A Case for Miniature Targeted Space Weather Sensors

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Contents & Assertion

Purpose

- Present various trade studies using AE9 / AP9 / SPM environment
  - GEO, MEO, and All EP GTO
- Use publicly, and internationally, available software & models
- Present business case for miniature Space Wx sensors

Assertion

- Space Wx hazards to satellite systems / operations are accepted & understood
  - Total Ionizing Dose, Non Ionizing Dose, Surface Dose, Single Event Effects, Spacecraft Charging, MMOD, EMP, …

AE9 / AP9 / SPM

- **Industry standard (AE8 / AP8) suffered from -**
  - **Limited datasets, inaccuracies, lack of indications of uncertainty leading to excess margin**
  - **No plasma specification with the consequence of unknown surface dose**
  - **No natural dynamics with the consequence of no internal charging or worst case proton single event effects environments**
- **AE9 / AP9 improvements**
  - **Larger dataset, more coverage in energy, time, location for trapped and plasma particles**
  - **Includes estimates of instrument error and space weather statistical fluctuations**
  - **Designed to be updateable as new data sets become available**

Model requirements – improve energy range over AX8

Priority	Species	Energy	Location	Period	Effects
1	Protons	>10 MeV (>80 MeV)	LEO & MEO	Mission	Dose, SEE, DD, nuclear activation
2	Electrons	>1 MeV	LEO, MEO & GEO	5 min, 1 hr, 1 day, 1 week & mission	Dose, internal charging
3	Plasma	30 eV–100 keV	LEO, MEO & GEO	5 min, 1 hr, 1 day, 1 week & mission	Surface charging, dose
4	Electrons	100 keV–1 MeV	MEO & GEO	5 min, 1 hr, 1 day, 1 week & mission	Internal charging, dose
5	Protons	1 MeV–10 MeV (5–10 MeV)	LEO, MEO & GEO	Mission	Dose

Ginet (2013)

Goals / requirements

- **Recognized (available to) by buyers / operators**
- **Easy to use / interpret by engineers**
- **Particle priorities**
  - **Energetic ions (10 MeV to 500 MeV) in inner magnetosphere (400 km to 15000 km)**
  - **Energetic electrons (>1 MeV) in inner magnetosphere (400 km to 15000 km)**
  - **Plasma electrons / ions (<10 keV)**
  - **Slot & outer zone electrons (6000 km to 36000 km)**
  - **Protons which affect solar cells (1 MeV to 10 MeV)**

AE9 / AP9 / SPM

√ Discussed herein

	Analysis Type	Recommended Run	Duration	Comments[1]
√	Total Dose	Perturbed Mean	Several orbits (days)	Plasma + AE9 Plasma + AP9 + Flare
√	Displacement Damage	Perturbed Mean	Several orbits (days)	AP9 + Flare
	Proton SEE	Monte Carlo	Full mission	AP9 + Flare
√	Internal Charging	Monte Carlo	Full mission	AE9

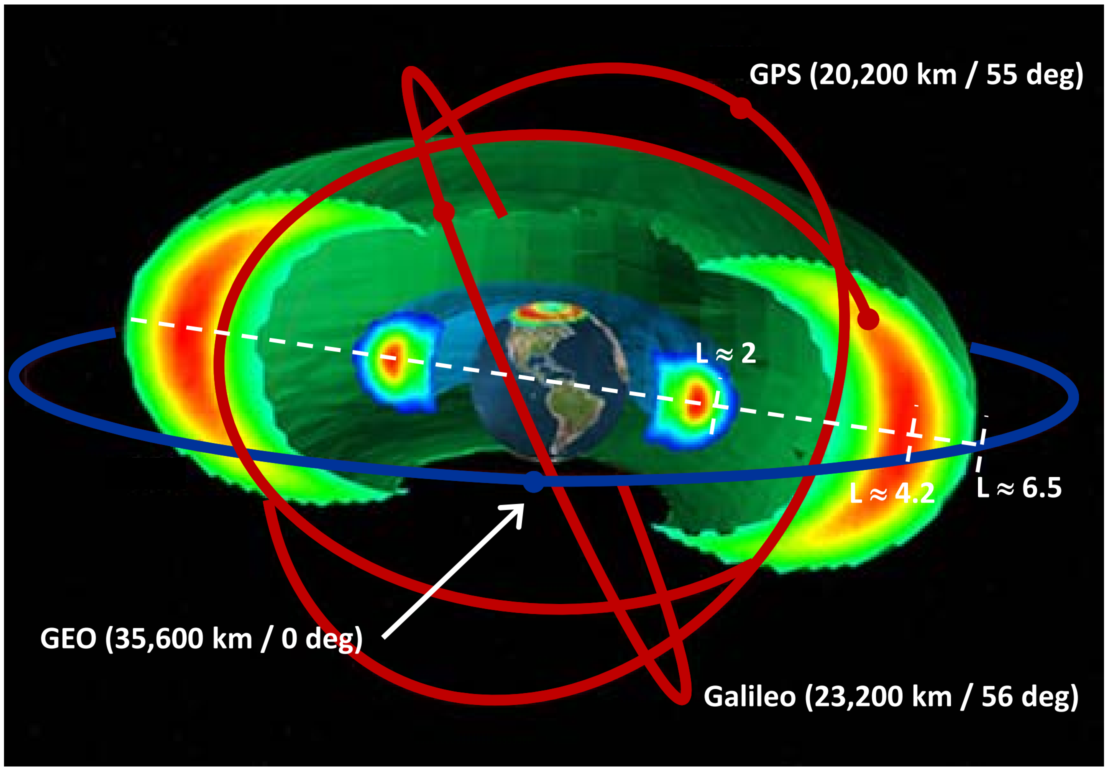
[1]Runtime based on 64 Bit 3.33 GHz Intel Xeon CPU (16 GB RAM)

User notes and lessons learned

- **Number of scenarios in Perturbed Mean >100**
- **Number of scenarios in Monte Carlo >100**
- **Step size to ensure >100 points per orbit**
- **Start time and epoch matter**
  - **IGRF model incorporated in 5 yr increments (latest accurate to 2015)**
- **All results presented herein used Version 1.04**

AE9 / AP9 Trade Study

NASA Van Allen Probes



<u>Why All EP?</u>
Expanded use of EP for GEO & GTO offers satellite operators the opportunity to reduce mission costs and increase revenue by enabling high dry mass to orbit

Missions considered

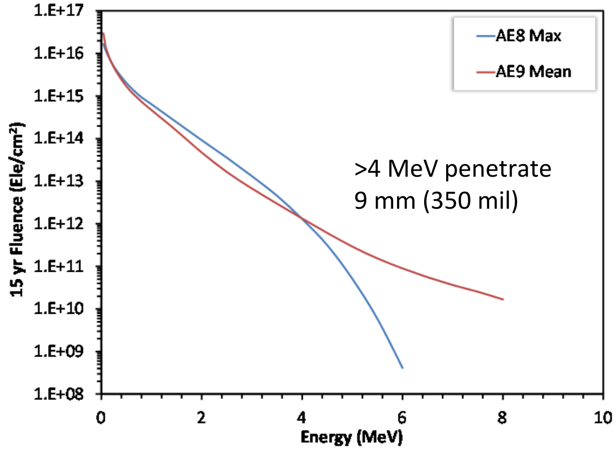
- **Navigation**
  - **GPS / Galileo**
- **GEO Telecom**
  - **“All EP” GTO (~200 d)**
  - **Ariane 5 launch to 500 km**
  - **Continuous EP burn**

Objectives

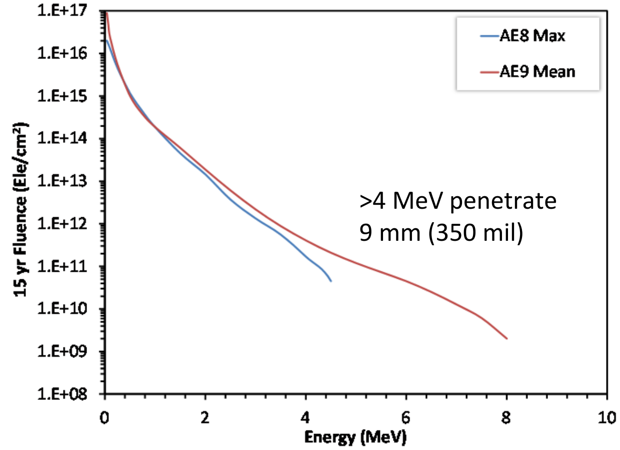
- **Compare environments**
- **Compare basic design impacts (practical implications)**
  - **Dose, solar cells, charging, …**

Trapped Particle Fluences

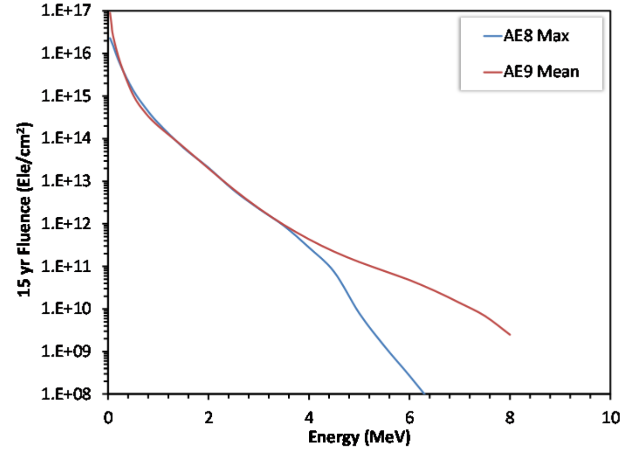
MEO Trapped Electrons



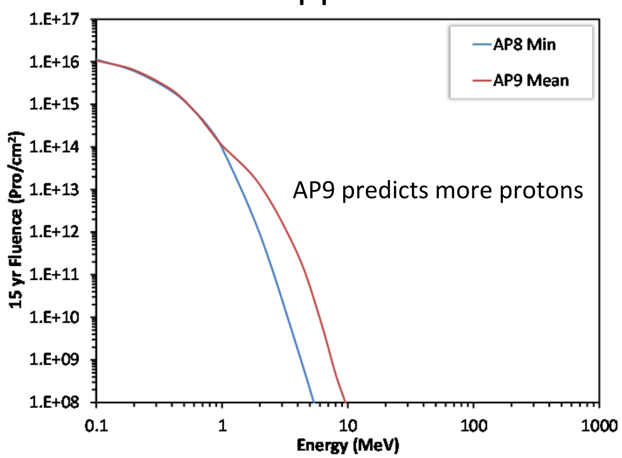
GEO Trapped Electrons



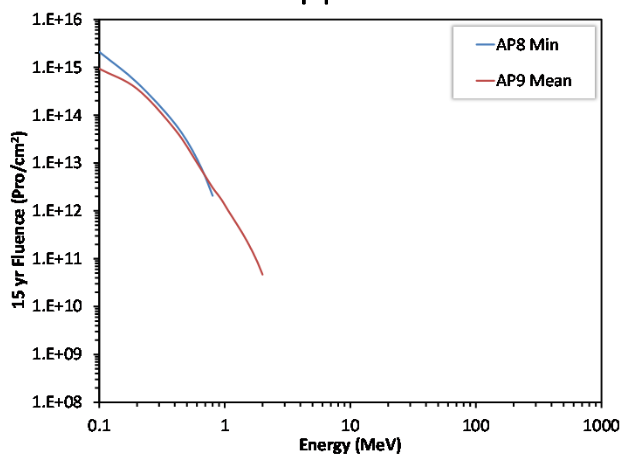
GEO + GTO Trapped Electrons



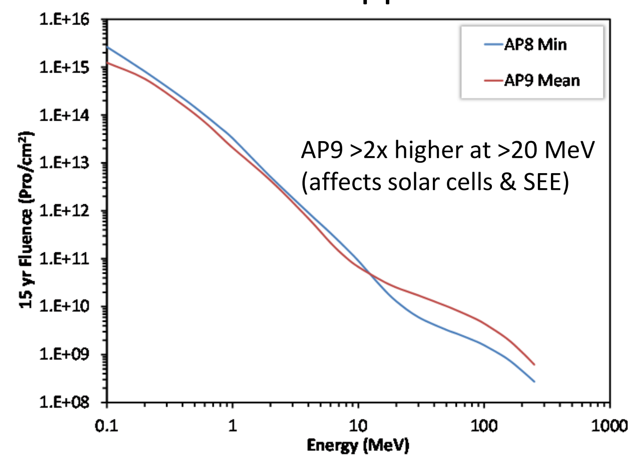
MEO Trapped Protons



GEO Trapped Protons

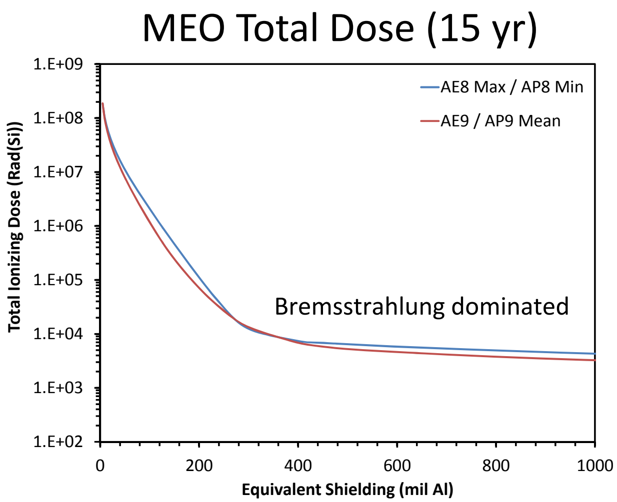


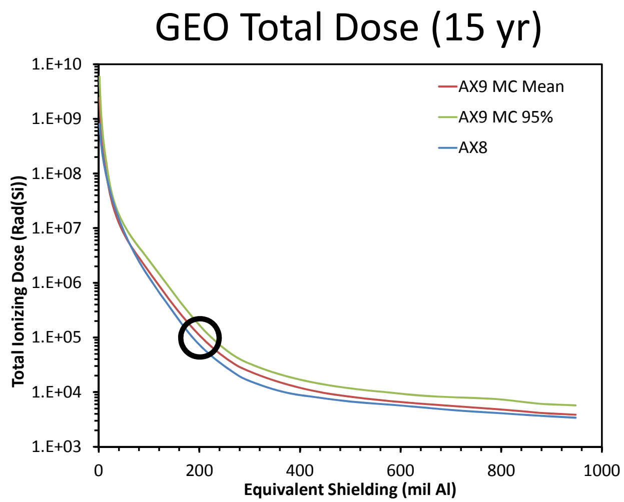
GEO + GTO Trapped Protons

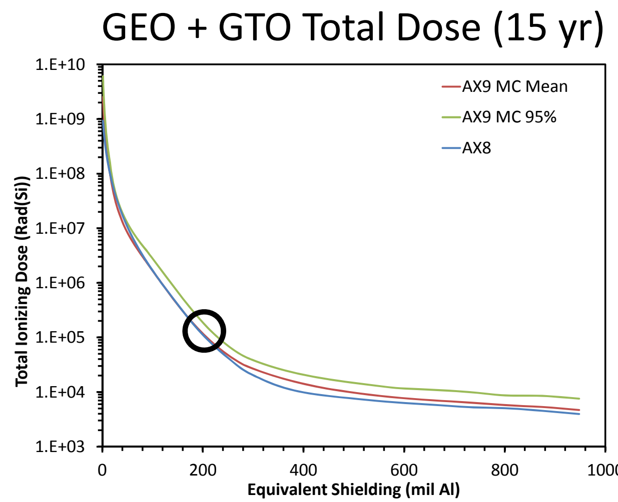


Both models capture significant proton fluence associated with long-duration All EP GTO

Total Ionizing Dose







For All EP missions AX8 (x2 DM) > AX9 (95%) and AX9 Mean (x2 DM) > AX9 (95%)

Mission	AX8	AX8 (x2 DM)	AX9 MC Mean	AX9 MC Mean (x2 DM)	AX9 MC 95%	AX9 MC 95%
GEO Only	50.6	101.2	74.5	149.0	111.5	223.0
GEO + GTO	75.1	150.2	80.3	160.6	124.5	249.0

Design Impacts – Solar Cells

- **Assessed using SPENVIS tools**
  - **Considered generalized cell shielding**
- **Table shows ±% increase or decrease relative to AX8 "baseline" fluence**
- **Effects are more dramatic for (GEO +) GTO mission than MEO**

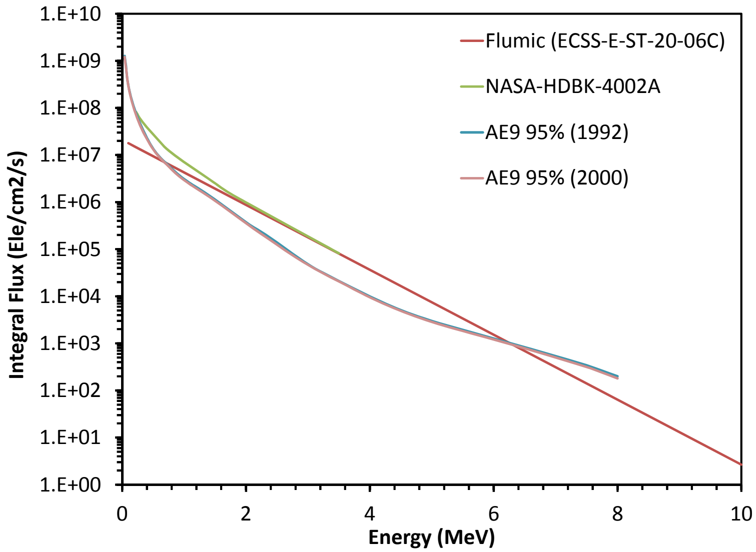
Equivalent 1 MeV Ele fluence comparison (AX9 to AX8) for MEO[1] and GEO[1] + GTO

Cell Type	Parameter	AX9 Pmean	AX9 P95%	AX9 MC Mean	AX9 MC 95%
SPL ZTJ	I_{sc}	-21%	+8%	-19%	+27%
	V_{oc}	-12%	+20%	-21%	+58%
	P_{mp}	-3%	+36%	-21%	+36%
SPL XTJ	I_{sc}	-14%	+19%	-20%	+32%
	V_{oc}	-7%	+23%	-21%	+35%
	P_{mp}	-7%	+31%	-24%	+25%
Azur 3G28	I_{sc}	-5%	+32%	-35%	+12%
	V_{oc}	-13%	+54%	0	+78%
	P_{mp}	-16%	+55%	-14%	+45%

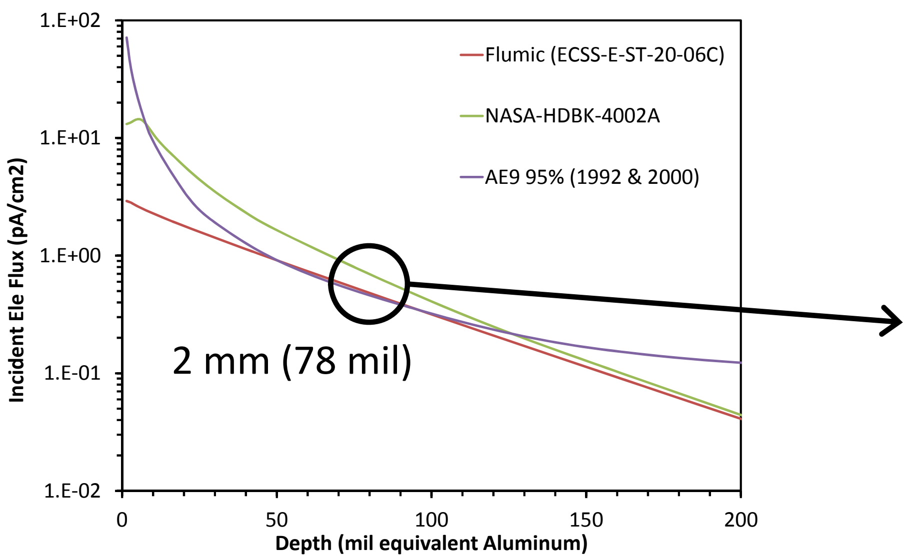
MEO
GEO

[1]ESP 90% Solar Flare protons used for all cases

Deep Charging



Extrapolate 4002A w/ FLUMIC for transport analysis
Solid sphere kernal (not finite / back slab)



- **AE9 (95%) results returned for 1 yr at GEO**
- **Compared to common design guidelines / design standards**
- **AE9 extends energy range beyond NASA**
- **Results are significant**
  - **Represents (by simple *V = IR*) difference between a potential of >700 V and <500 V for 1 cm^2 surface grounded through 10^{15} Ω**

Environment	Incident Flux at 2 mm (pA/cm2)
Flumic	0.49
NASA HDBK 4002A	0.71
AE9 (95%)	0.47

Definitions and Abbreviations

Name	Acronym[1]	Description
Lightly Shielded Dose	LSD	Dose under <2 mm equivalent aluminum
Heavily Shielded Dose	HSD	Dose under >2 mm equivalent aluminum
Lightly Shielded Dose Rate	LSDR	Dose rate under <2 mm equivalent aluminum
Heavily Shielded Dose Rate	HSDR	Dose rate under >2 mm equivalent aluminum
Surface Dose	SUD	Solar cell damage / <0.25 mm
Single Event Effect	SEE	Upset detection
Surface Dielectric Charging	SDC	Flux responsible for surface charging (<250 keV)
Deep Dielectric Charging	DDC	Flux responsible for deep charging (>250 keV)
Spacecraft Potential	CPA	Return surface / satellite floating potential (ultimate / diff charging)
Hypervelocity Detection	MMOD	Attitude disturbance or plasma / RF detection
ESD Detection	ESD	Event detection (current, RF, or plasma)
Nuclear Event Detection	NUC	Nuclear event detection

[1]Based upon CEASE acronym list
[2]O'Brien, et al (2008)

Comprehensive Sensor[2]

- **Measure one or more aspects of space environment whilst return detailed energy / angular resolution with large dynamic range**
  - **Consider those instruments aboard GOES, POES, LANL, …**

Targeted Sensor[2]

- **Measure space environment hazards to the host vehicle with focus on specific effect or set of effects**
  - **Actual environment may be derivable after the fact (higher order)**

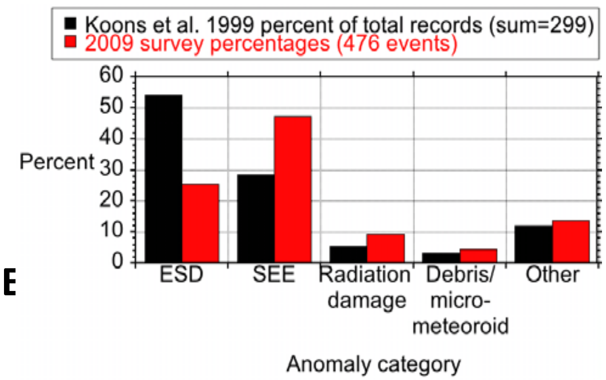
"Whiteboarding" Available / Conceived Sensors

Comprehensive / Targeted

Name	Supplier	Hazards	Host	Mass (kg)	Power (W)
CEASE	AmpTek	LSD, HSD, LSR, HSR, SUD, SEE, SDC, DDC	TSX-5	1.3	1.7
CEASE II	AmpTek	LSD, HSD, LSR, HSR, SUD, SEE, SDC, DDC	DSP-21 & SES-12	1.3	1.7
ERM	APL	LSD, HSD, LSR, HSR, DDC	RBSP (VA)	2.9	>0.25
LM CPA	LM	SDC	INTELSAT & SES		
LM / JPL Dosimeter	LM / JPL	LSD, HSD, LSR, HSR	INTELSAT & SES		
μDosimeter ADS02	Aerospace / Teledyne	LSD, HSD, LSR, HSR	Multiple	20 gm	
RHAS	AFRL	LSD, HSD, LSR, HSR	GEO (2016)	0.9	1.5
EDR	Aerospace	SDC (Recorder)	In development		
CDS	Aerospace	SDC	In development	50 gm	
R2D3	NRL	DD	In development	In development	
BDD / CXD	LANL	LSD, HSD, LSR, HSR, SEE	GPS		
IESDM	JPL	DDC	In development	In development	
OSL	Montpelier	LSD, HSD, LSR, HSR	Robusta	<0.01	?
Merlin	QinetiQ	LSD, HSD, LSR, HSR, SDC, DDC	Giove	1	2.5
REPTile	CU Boulder / LASP	DDC, LSD, HSD, LSR, HSR	CSSWE	1.25	
FLAPS	AFRL	DDC, LSD, HSD, LSR, HSR		0.4	1.5
MicroRAD101	Space Micro	LSD, HSD, LSR, HSR, SEE		0.3	0.4
SSJ4/5	LANL	SDC	DMSP	3.2	
SEM	NOAA	LSD, HSD, LSR, HSR, SUD, SEE, SDC, DDC, NUC	GOES & POES	>10	?

Cost of a Satellite Anomaly

Mazur (2010)



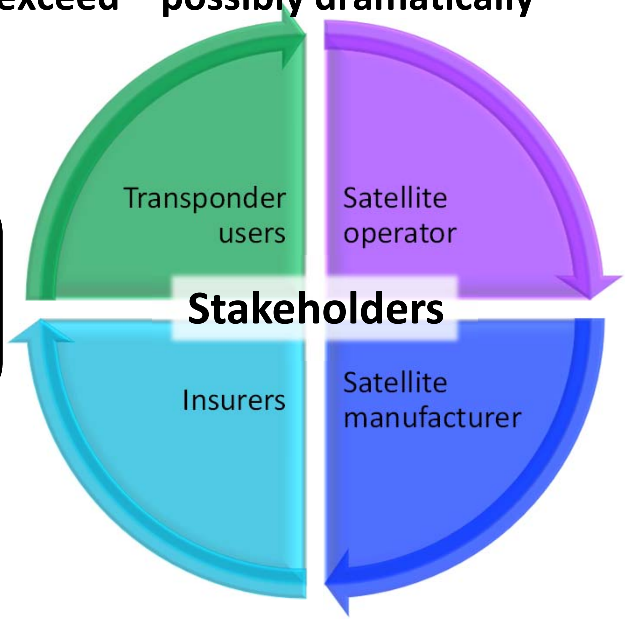
- **Focus on hosted payload opportunities (GEO Telecom)**
  - **Typical cost ~USD 200 M + 20% in insurance**
- **On-orbit claims continue to out pace launch losses**
  - **Space Wx claims >USD 500 M (1994 to 1999) led by ESD & SEE**
- **Anomaly cost is difficult to bound**
  - **Category 2 First Order costs ~USD 1 M**
  - **Secondary Order costs likely exceed – possibly dramatically**

Satellite Anomaly Categories

Category 1	Nuisance Monitor & collect data only
Category 2	Recoverable System Impact Either autonomous or commanded recovery; possible traffic & life impacts if not addressed
Category 3	Catastrophic Immediate system, operational, and / or life impact

Focus on Category 2

Likely to result in investigation & action at all stakeholders



First Order costs
- Failure diagnosis
- Manufacturer & customer interface
- Insurance interface
- On-console monitoring

Second Order costs
- Fleet impacts
- Corrective action implementation

First Order costs
- Failure investigation
- Tests & analyses
- Reviews & documentation
- Independent reviews

Second Order costs
- Fleet impacts
- Customer & insurance meetings
- Corrective actions & design changes

Value Proposition

***Traditional paradigm "commercial bus providers look at sensors as additional cost … biased against flying something that is not part of the main mission"**

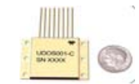
- **Consider the type & magnitude of benefits created when satellites fly hosted sensors**
- **All entities listed below considered potential funding sources (provided business case can close)**
- **Consider the value proposition (ROI) for various entities**
  - **Varies greatly depending upon –**
    1. **Data are deemed competition sensitive / proprietary by owner**
    2. **Freely distributed (real-time or near-real-time)**

- **Strategic**
  - **IP / PI**
- **Technology**
  - **Demonstration (grow TRL)**
- **Scientific**
  - **Pure physics / science**
- **Economic**
  - **Consumer pricing & cost competitiveness**
- **Educational**
  - **Improve public understanding / knowledge**

Entity	Description of Value Proposition(s)
Satellite manufacturer	Intimate, detailed knowledge of actual environment; enables comparison against design environment and margins; useful in anomaly resolution; reduced risk when introducing / demonstrating new technologies; enable COTS-like technologies; managed outages; lower cost
Satellite operator (owner)	Immediate & Intimate knowledge of Space Wx conditions at location of asset; increased reliability; reduced outages; reduced uncertainty about on-orbit environment; reduced operational risks; useful in anomaly resolution; lower cost
Customer (transponder user)	Increased transponder reliability; lowest (optimized cost)
Satellite insurers	Intimate, detailed knowledge of actual environment; enables comparison against design environment and margins; reduced risk when introducing / demonstrating new technologies
Scientific community	"Effect sensors" necessarily a very local and extrapolation is difficult; true particle sensors (CEASE, MERLIN, …) much more valuable
"Third party" e.g. SSA Warning Systems	Increased real-time or near-real-time data for "for fee" product; increased statistics; increased spatial / temporal resolution; model / product validation; reduced errors in predictions
Public / students / adjacencies	Improved public / adjacent awareness; development of adjacent markets

Estimated Cost to Accommodate Sensors

Photos not to scale

	 Photo: Amptek	 Photo: JHU APL	 Photo: Likar (2010)	 Photo: TeledyneMicro
	CEASE-2	ERM	LM CPA	ADS01
Mass (kg)	1.3	2.9	<200 gm (est)	20 gm
Engineering, Manufacturing, and Test Labor Impacts	**Moderate** Optimally add HTR control (inc FSW) Update CMD / TLM process Optimally test in ATLO Other engineering updates	**Significant** Redesign custom interface Redesign custom data format Updates to HTR control and CMD / TLM Other engineering updates	**Minimal** Drawing updates Standard mechanical install Standard interface	**Minimal** Drawing updates Dry or wet mount Standard interface
Engineering Accommodations Impacts	**Minimal** Ensure clear of thruster FOV Standard mechanical install Access during ass'y & test	**Moderate** Ensure clear of thruster FOV Standard mechanical install Update to CDH interface Access during ass'y & test	**Minimal** No verification during ass'y & test Minor update to CDH	**Minimal** No verification during ass'y & test
Estimate Hardware Cost	**Moderate**	**Moderate**	**Minimal**	**Minimal**
Overall Impact	**Moderate**	**Significant**	**Minimal**	**Minimal**

>500 k USD **250 k USD** **100 k USD** **10 k USD**

Significant **Moderate** **Minimal**

Sensor cost not included

"Housekeeping" Space Wx / Effect Knowledge Available at Minimal Recurring Cost

Conclusions

AX9 summary

- **Long duration "All EP" transfer results in higher accumulated dose**
  - **Less dramatic (2x to 4x) for spacecraft electronics (5 mm or ~200 mil) when predicting with AX9**
- **GEO internal charging effects predicted with AE9 (95%) less severe than those predicted with NASA HDBK 4002A**

Sensors summary

- **Conceivable to achieve ROI for manufacturers & operators …**
  - **After 1 anomaly investigation**
  - **After new technology demonstration (1 day, 1 week, or 1 mo)**
- **Credible cost to accommodate, and operate, some Space Wx sensors is approximately that of accommodating temperature sensors**
  - **Assemblies / components are qualified for both temperature & space radiation**
  - **Benefit to multiple end-users may exceed that of temperature sensors**