60 Years of Analytic Excellence

Institute for Defense Analyses

Career Day Overview

Texas A&M University

July 25, 2016

Dr. Tye W. Botting
Operational Evaluation Division
Institute for Defense Analyses
(703) 845-2050
tbotting@ida.org

https://www.ida.org/

IDA Mission

IDA is a *non-profit corporation* that operates three federally funded research and development centers to provide *objective analyses of national security issues*, particularly those requiring scientific and technical expertise, and conduct related research on *other national challenges*.

IDA History

- Formed in 1956 at request of Secretary of Defense
  - —Systems Evaluations
  - —Technology assessments
  - —Cryptology
- Originally run by a consortium of universities (MIT, Columbia, Princeton, Pennsylvania, Michigan, Wisconsin, Stanford)
- Became an independent, non-profit corporation in 1968 with no change in mission
- Now operates three Federally Funded Research and Development Centers (FFRDCs)
- Approximately 1000+ full time people, 500+ adjuncts, 500+ consultants

Federally Funded Research and Development Centers (FFRDCs)

Special category of non-profit, private institutions with long-term, unique relationships with Government

- **10 FFRDCs sponsored by the Department of Defense (DoD):**

Studies & Analyses

- IDA / Systems & Analyses
- Center for Naval Analyses
- RAND / Arroyo Center, NDRI, Project Air Force

Laboratories

- IDA / Comm & Computing
- Lincoln Laboratory
- Software Engineering Institute

Systems Engineering & Integration

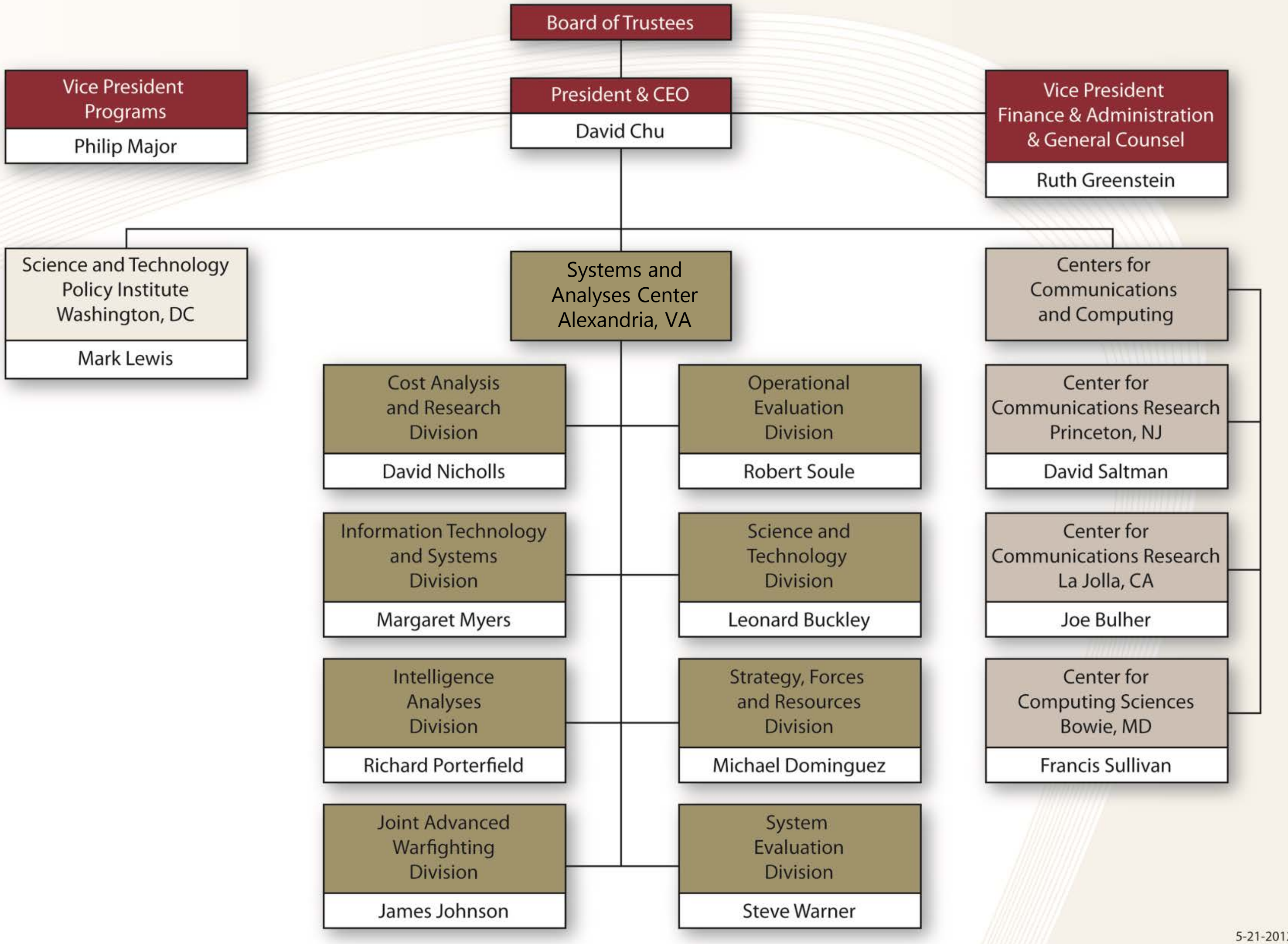
- Aerospace
- Mitre

- **29 FFRDCs sponsored by other Government organizations, including IDA / Science and Technology Policy Institute**
  - DOE (16), DHS (3), FAA (1), IRS (1), NASA (1), NIH (1), NSF (5), NRC (1)

What Does IDA Do?

- Assists the Federal Government with **scientific research and analysis, development and acquisition, and systems engineering and integration** – with focus on national security issues
- Addresses complex, long-term problems **objectively** and identifies creative and cost-effective approaches
- Helps decision makers select optimal courses of action in the face of complexity and uncertainty
- Provides second opinions and *<u>is no one’s advocate</u>*
- Is removed from the “tyranny of the in-box”
- Reaches out and has extensive access to academia, industry, and other subject matter experts
- Seeks to maximize contributions to Government decision-making, not profits or program size

IDA Organization



IDA | Science and Technology Policy Institute (STPI)

- IDA began running STPI in 2003
- **Primary sponsors**:
  - Office of Science and Technology Policy (OSTP)
  - National Science Foundation (NSF)
- Line-item in NSF budget supports OSTP – task-by-task funding from other sponsors
- Provide analyses of national science and technology issues of interest to OSTP and other agencies

Systems and Analyses Center (SAC)

- **Sponsors**:
  - Primary sponsor: Under Secretary of Defense (Acquisition, Technology and Logistics)
  - Sponsoring organizations: Office of the Secretary of Defense, Joint Staff, Combatant Commands, and Defense Agencies
  - Work for Military Departments with co-sponsor from above list
  - Work for other government agencies on issues consistent with IDA/SAC skills and expertise, subject to approval of primary sponsor
- **Research areas**: systems & capabilities evaluations, technology assessments, force & strategy assessments, resource & support analyses
- Research projects organized as a set of discrete tasks (~300 per year)
- Project funding originates in various program elements available to sponsoring organizations – *no line-item funding*
- Single, long-term contract with Department of Defense
- In some Divisions, researchers track classes of systems for years; in others, researchers work on a rotating profile of 2-3 tasks at any one time

IDA SAC Research Divisions

COST ANALYSIS AND RESEARCH DIVISION (CARD) - collects, analyzes, and estimates the full life-cycle costs of acquiring and operating forces, systems, and components

INTELLIGENCE ANALYSES DIVISION (IAD) - supports the Department of Defense and the Intelligence Community by providing analyses of critical intelligence issues affecting national security

INFORMATION TECHNOLOGY AND SYSTEMS DIVISON (ITSD) - analyzes the development, application, and management of computer & information technologies

JOINT ADVANCED WARFIGHTING DIVISION (JAWD) - serves as a catalyst for stimulating innovation and breakthrough improvements in joint military capabilities

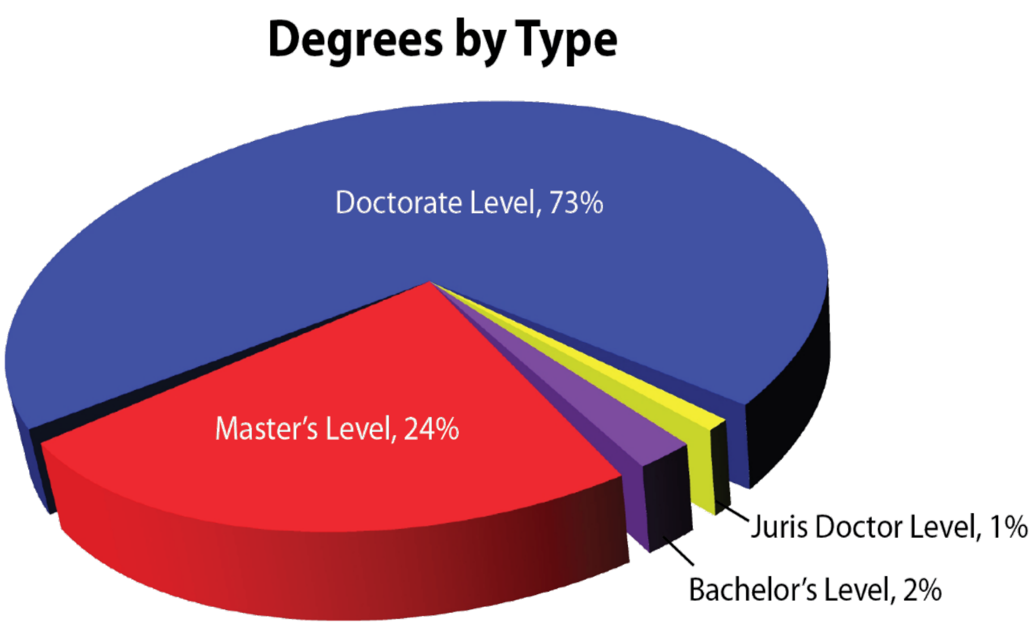
OPERATIONAL EVALUATION DIVISION (OED) - supports the Office of the Secretary of Defense in the planning, observation, and evaluation of Service operational tests of major new weapon systems and the Live Fire Tests of the lethality and vulnerability of weapons and platforms

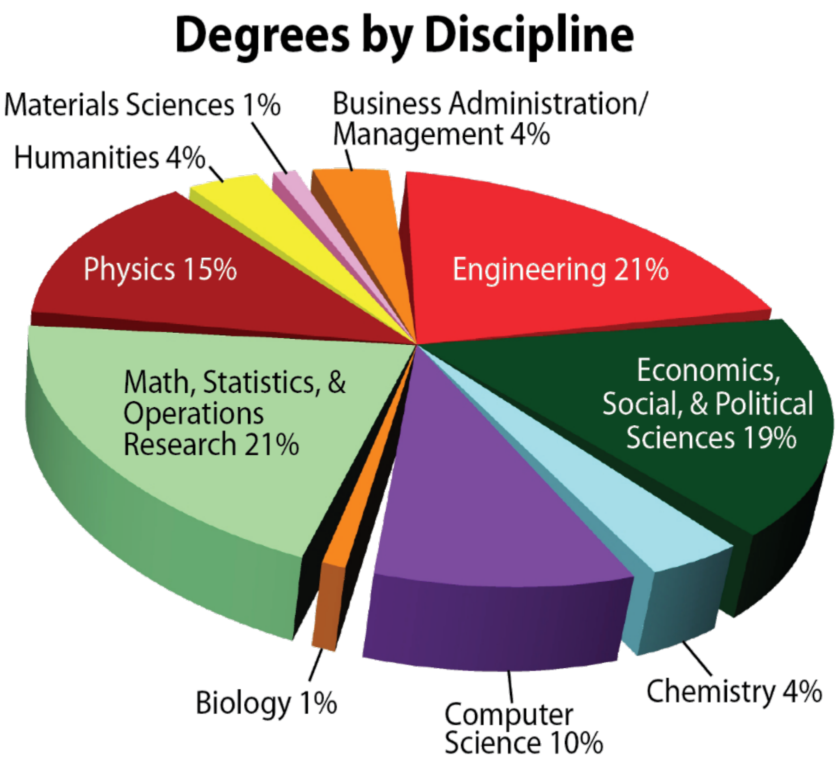
SCIENCE AND TECHNOLOGY DIVISION (STD) - investigates and models scientific phenomena and conducts technical characterizations and evaluations of devices and systems, the environments in which they operate, the targets they engage, and the missions they perform

STRATEGY, FORCES AND RESOURCES DIVISION (SFRD) - performs integrated, interdisciplinary studies of plans and policies related to national security strategy, the structure and capabilities of foreign forces, and the infrastructure supporting forces

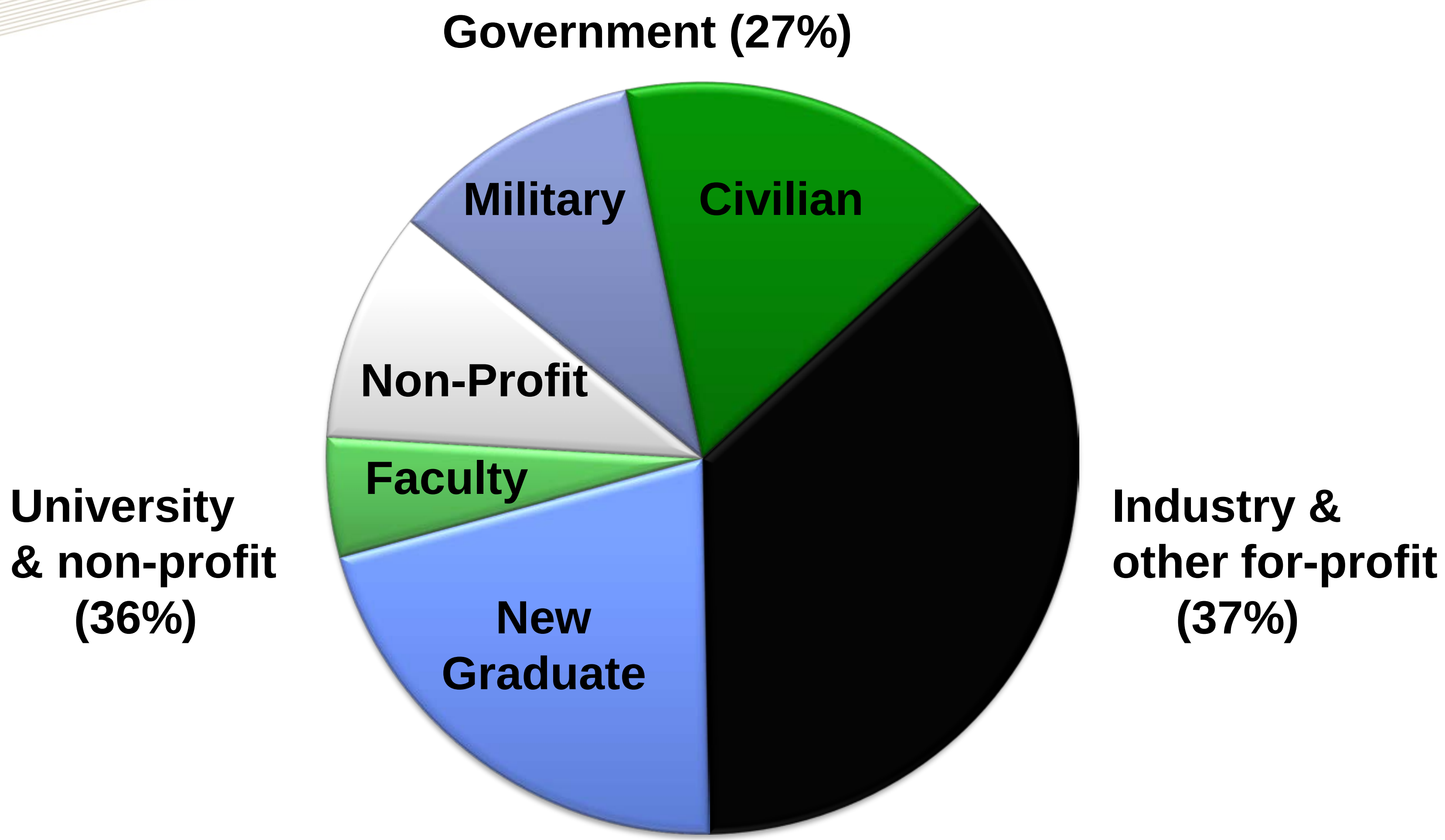
SYSTEM EVALUATION DIVISION (SED) - assesses military effectiveness, system performance, and joint and allied interoperability

Research Staff





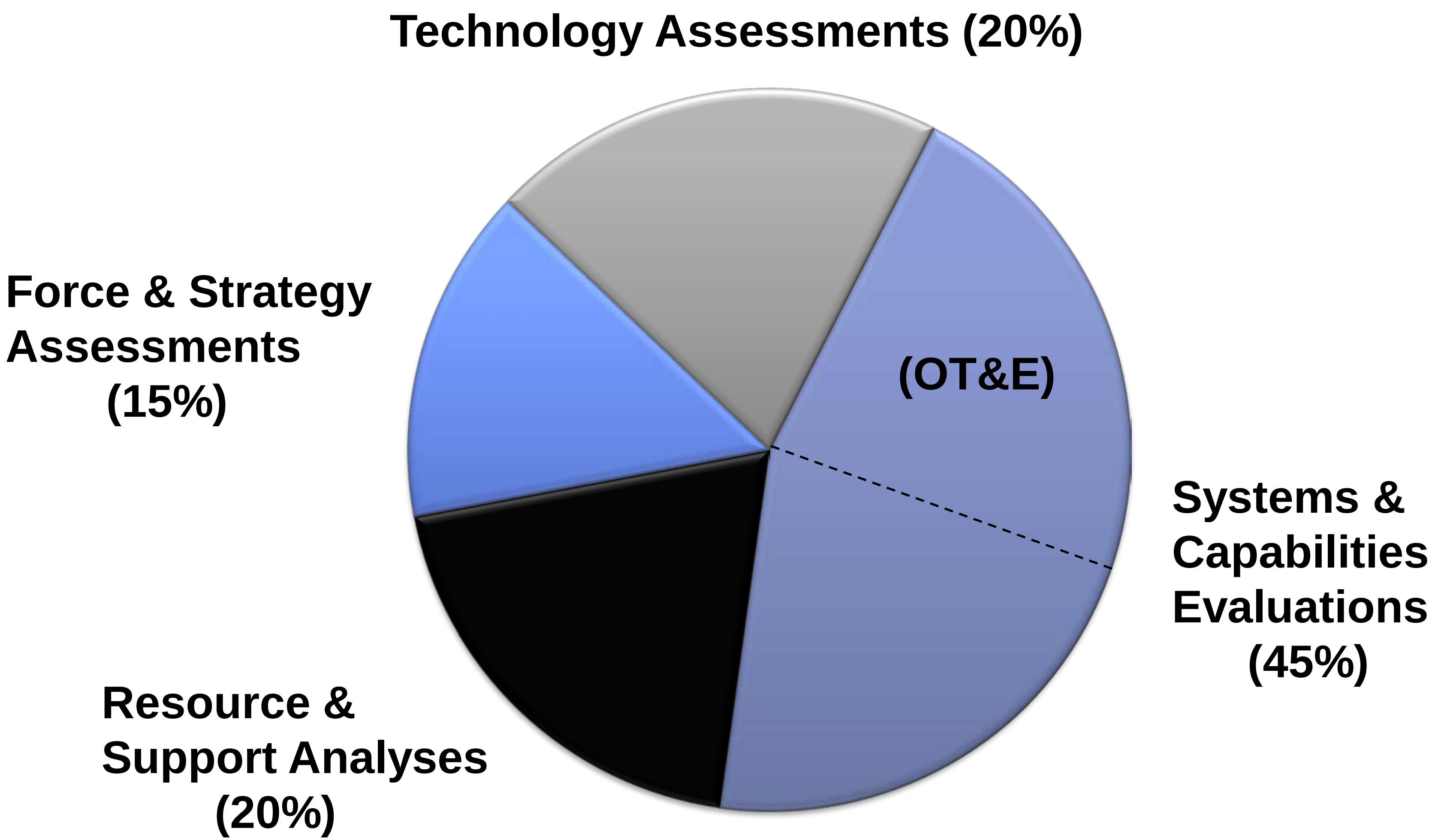
Research Staff – Prior Experience



IDA Systems and Analyses Center

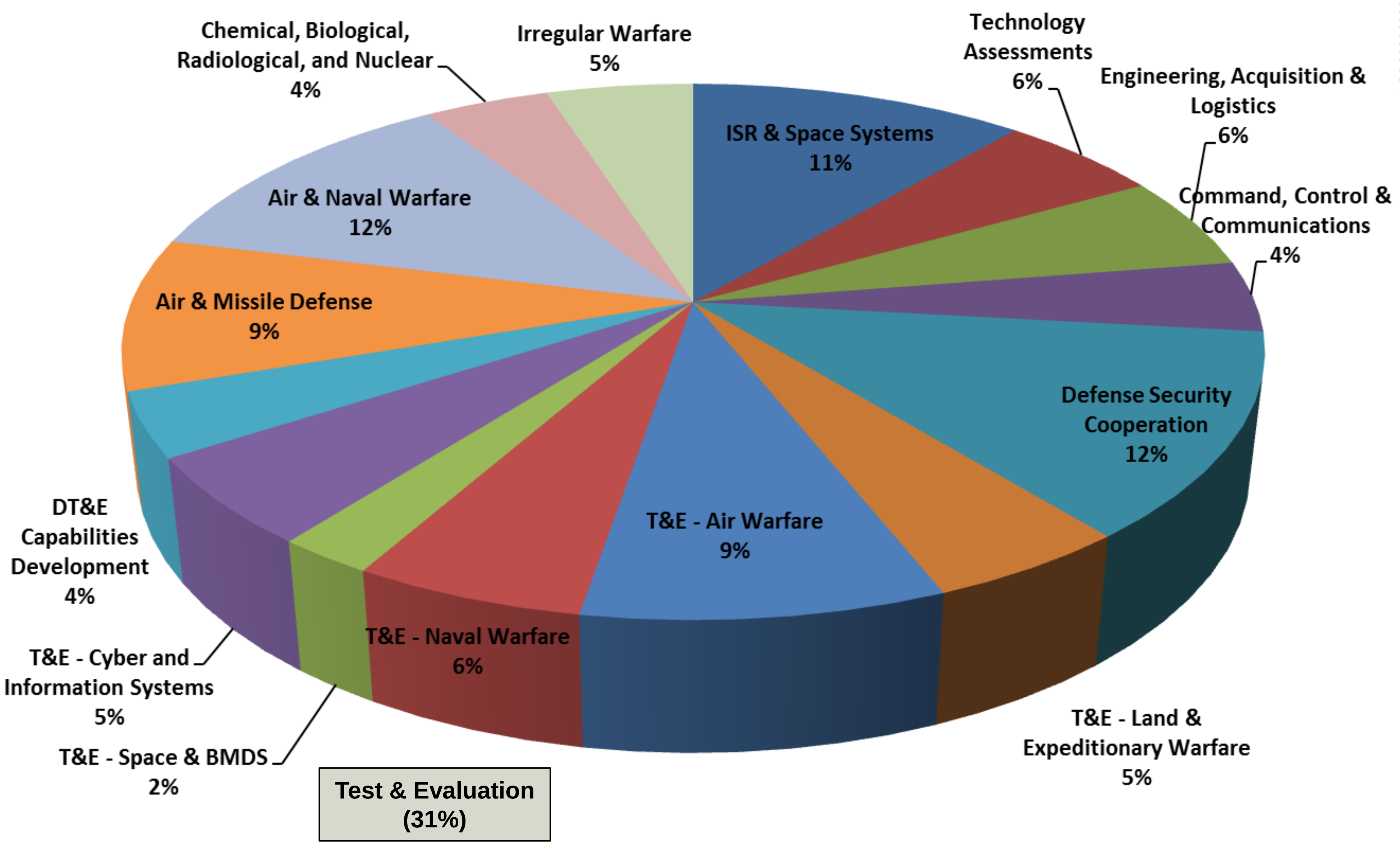
Core Research Areas

Systems and Analyses Center

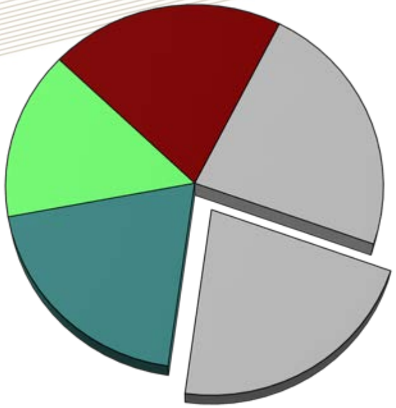


What Topic Areas Do We Study?

SED FY 2014 Study Topics



Systems Evaluations

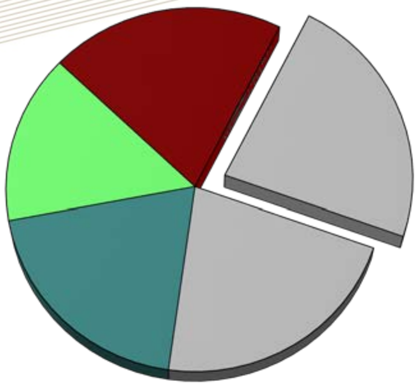


Capabilities / Competencies

- Strategic systems and missile defense
- Tactical systems – land, air, naval, mobility
- Counter-insurgency capabilities
- C3, ISR and space systems
- Information and computing systems; cyber security
- Test and evaluation – developmental, joint, facilities

- European Phased Adaptive Approach for ballistic missile defense
- Space-Based Interceptors (with Aerospace, APL, Draper, Lincoln, MITRE, Sandia)
- Ground Combat Vehicle analyses
- ISR architectures – joint airborne; overhead radar
- Ground tactical network assessments
- Cyber security for nuclear command and control
- Assessment of financial IT systems
- Developmental Test & Evaluation – technical assessments

Systems Evaluations Test & Evaluation



Capabilities / Competencies

- Operational test & evaluation
  - land & expeditionary warfare
  - air warfare
  - naval warfare
  - net-centric systems
  - ballistic missile defense
- Live fire test

Test planning
Test monitoring
Data analyses
Assessments of:
- effectiveness
- suitability
- survivability
- lethality

- Supported DOT&E analyses of more than 300 T&E oversight programs – 14 major operational and live fire T&E reports
- Analyses supported programs needed in combat theaters, including:
  - MRAP (2 versions), armored wheeled vehicles, Excalibur 155mm round
  - CV-22 special operations aircraft, AH-1Z attack helicopter
  - DON large aircraft IR countermeasures system, SOF radar warning
- Prepared early fielding reports on Littoral Combat Ship and Extended Range Multiple-Purpose UAV system to support accelerated deployments
- Supported live fire analyses of personal protective equipment and crew casualties

Working at IDA…

…is fascinating…

and here's the way in…

Ph.D. Required

- **Research Analyst**: Chemical and Biological Warfare (Operational Evaluation Division)
  - Requires Ph.D. in physics, chemistry, chemical engineering, or similar
- **Radar Analyst** (Science and Technology Division)
  - Requires Ph.D. in physical sciences or engineering

Other

- **Research Assistant/Associate** (Strategy, Forces, and Resources Division)
  - Requires B.S./M.S. in physical sciences, mathematics, or engineering

IDA is always looking for talented, energetic researchers with technical degrees who are good fits for our needs, so we encourage you to apply, regardless of the specific job postings.

https://chk.tbe.taleo.net/chk01/ats/careers/requisition.jsp?org=INSTITUTEDA&cws=1&rid=561

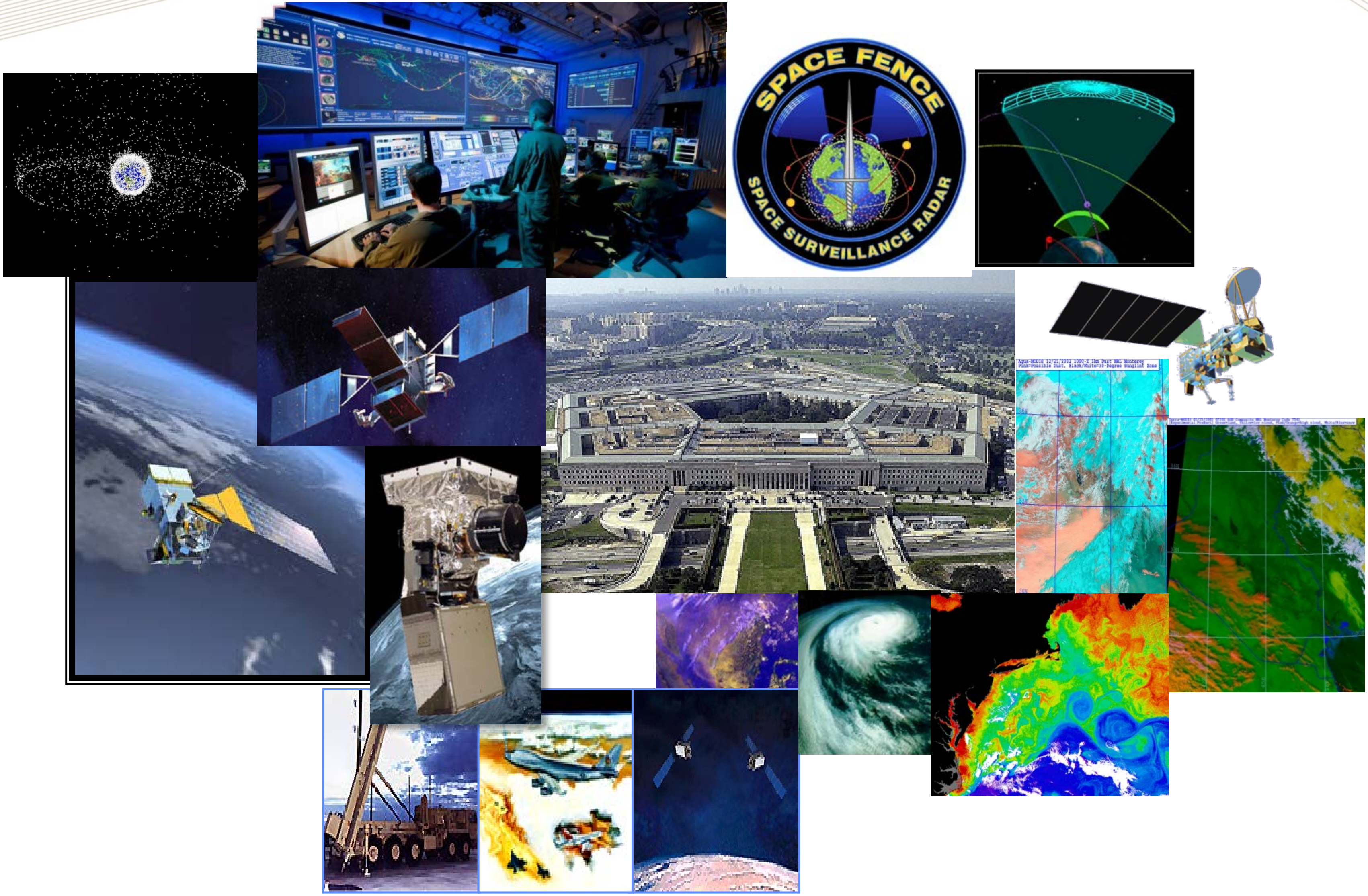
Some of My Projects at IDA

- Cybersecurity Operational Test and Evaluation for all DOD oversight programs
- Joint Space Operations Center (JSpOC) Mission System (JMS)
- Space-Based Space Surveillance (SBSS)
- National Polar-Orbiting Environmental Satellite System (NPOESS) and successors
- Space Fence
- Geosynchronous Space Situational Awareness Program (GSSAP)
- Space-Based Infrared System (SBIRS)

- Analyst Training
  - Cybersecurity Operational Test and Evaluation
  - Design of Experiments
  - Advanced Statistical Methods
  - Reliability
- Test and Evaluation Concepts
- Independent Program Assessments
- Cross-divisional Panels

In these studies, I have worked with members of most of IDA's other divisions.

Some of My Projects at IDA



IDA

My Career – So How Did I Get Here?

- – 1999: TAMU PhD work on timescales of fusion-fission reactions using GDR γ–ray and neutron clock methods (DOE)
- 1999 – 2003: Postdoc with TAMU Nuclear Engineering department working on microdosimetry research and running a 2MV Tandem Van de Graaff accelerator (DOE)
- 2004 – 2006: Joint Faculty Researcher at Northwestern State University of Louisiana and the National Center for Preservation Technology and Training, teaching chemistry and doing materials science in preservation (DOI)
- 2007 – Present: Researcher at the Institute for Defense Analyses supporting the Department of Defense (DOD)
  - 2007 – 2015 : Analytical lead supporting oversight of operational testing for space surveillance systems
  - 2015 – now : Analytical lead supporting oversight of operational cybersecurity testing for all DOD programs on oversight (~300)

Working at IDA

- I’ve been there 10 years
- It’s fun (most of the time)
- Reasonable facilities
  - —Great library
  - —Individual offices
  - —Access to multiple networks
  - —Small but usable gym and cafeteria
- Great colleagues, collegial atmosphere
- Interesting sponsors

Attributes of Successful Staff

- Insatiable curiosity
- Willingness to take intellectual risks
- Ability to apply knowledge and skills from one domain to other domains
- Willingness to give up laboratory work
- Strong communication skills
- Self reliant
- Contributes to peer-review and mentoring
- Intellectually demanding and HONEST

Why Consider an FFRDC like IDA?

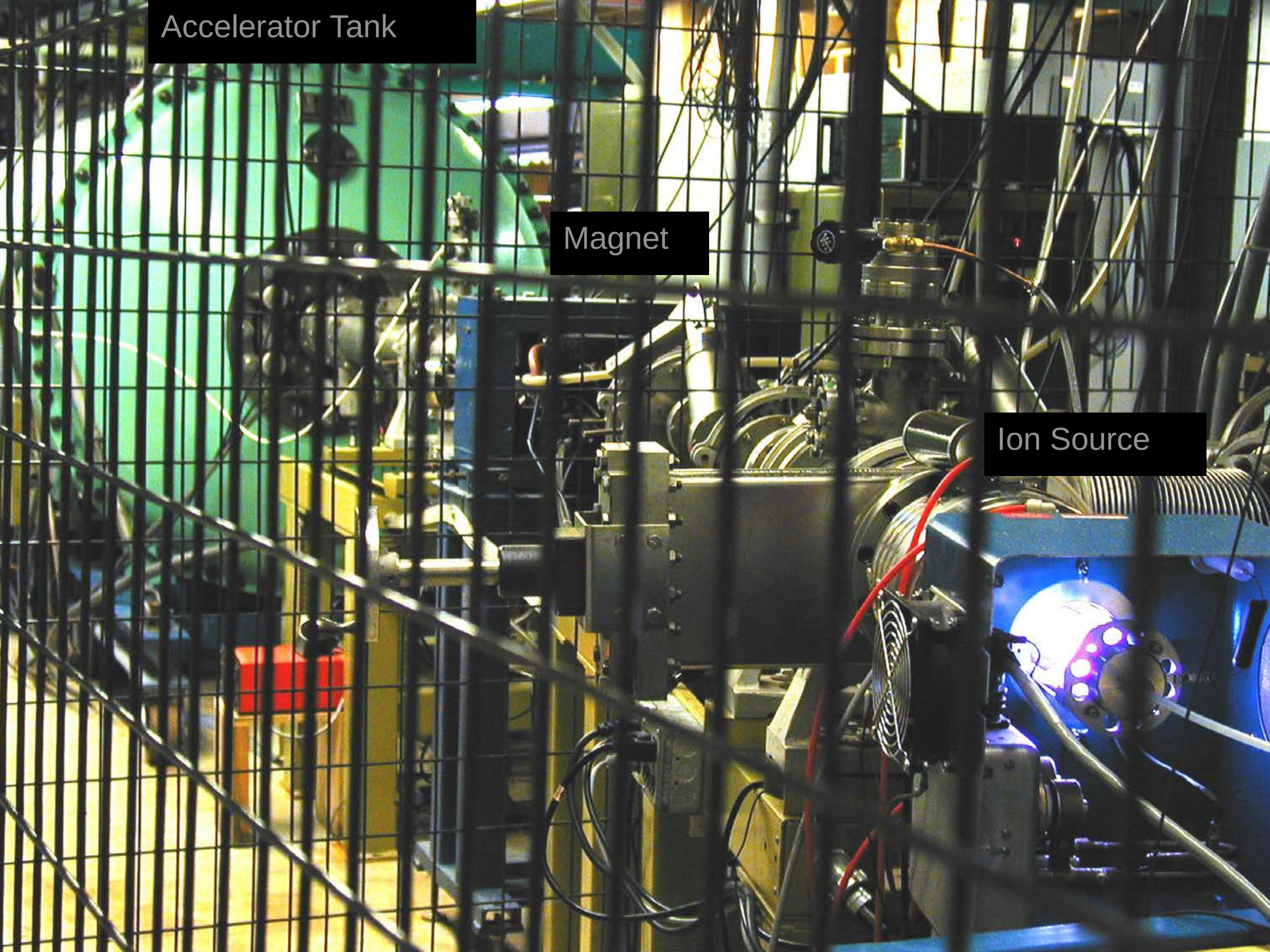
- Make a difference
- Interesting work and problem-solving
- Contribute to the larger good
- Participate in decisions that affect large numbers of people, dollars, organizations and persist for a long period of time
- Firmly funded – relatively secure
- Be part of history

Questions?

Backups

Accelerator Development

- Plasma ion source stability
- Beam development
- Software development
  - Accelerator control
  - Microbeam targeting
- Additions
  - Neutron “beam” production
  - Networking and Web presence


Accelerator Tank
Magnet
Ion Source

IDA

Pelletron Charging System

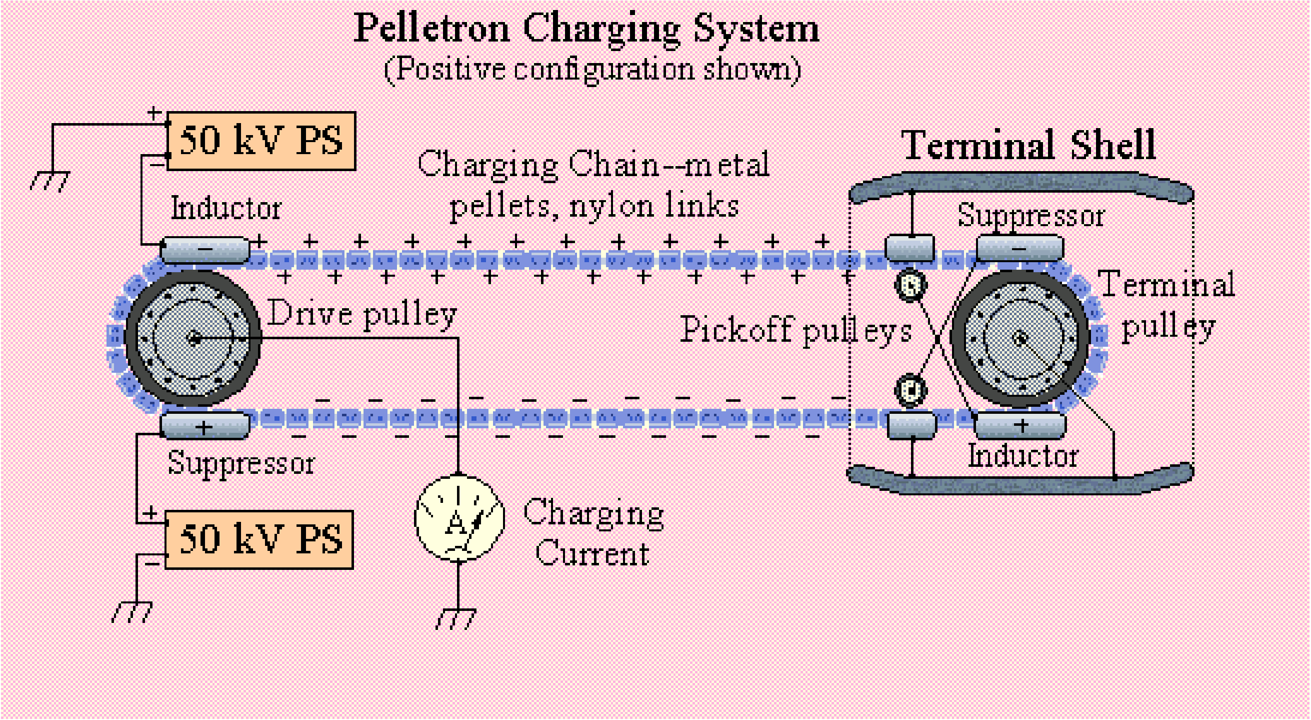
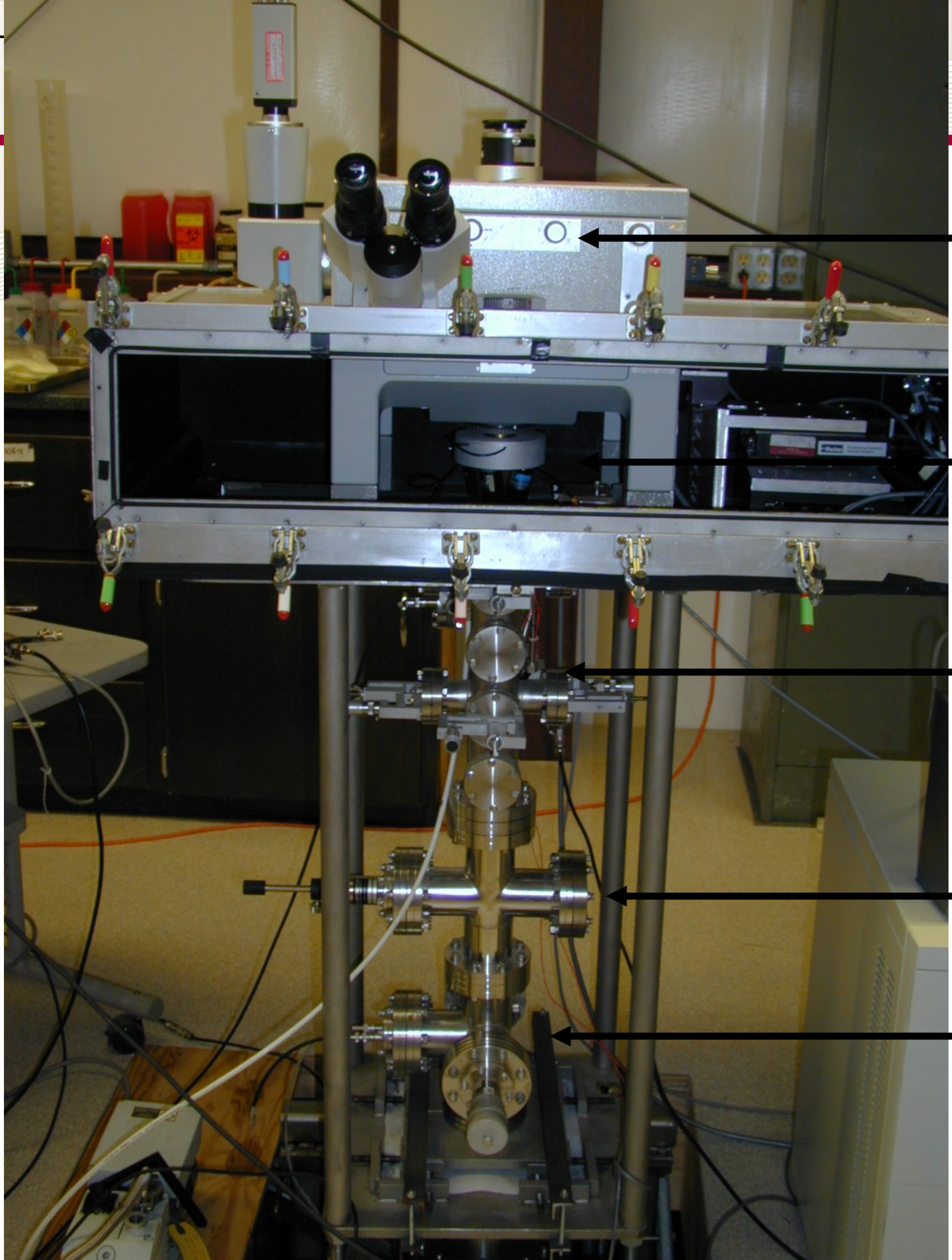


Illustration courtesy of...

National Electrostatics Corp. (*http://www.pelletron.com*)

Microbeam



Microscope Assembly
direct and camera

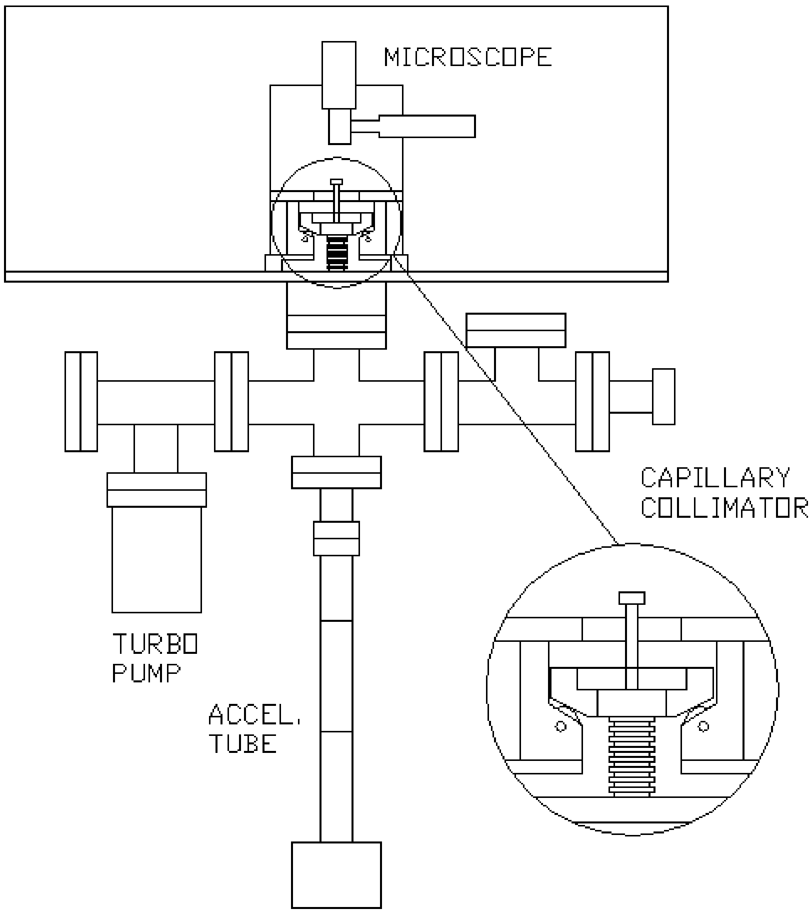
Detectors (3 photomultipliers)
special petri dishes go below

Fine collimators
2 sets of x and y axes

Beam Stop

Coarse collimators
1 set, only y axis

Electron Accelerator

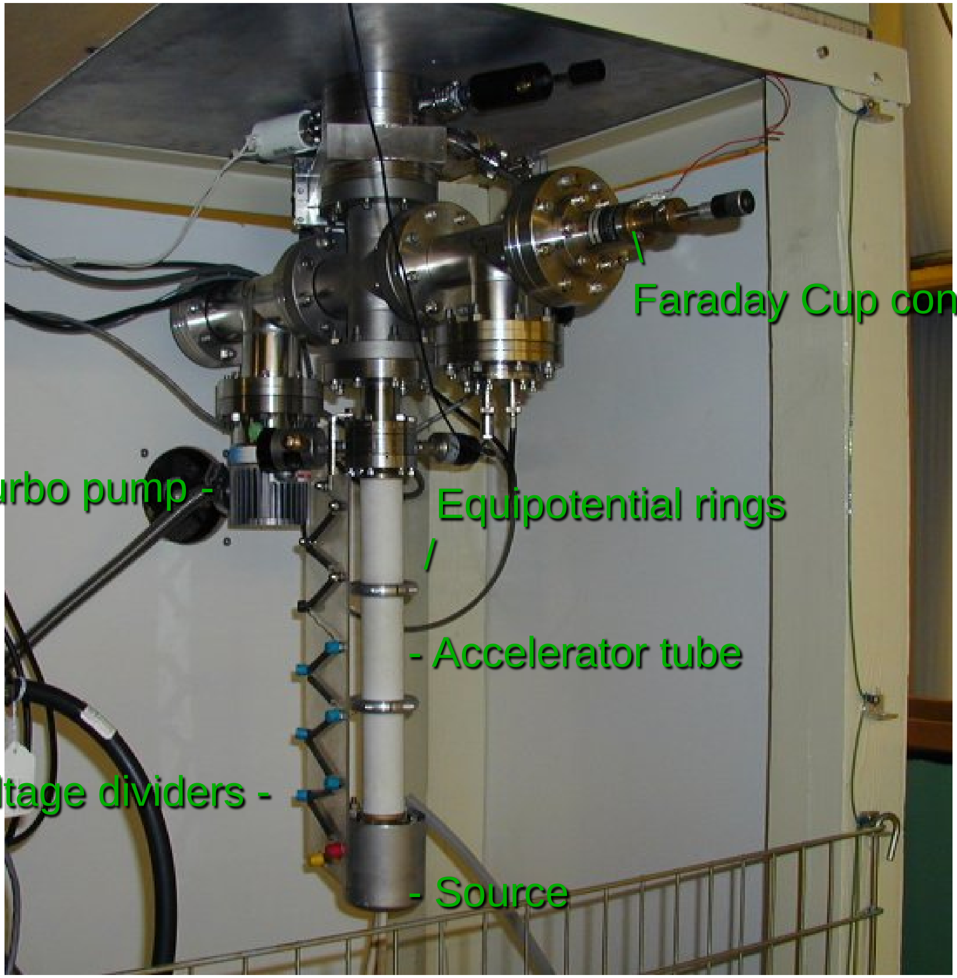


Only 4 feet high

Capillary collimator assembly

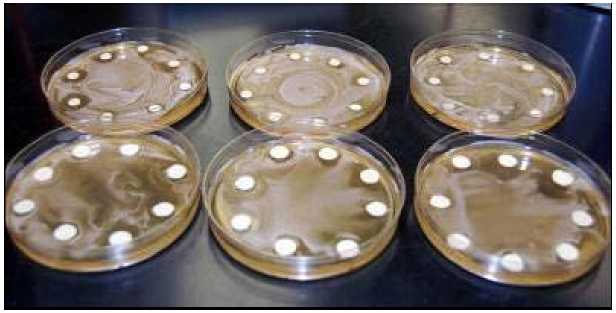
Accelerator tube uses up to 100,000 Volts to produce up to 100keV electrons

Source and Accelerator

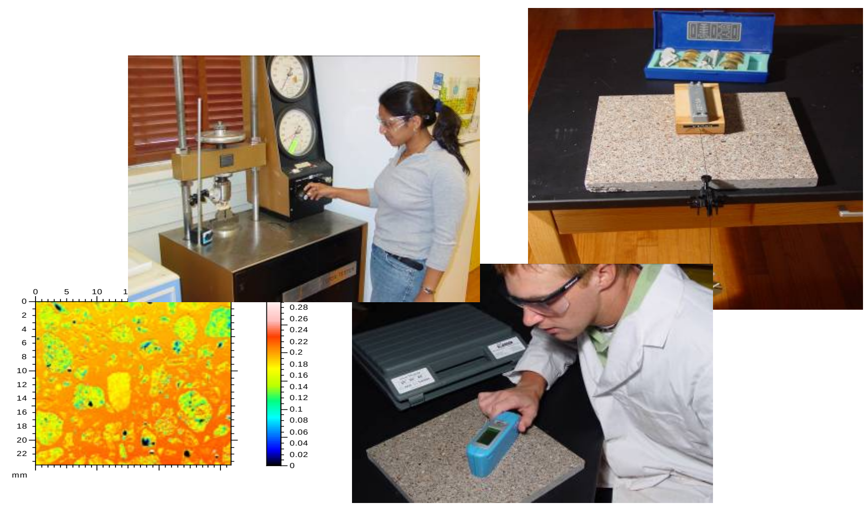


Pollution resistance of consolidated stone

Alkoxygermanes as possible stone consolidants or dopants to give biocidal properties



Vitrification as a valid treatment for historic terrazzo



JMS Mission, Benefits, and Capabilities

Warfighter Benefits

- Joint Space Operations Center (JSpOC) Mission System (JMS) to provide JFCC Space an integrated, net-centric Command & Control (C2) and Space Situational Awareness (SSA) capability to control space forces
- JMS answers 3 questions for US commanders:
  - How many and what types of objects are in space?
  - Do these objects pose a threat to our systems?
  - How do we respond to these threats so our critical space systems are safeguarded?

Mission

- JMS will upgrade the JSpOC with integrated command & control and space situational awareness capabilities

Mission Applications

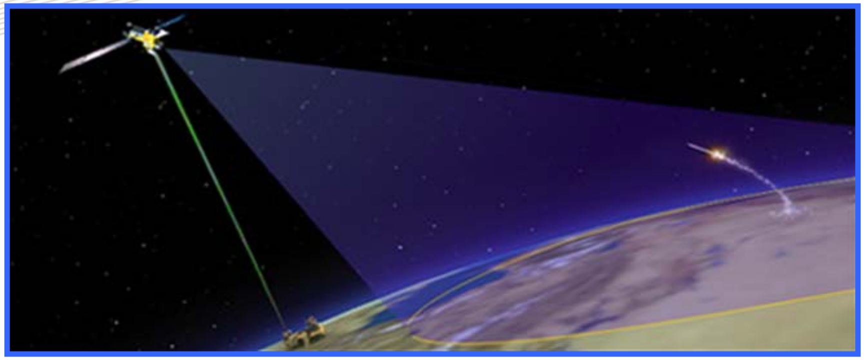
- Capability to effectively command & control assigned & attached space forces
- Ability to maintain and support database of space objects
- Ability to develop and share C2 and visualization tools
- Timely and synchronized space effects to support Unified Command Plan space operations responsibilities
- Threat identifications and notifications

System Capabilities

- Near-real-time High Accuracy Catalog (HAC) of space objects
- User-Defined Operational Picture (UDOP) with Space Situational Awareness (SSA) Web Services providing safety of flight, collision avoidance, maneuver detection, launch processing, space order of battle, intelligence, space C2, and environmental effects
- Net-centric, service-oriented architecture (SOA) infrastructure interfacing with Air Operations Centers
- Common enterprise services: collaboration, workflow management, security, discovery, orchestration, visualization
- Commercial off-the-shelf hardware

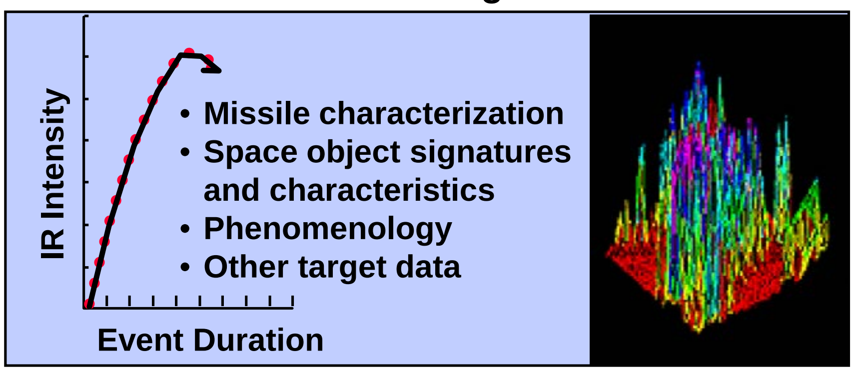
SBIRS Missions

Missile Warning

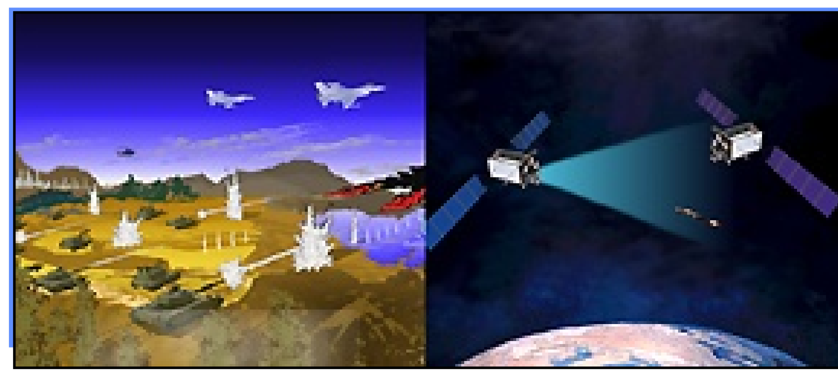


Missile Defense (Boost phase cueing)

Technical Intelligence



Battlespace Characterization



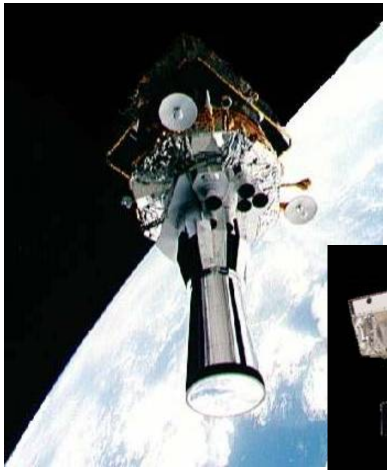
Key Performance Parameters (KPP)

Interoperability: Satisfy 100% interface requirements
Coverage: Region of earth covered and refresh rates
Focus Areas: Size and number of regions requiring higher resolution or faster revisit
Probability of Warning against threat missiles

Probability of Collection for technical intelligence data
Minimum Threat: Most challenging target
Data Availability: Direct data to theater
Report Time: Thresholds for initial and updated reports

SBIRS Space Segment

- Defense Support Program (DSP)
  - — Legacy satellites
  - — Spin stabilized IR detector
- Highly Elliptical Orbit (HEO) payload
  - — 2-axis reactionless gimbal
  - — Bar scanner IR detector
  - — Provides enhanced northern hemisphere coverage
- Geosynchronous Earth Orbit (GEO) satellites
  - — 3-axis stabilized
  - — Two IR detectors:
    - – Bar scanner
    - – Step-starer
  - — Transmits data via numerous links



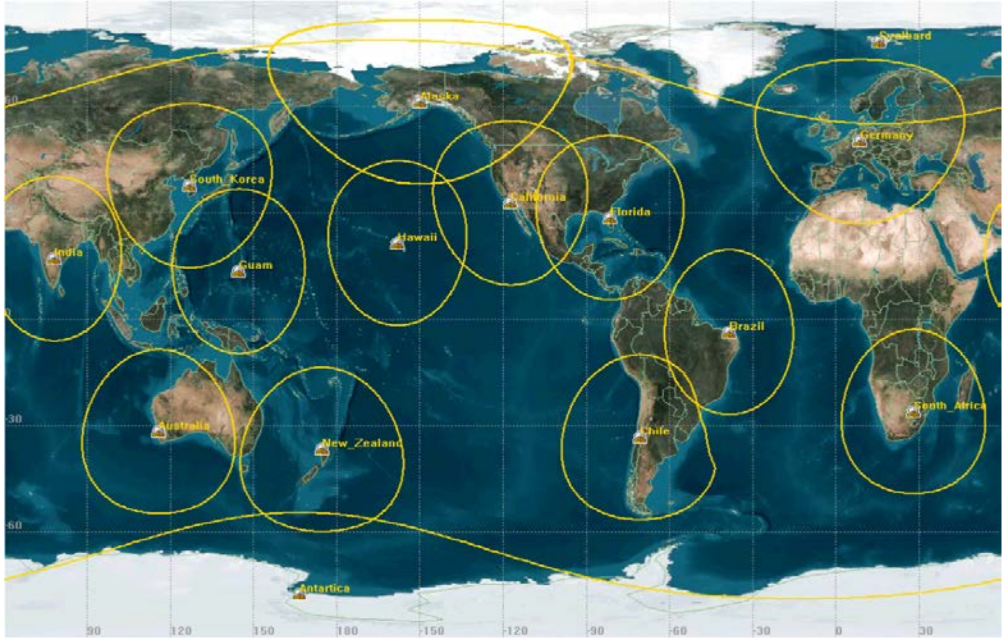
IDA

JPSS / NPOESS FO Ground Segment

- Command, Control, and Communications (C3)
  - — Mission Mangement Center (MMC) at Suitland, MD
    - – Backup (AMMC) at Aurora, CO
  - — Remote Ground Stations (SafetyNet™)
    - – 15 globally-dispersed sites
- Interface Data Processing (IDP) at four central locations
  - — AFWA, Offutt AFB
  - — FNMOC, Monterey, CA
  - — NAVO, Stennis, MS
  - — NESDIS, Suitland, MD
- Field Terminals (FT)
  - — Field terminal compatibility only
- System Users
  - — DoD / warfighters
    - – Air Force, Army, Navy, Marines
  - — DOC / NOAA
    - – NESDIS, NCEP, NWS
  - — NASA
  - — Secondary civilian users

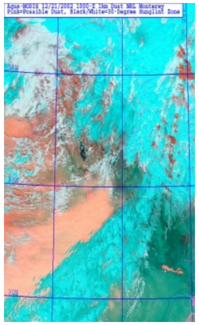
Field Terminals

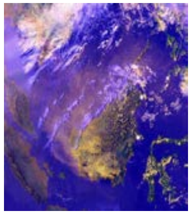
SafetyNet™ Receptors

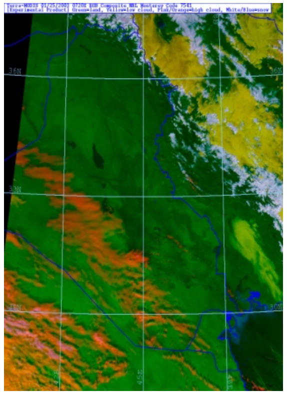


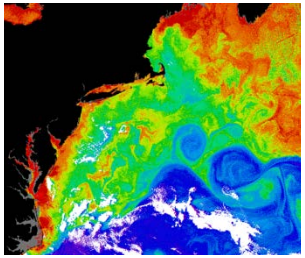
NPOESS / JPSS Products

- NPOESS data is available at three levels of processing
  - Raw Data Record (RDR)-unprocessed
  - Sensor Data Record (SDR)-calibrated and geolocated sensor data
  - Environmental Data Record (EDR)-retrieved environmental quantity such as atmospheric temperature
    - EDRs are typically processed using model outputs and algorithms
- IORD-II specifies the system requirements via EDR performance
  - Draft CPD continues to use EDR-based requirements
- In the Last 15 years there has been a trend of using the SDR directly rather than the EDR. NPOESS users are likely to use many SDRs directly, or develop their own EDRs rather then use the NPOESS EDR
- This complicates system testing, because DT will assess EDR quality

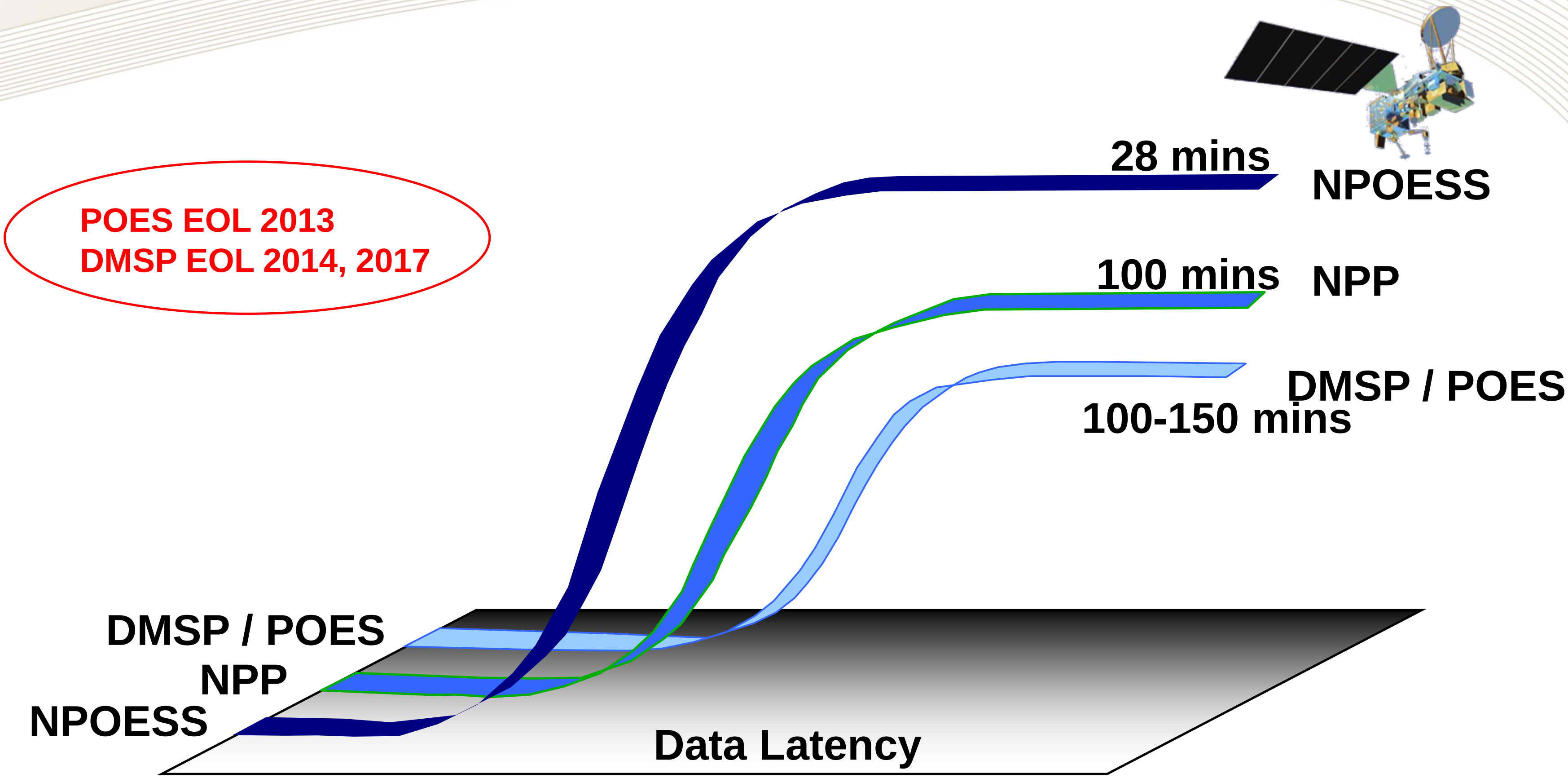








Capabilities Shortfalls and Needs

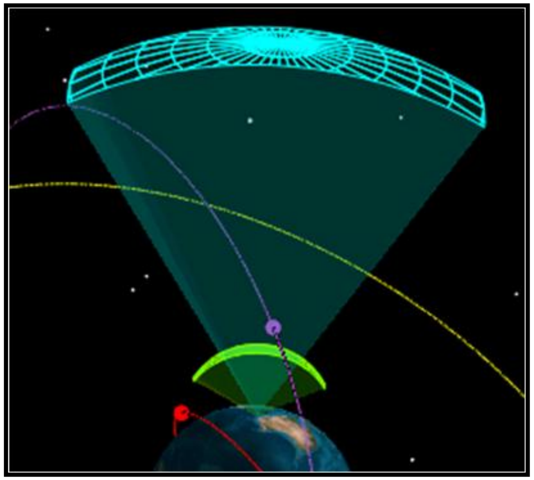


Improvements over Heritage	Data Rate	Data Volume	Encryption	Spectral Capability	Vertical Resolution
NPOESS	20Mbps	5.4 TB/day	Selective	22 bands	1300 bands
Heritage	1.5Mbps	6.3 GB/day	Total	5 bands	40 bands

NPOESS Satisfies Evolutionary Program Needs with Enhanced Capabilities

EOL – End of Life

Space Fence Capabilities



- **Space Fence will provide dedicated surveillance for Southern Hemisphere and high interest foreign launch corridor coverage**
- **Supports Defensive and Offensive Space Control**
  - Precise positional and orbital metric data
    - » Higher resolution, detection, and track capacity
    - » Custody of all significant RSOs
  - Improves timeliness (shorter time to detect launches, maneuvers, and breakups)
  - Supports overall accuracy of SSN radar observations
  - Maintains common element set database with the JSpOC catalog
- **Dispersed sites provide 2x current revisit rates and cuts detection times**
- **Contributes to spacecraft safety**
  - Deconfliction and conjunction assessment
  - Improved warning and avoidance
- **Strengthens Space Superiority**
  - Improved collection of data on friendly and potential adversary space assets

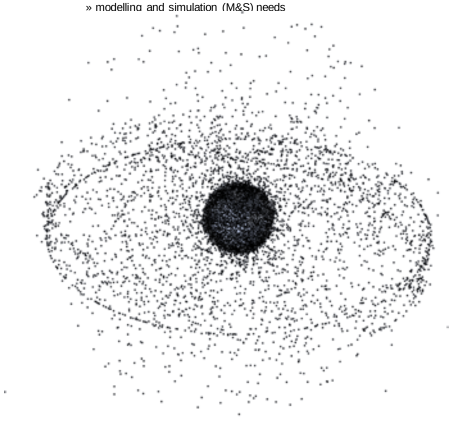
UNCLASSIFIED

Identifying On-Orbit Test Target for Space Fence Operational Testing

Daniel L. Pechkis, Nelson S. Pacheco, and Tye W. Botting
Institute for Defense Analyses

Introduction

- Space Fence will be an integrated system of two ground-based, S-Band (2 to 4 GHz) phased-array radars located in Kwajalein and perhaps western Australia [1].
- We present a rigorous statistical test design intended to characterize Space Fence performance across its intended operational envelope
  - Use altitude, size, and inclination as independent factors in statistical tests of dependent variables (e.g., observation)
  - Derive the type and number of necessary test targets.
  - Compare these with the number of known targets to identify
    - » the number of test days
    - » modelling and simulation (M&S) needs

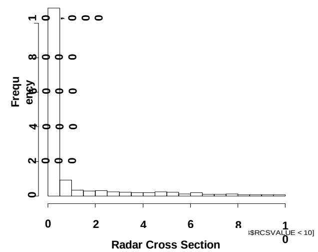


Space Fence Mission [2]

- Dramatically improve Space Command's ability to detect, track, identify, and characterize objects in low-earth orbit (LEO) and medium-earth orbit (MEO) [3].
  - Populate and maintain a complete Space Catalog
  - Observe smaller objects (basketball -> softball size)
  - Increase number of observations per object
  - Improve timeliness of event notification
  - Flight safety: Conjunction analyses and debris monitoring
  - Work with the Joint Space Operations Center to provide an integrated picture of the space operating environment.

SATCAT Analyses [4]

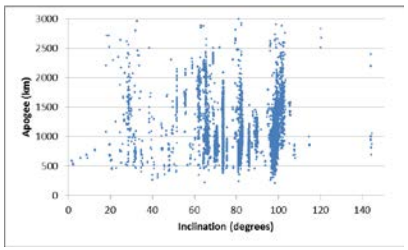
No. of Objects vs Radar Cross Section



Smaller objects dominate the SATCAT

SATCAT Analyses Cont.

Altitude vs. Inclination



- Objects clustered in inclination bands
- High object flux density might stress the radar's energy management and/or data processing to its limits
- Inclination as an experimental design factor
  - 9 - 45 degrees; low population density, high many observations per object
  - 45 – 80 degrees; centered on the highly populated mid-60 degree band
  - 80 – 171 degrees; representing near-polar and retrograde orbits

Test Design Considerations

- Altitude, Size, and Inclination are independent Factors that can influence radar detection and tracking performance.
  - Altitude influences
    - » Range -> affects strength of radar return signal
    - » Apparent Velocity -> affects range rate and track time window
  - Size influences
    - » Radar Cross Section (RCS) -> affects strength of radar return signal
  - Inclination influences
    - » Number and duration of passes across the radar's field of view
    - » High object flux density in certain inclination bands that might stress the radar's energy management and/or data processing to its limits.
- Shape, permittivity, and permeability are uncontrolled factors and should be logged.

2 Statistical Methods Required

- 1-Sample Variance Test and a full factorial DOE
  - Observation accuracy (range, range-rate, angle, time)
  - RCS Accuracy
- Test of 1-Proportion and Logistic Regression Model with a full factorial design
  - Probability of Track
  - LEO Surveillance and Track Coverage
  - Object Correlation
  - Minimum Detectable Target Size
  - Flexible Coverage
  - Initial Orbital Determination Accuracy

Observation Accuracy

- Problems
  - Except for few objects known to high precision, uncertainty in the majority of resident space object ephemeris is greater than the Space Fence accuracy thresholds
  - Objects experience ever changing forces, making orbital predictions imprecise
  - Therefore:
    - » For majority of objects, Space Fence position and velocity measurements cannot be compared to exact (ground truth) data
    - » Difficult to quantify errors in Space Fence accuracy measurements against ground truth for all objects
- Testing Approach
  - First, compare Space Fence measurements against objects known to high precision, e.g.,
    - » International Laser Ranging Service (ILRS) satellites [5])
    - » from multiple space surveillance sensors (perhaps from High Accuracy Satellite Drag Model (HASDM) ...
  - Then, compare radar track prediction against all objects tracked.

Altitude (kilometer)	Number HASDM/ILRS
250 - 600	76/4
600-2,000	10/17
2,000-6,000	0/1
> 6,000	0/15
Total	86/37

1-Sample Variance Test

Metrics: Measurement Errors

σ_o ≡ radar accuracy requirement

Hypothesis test on σ

σ_o: angle = A
σ_1: angle > A
σ_o: range = C
σ_1: range > C
σ_o: time = B
σ_1: time > B

Effect Size ≡ $\sigma_1 = 110\% \times \sigma_o$
Confidence ≡ 95%

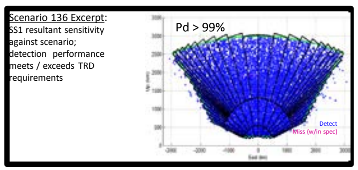
Probability of detecting an effect given that the radar does not meet requirements

Sample Size	Power
300	0.7620
450	0.8892
600	0.9507

- **Effective accuracy:** σ_o for each metric is not rejected for any level
- **Test Period:** 600 observations can be collected in 2.5 days of Space Fence operations, assuming 2 acceptable passes per day, plus time needed by ILSR/HASDM sensor resources.

Performance Demonstrated in M&S

PAS Scenario 136: 11,800 objects plus tasking



Full Factorial Design of Experiments in inclination, altitude, and size bands consistent with requirements

Inclination (degrees)	Altitude (kilometer)	SATCAT RSOs of Size (centimeter)		Real Tracks/ Min Test Days		M&S Tracks Needed	
		<10	≥10	<10	≥10	<10	≥10
9-45	250-600	1	32	25/25	25/1	0	0
	600-2,000	4	93	25/4	25/1	0	0
	2,000-6,000	0	6	0	25/3	25	0
	6,000-22,000	0	2	0	25/7	25	0
45-80	250-600	16	85	25/2	25/1	0	0
	600-2,000	534	2,497	25/1	25/1	0	0
	2,000-6,000	0	10	0	25/2	25	0
	6,000-22,000	1	246	25/13	25/1	0	0
80-171	250-600	28	272	25/1	25/1	0	0
	600-2,000	1,372	5,727	25/1	25/1	0	0
	2,000-6,000	0	89	0	25/1	25	0
	6,000-22,000	0	2	0	25/7	25	0
Total		1,956	9,061	175/25	300/7	125	0

Factor	Power
Inclination (I)	99.9%
Altitude (A)	99.5%
Size (S)	> 99.9%
Interaction (I x A)	96.1%
Interaction (I x S)	99.9%
Interaction (A x S)	99.5%

- **25 day test period**
- **M&S required.**

Probability of Track

Test of 1-Proportion

Metrics: Measurement Errors

p_o ≡ probability of an object being tracked

Hypothesis test on p

H_o: $p_o \geq 0.5$
H_1: $p_o < 0.5$

Effect Size	Power	Alpha	Sample Size
10% (p≤0.40)	95%	5%	269
	80%	5%	158
	70%	5%	122
5%(p≤0.45)	95%	5%	1081

Effect Size ≡ $p_1 = p_o$ – Effect
Confidence ≡ 95%

Summary and Conclusions

- Applied statistical methods to the other radar requirements
  - Space Fence can be tested with 53 factor/level combinations, using mostly on-orbit targets
  - M&S is required for objects
    - » < 10 cm at altitudes above 2,000 km
    - » < 10 cm at altitudes between 250 and 3,000 km in inclinations between 9 and 45 degrees
    - » 10 cm at altitudes above 2,000 km
  - Testing can be accomplished in 25 days

References

[1] L. Haines and P. Phu, "Space Fence PDR Concept Development Phase," 2011 AMOS Conference Technical Papers.

[2] Picture provided by the Space Fence Program Office, Air Force Life Cycle Management Center, Hanscom AFB, MA 01731-1700.

[3] "Space Fence Contract Award", Air Force Space Command Press Release (http://www.afspc.af.mil/news/story.asp?id=123413302), (2014)

[4] The publicly available SATCAT as of June 2013, contains 16,845 objects, of which 15,842 are in Earth orbit and have complete data.

[5] Noll, C. and Pearlman M., *International Laser Ranging Services 2009-2010 Report*, NASA TP 2013-217507, (2012)

[6] M.F. Storz, et.al., Adv. Space Res. 36, 2497 (2005).

Acknowledgements

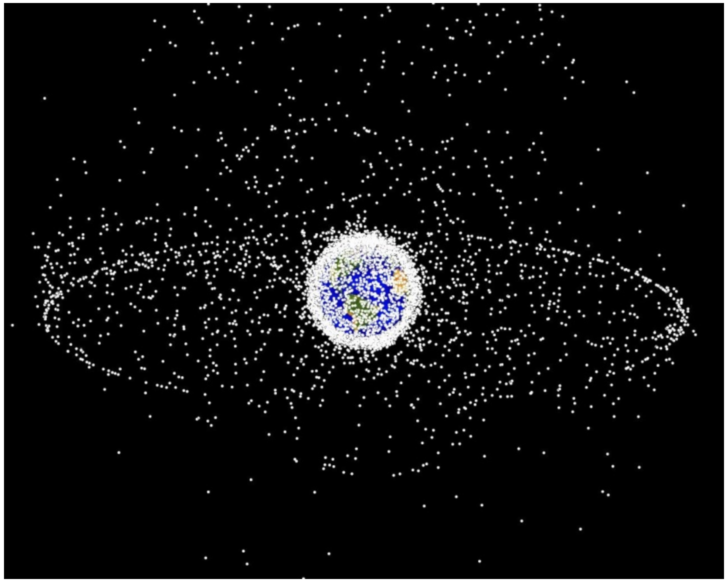
We acknowledge useful discussions with Dr. Kelly A. McGinnity and Mr. Michael T. Tuley. We would also like the thank the Space Fence Program Office providing for the Space Fence radar concept picture.

UNCLASSIFIED

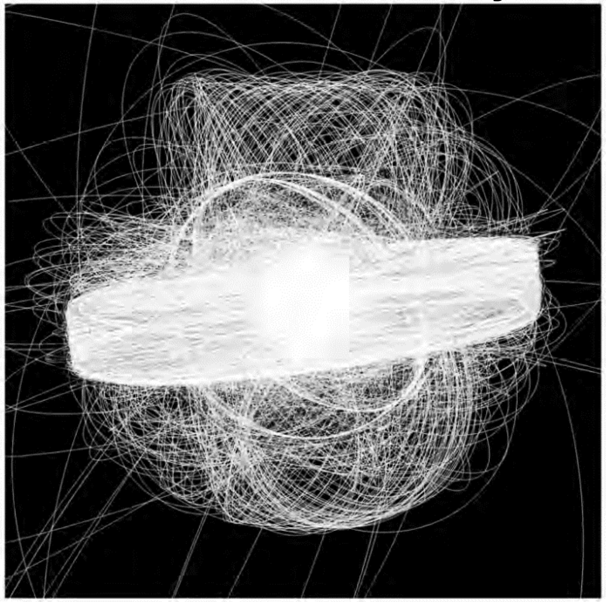
Size Considerations in Current SATCAT

~22,000 objects

Snapshot in time



One orbit for each object



- **~ 22K orbital objects above 10 cm currently tracked and maintained**
- **NASA prediction: ~500k orbiting objects down to 1 cm**
  - International Space Station shielded to withstand impacts of objects ≤ 1 cm
- **Space Fence detection threshold is 2 cm; critical to fill awareness gap below 10 cm**
- **Experimental Design Object Groupings:**
  - ≥ 10 cm (current SSN tracking limits) & < 10 cm (capture Space Fence sensitivity improvements)