18	Washington University, St. Louis	EDU	US														1	2	2	2	1	1	3	4	2							
18	California Polytechnic State University	EDU	US														1	1	1	1	1		1	1		1		2	1	5		2

Figure 10: Organizations with > 17 papers, ordered by total number of papers then first contribution year

Consistent across the history of the conference is the level of involvement from the host organization, Utah State University (which, from dual affiliation and collaboration, overlaps on many papers credited also to Space Dynamics Laboratory). Other organizations show pronounced peaks of activity: University of Surrey in 1999-2001, with a subsequent rise in Surrey Satellite Technology Ltd. Publications 2002-2007, NASA Goddard with a peak in 1998, JPL with a peak in 1994 but little involvement until recent interplanetary cubesat activity, AeroAstro in 2002-2003, NRL in 1994, etc.

Notable is the *variety* of organizations. Through both design by the conference organizers and level of interest of organizations, the conference is not dominated by one sector of the industry. The list of most prolific organizations includes military, civil, educational, and commercial entities, and spans both US and non-US entities.

Three decades of mergers and acquisitions within the industry complicate the analysis. For instance, when Orbital ATK is credited with all constituent organizations recorded distinctly in the data (Orbital Sciences Corporation, Fairchild, Spectrum Astro, ATK, Swales, Defense Systems Inc., CTA, Thiokol, Programmed Composites, and Composite Optics) they in fact exceed USU with 125 papers.

More evident in the less prolific organizations are several patterns of involvement. A few have been involved since the beginning at an occasional level of participation (e.g. Boeing, Swedish Space Corporation). Others formed or became engaged more recently and have been consistently represented since then (e.g. Ryerson U., Morehead State, Astra LLC). Some had a concentrated period of involvement before stopping (e.g. Globesat, Inc.) or being acquired. Others have been episodic, as internal support for smallsat activity has waxed and waned with research priorities, professors' labs or programs, etc. For example, the early Naval Postgraduate School contributions are dominated by the PANSAT project, but they reemerge in 2007 with a new range of projects, whereas the Washington University, St. Louis contributions end abruptly as the professor relocated his program to St. Louis University and continued contributions from there.

Involvement by Industry Sectors

To truly observe the evolution of the conference, it is illustrative to examine not just individual organizations, but the involvement of the different sectors. To this end we categorized all 961 uniquely named organizations broadly into Government, Commercial, and Academic entities with additional sub-categorization.

- Military (MIL), subcategorized as US Air Force (AF), US Navy (NAVY), US Army (ARMY), US Department of Defense (DOD), other US military or intelligence community (Other), and European military (Europe)
- Civilian Government (CIV), subcategorized as NASA, US Department of Energy (DOE), Other US government (Other), and civilian agencies from the rest of the world.
- Federally Funded Research and Development Centers (FFRDC), subcategorized as being primarily for civilian (CIV) or military (MIL) work. This sub-categorization is inadequate for organizations like the Johns Hopkins University Applied Physics Labs, which were assigned to CIV but participate in both, so we will not draw conclusions from this distinction.
- Commercial (COM), subcategorized by US or other world regions
- Academic Institutions (EDU), subcategorized by US or other world regions

Note that this analysis focuses on degree of participation. In the statistics development a paper with authors from two different US companies, two distinct NASA centers, and a European university would be counted as 2 COM-US credits, 2 CIV-NASA credits, and 1 COM-Europe credit.

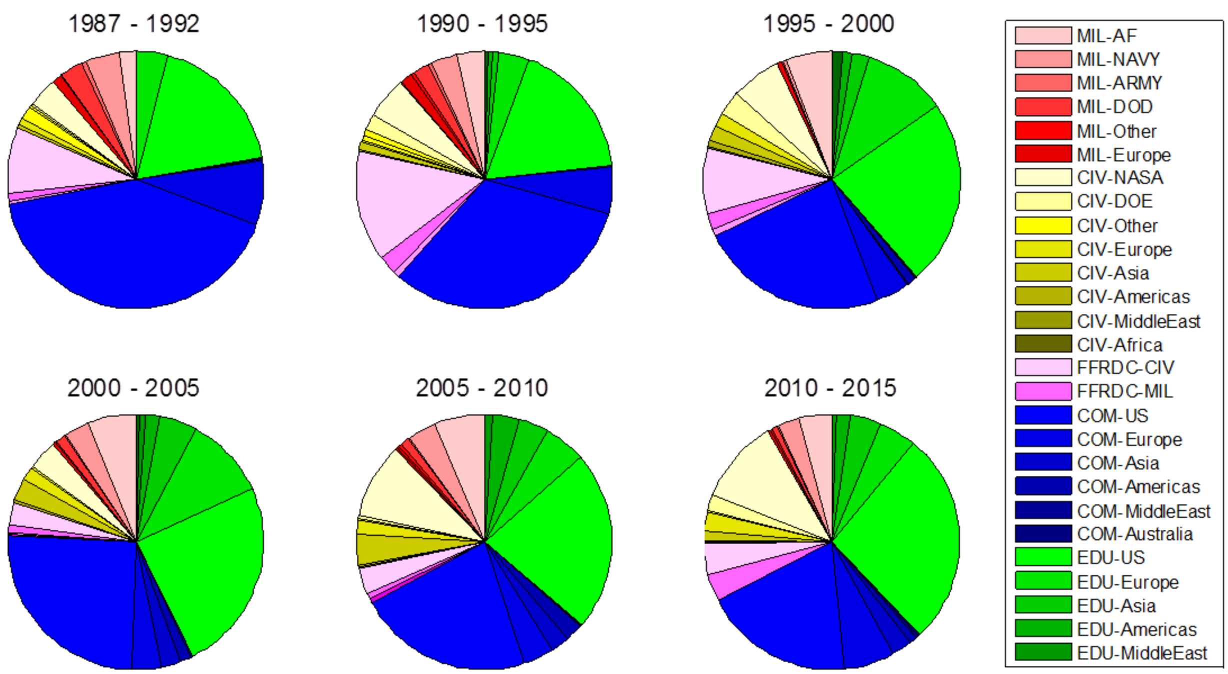

Figure 11: Paper credits by organization category, showing evolution and current balance between government, civil, and commercial sectors, as well as increase in international participation

Figure 11 illustrates the number of papers with an authorship credit from each type of organization aggregated over 5 year intervals. The progression shows a play between the different sectors as the conference grew and the industry ecosystem developed (perhaps also mediated by organizer intent), that has led to nearly balanced representation of government, commercial, and academic paper contributions.

This was not the case in the first 5 years of the conference, where commercial entities represented half of the paper contributions and academia was the least represented. The early 90's saw a rise in FFRDC participation, then a surge in academic participation in the late 90's which continued through the early 2000's with a subsidence of FFRDC participation. From 2005 to 2015 we see the resurgence of NASA described earlier in this paper, and a return of FFRDC participation as well. Surprisingly, the US AF we not initially well represented, but the entry of the Air Force Research Labs in 1993, among other things, increased the role to what we're familiar with today.

Throughout this process, we see a steadily increasing international diversification in each sector. Whereas the first 5 years are almost exclusively US and European, in the early 90's we see international academic participation from Asia, the rest of the Americas, and others regions increasing gradually over time, followed by commercial participation as well. Within the academic sector we do see a pushback, with US schools proportionally increasing again from 2005 on. This can be attributed to the explosive growth of Cubesats described earlier in this paper, sparking the creation of many new programs across US schools.

Collaboration

Number of Authors

Another interesting statistic to observe is the steady increase in the average number of authors per paper during the conference history. When the conference started the average number of authors per paper was just above 1, by 2015 the average number of authors had grown linearly to just below 5. Figure 12 provides statistical insight into the changes driving that, and illustrates the difference between the character of the first 5 years versus the last 5 years.

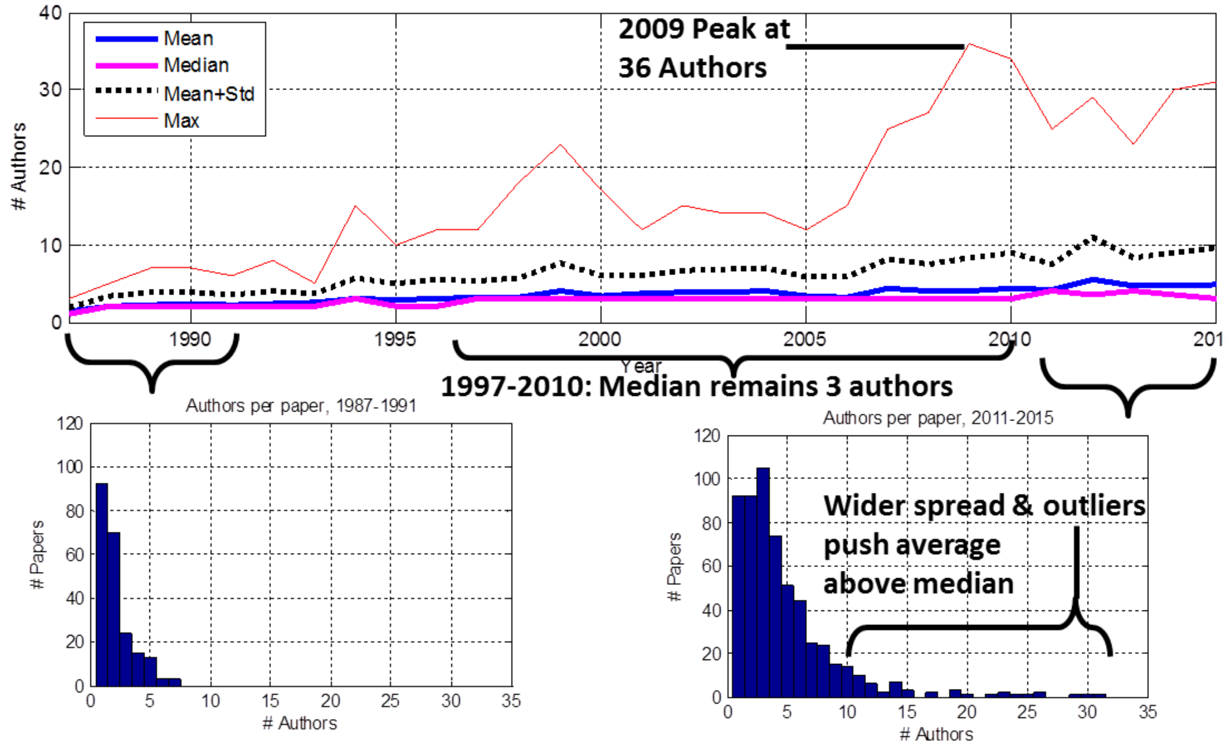

Figure 12: Change in number of authors per paper over conference history, calling out comparison of statistics for first five to last five years

As shown, the median number began at 1, soon increased to 2, then held steady at 3 for the majority of the conference, today hovering between 3 and 4. However, the spread in number of authors has continued to increase, and the appearance of extreme outliers in the past 10 years has consistently dragged the average number up.

We can hypothesize multiple factors influencing this. One is the change in character of the early years of the conference, when smallsats were considered a fringe concept and often ridiculed, toward increasing legitimacy now recognized as an established part of the greater industry. The initial participants were often mavericks within their organizations. As smallsats matured and evolved, more funded opportunities for multi-author collaboration became available. And as the limited number of accepted papers made the conference more and more selective, the sorts of efforts qualifying for discussion tend towards requiring multiple author efforts.

Another factor is the trend over the last several decades toward increasing numbers of authors in scientific papers (most notably in the sometimes thousands of authors in physics papers). Where publication is currency, primarily in academia and research centers, the ethos has evolved to include as authors not just the individuals writing about the work, but the participants who contributed to make the work possible.

Indeed, the most authored paper in the conference, 2009's "Initial Flight Results from the PharmaSat Biological Microsatellite Mission"[10], with 14 from Santa Clara University, 22 from the NASA Ames Small Spacecraft Office, and 1 from University of Texas, fits this mold, as do the majority of each year's paper with the highest number of authors.

As the conference has grown, it continues to straddle these worlds, and to share with the community papers spanning from the results of larger and funded collaborations, to mavericks with important ideas.

CONCLUSIONS

The authors have attended the SmallSat Conference since their student days. This paper was inspired by the conversations we had during the years and as we watched trends come and go, topics mature, and exciting new technologies evolve. The smallsat community is relatively small, and very tightly knit; we personally know a majority of the most prolific authors. However, smallsat is more than a community, more than a conference, and more than a box of hardware massing less than 100 kg. Smallsat is a philosophy.

The philosophy of smallsat is small *programs*, maximizing efficiency and keeping unit costs low enough to afford the risk of first adoption of technologies and process improvements. Better performance than larger missions is a worthy goal (and sometime realizable through earlier adoption of new technology or architectures), but better *value*/$ by avoiding the cost overrun spirals that plague large programs is key to the equation.

Efforts to solve these hard problems often lead to new and innovative solutions. A thriving annual melting pot mixing the government, commercial, and academic sectors meets once a year in Utah where new schemes are hatched and ideas are shared.

Our analysis shows that while some slogans like "Faster, Better, Cheaper" or "Operationally Responsive Space" may fade in their effectiveness, their underlying ideals remain and continue to manifest themselves within the community. That's because these slogans are intimately related to the underlying technologies and philosophies espoused by the conference. The increase in collaboration across organizations, the mix of multiple sectors, and the evolving understanding of problems facing the industry show that the conference serves as a proxy for a community moving in a similar direction, collectively working out challenges and exploiting new ideas, and challenging all of us to a larger "small" future.

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We would also like to acknowledge the almost 6000 engineers, scientists, managers, administrators, policy makers, educators, and students who have actively contributed to this conference during the past 29 years. It is *your* dedication to the SmallSat Conference that has made it the success it is today.

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