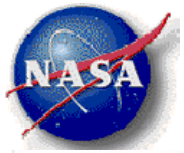
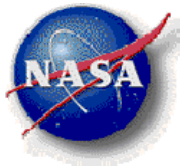


Lightning & EM Effects Mitigation

George Szatkowski - Lightning Mitigation Lead
Ken Dudley – Lightning SansEC Lead
Jay Ely – Lightning Environment Lead

NASA stock graphic.



Outline

- Background
- Milestone Road Map Plans
  - Lightning Mitigation
  - Lightning SansEC Sensors
  - Lightning Environment

Where this Work Fits:

- NASA AVSP (Aviation Safety Program)
  - SSAT (System-wide Safety Assurance Technologies)
  - VSST (Vehicle Systems Safety Technologies)
  - AEST (Atmospheric Environment Safety Technologies)
    - EI (Engine Icing)
    - AI (Airframe Icing)
    - AHSM (Atmospheric Hazards Sensors & Mitigation)
      - SVA (Smart Visual Awareness)
      - LEO (Lidar Electro-Optical)
      - IWS (Icing Weather Systems)
      - Advanced Radar
      - LEEM (Lightning & Electromagnetic Effects Mitigation)

"SansEC"= "Without Electrical Connection" refers to inductively-coupled, wireless sensing

Note: This is a publicly-releasable version of charts presented at the NASA AHSM Internal Review, on November 18, 2010

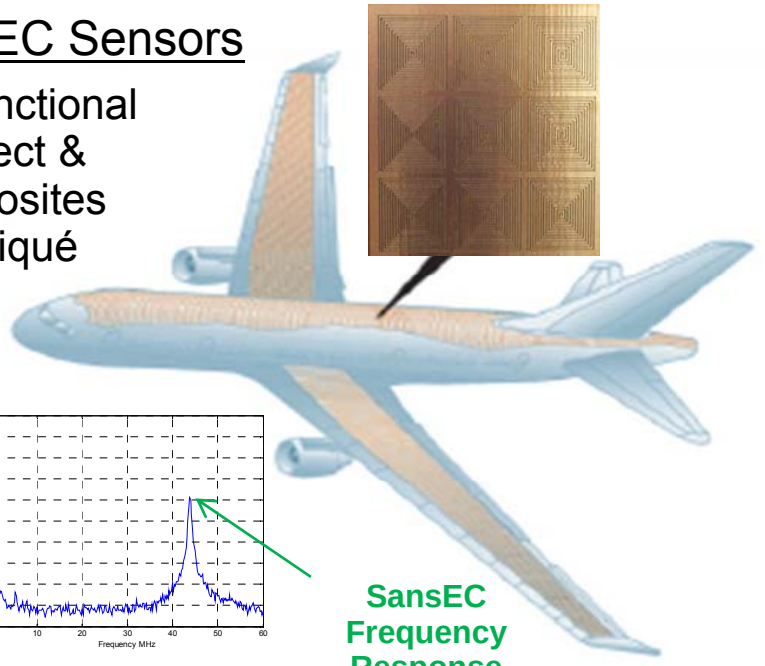
Develop innovative lightning strike sensing & mitigation technologies to minimize flight safety risks from electromagnetic environmental hazards (Lightning & HIRF)

Lightning Mitigation

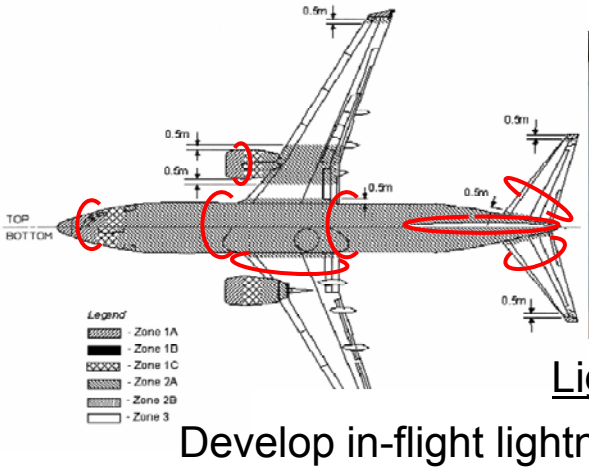
Develop mitigation strategies to improve aircraft lightning protection designs through passive or active methods.

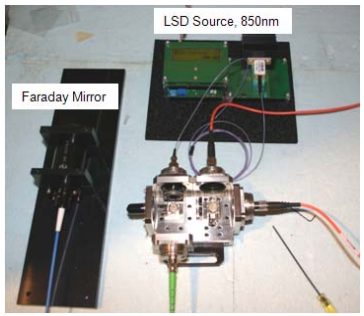
Lightning SansEC Sensors

Robust, multifunctional sensors to protect & diagnose composites with single appliqué



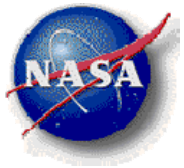
SansEC Frequency Response





Lightning Environment

Develop in-flight lightning measurement sensors to capture & record lightning waveforms which pose risk to flight safety.

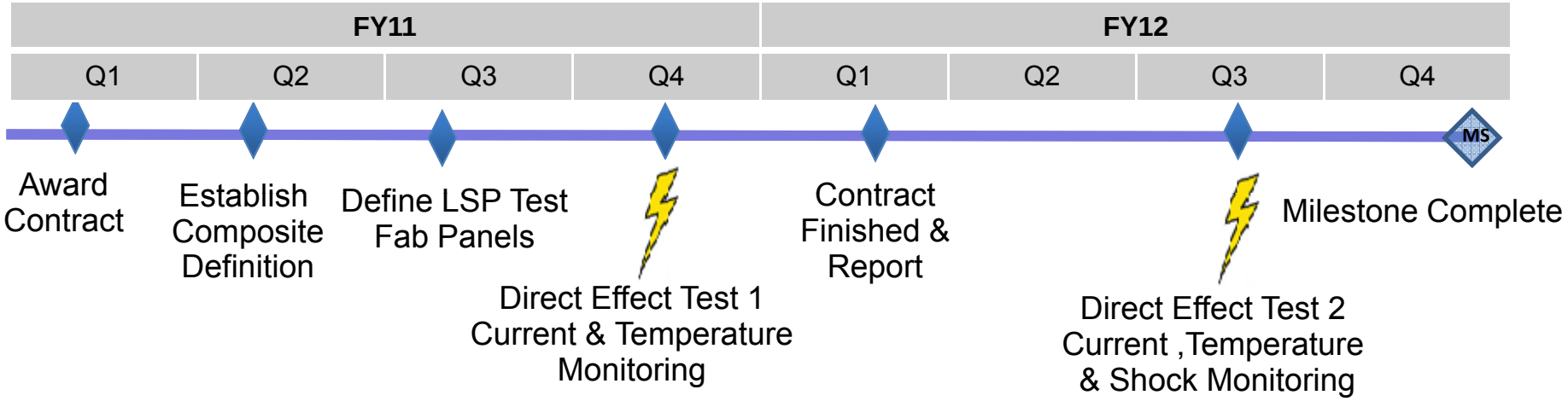


Lightning Mitigation Milestones

Milestone	Due Date	Milestone Title / *FTE POC*
AEST4.4.37	Sept 2012	**Develop lightning strike test bed to monitor current, temperature & shock . Standardize lightning test procedures. / G. *Szatkowski***
AEST4.4.38 GRC Lead	Sept 2012	**Investigate lightning strike damage mechanisms on composite panels. / S. *Miller***
AEST4.4.40 GRC Lead	Mar 2013	**Composite damage modeling. / S. *Miller***
AEST4.3.17	Dec. 2013	**Investigate mitigation approaches for lightning protection on composite aircraft. / G. *Szatkowski***

AEST4.4.37 Lightning Strike Test Bed FY12Q4

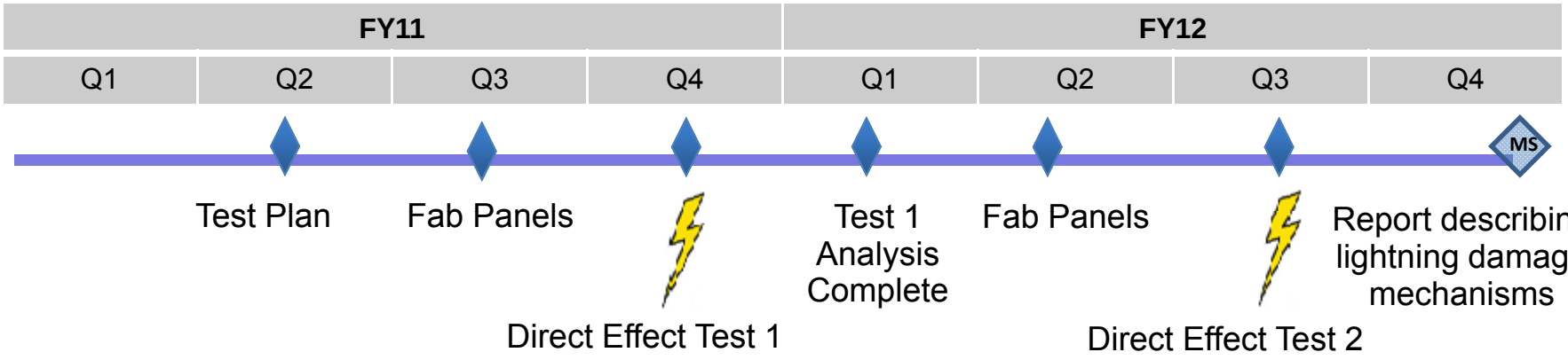
Demonstrate lightning strike test bed to capture current waveform, temperature and shock during laboratory lightning direct effect experiments. Develop lightning strike protection evaluation guidelines and procedures.



- Justification: Will enable full parameter characterizations of Lightning SansEC protection attributes and allow direct comparisons to existing/future LSP technologies
- Discoveries So Far: Fiber optic current and temperature sensing will be developed. Shock measurements will potentially use piezo electric sensors. Contract statement of work defined.
- Publications: 2013 International Conference on Lightning and Static Electricity (ICOLSE). George Szatkowski

AEST4.4.38 Lightning Strike Damage Mechanisms FY12Q4

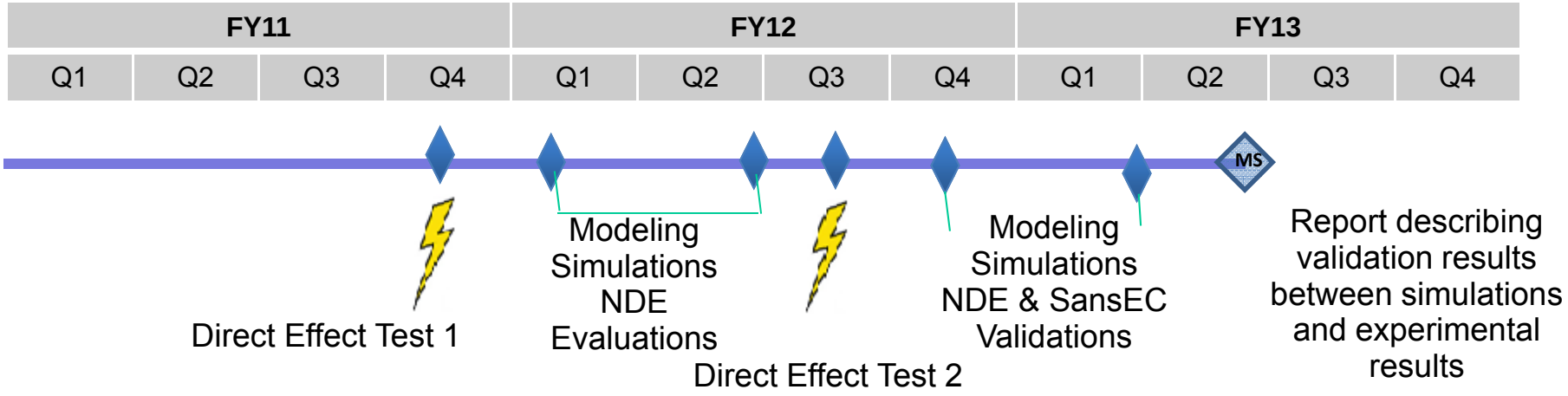
Investigate lightning strike damage mechanisms on composite panels to indentify the effects from Lorentz force, temperature & shock.



- Justification: Identification of lightning damage mechanisms will result in enhanced mitigation designs for lightning resilient composite aircraft.
- Discoveries So Far: Test bed development will support damage mechanism identification.
- Challenges To Come: Post test evaluations and required procedures to isolate damage mechanisms into separate categories, current, temperature & shock.
- Publications: Results will be published in journal and/or conference papers.

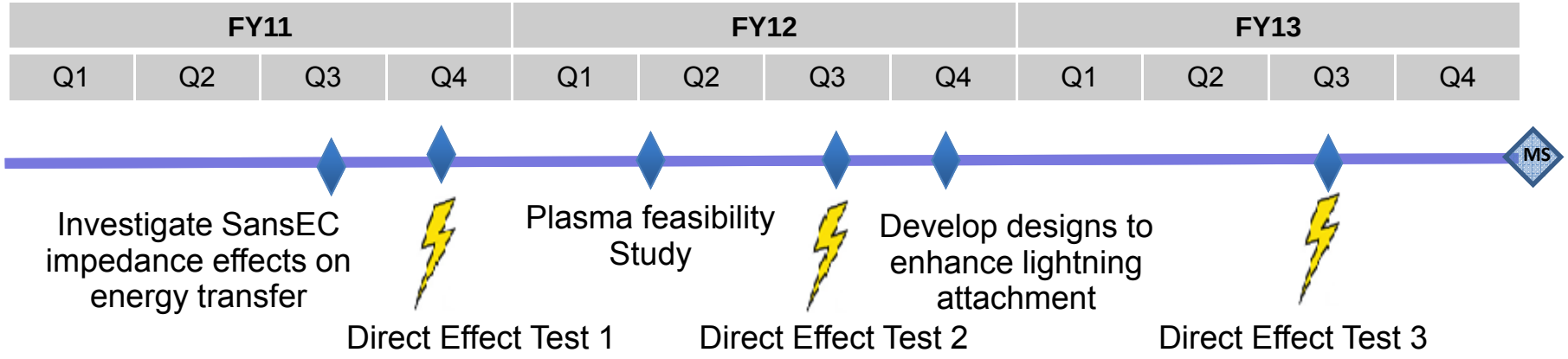
AEST4.4.40 Composite Damage Modeling FY13Q2

Develop computational models to simulate lightning damage on composite panels. Validate computations with experimental data. Compare common practice NDE data with SansEC sensor results to support damage mechanism identification.

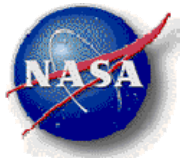


- Justification: Computer modeling of lightning damage mechanism will support enhanced mitigation designs for lightning resilient composite aircraft.
- Discoveries So Far: Possible new contract will define composite definition and geometry model.
- Challenges To Come: Establish computational damage models & acquiring appropriate experimental results for validation.
- Publications: Results will be published in journal and/or conference papers.

Investigate passive or active lightning mitigation approaches for composite aircraft lightning protection.



- Justification: Development of robust lightning attachment points which can safely attract, attach and manage lightning currents will provide new design methods to protect composite aircraft.
- Discoveries So Far: Most materials heat up with increased current, further increasing resistance. Plasma is unique in that the higher the current, the lower the resistance.
- Challenges To Come: TBD
- Publications: TBD



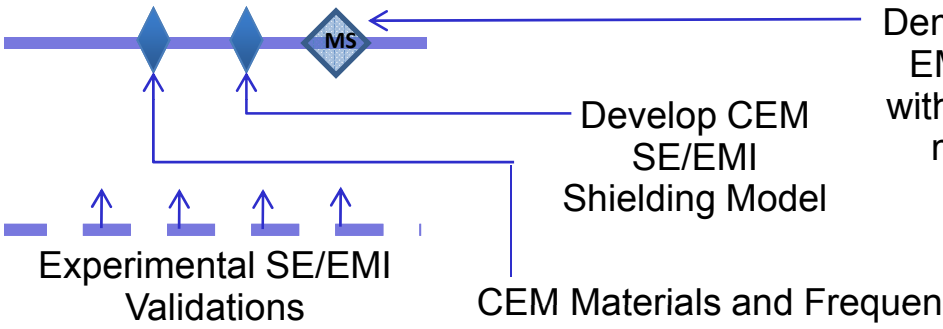
Lightning SansEC Sensors Milestones

Milestone	Due Date	Milestone Title / *FTE POC*
AEST4.4.33	June 2011	Develop computational EM tools to predict shielding effectiveness characteristics of lightning SansEC sensors. */K. Dudley*
AEST4.4.34	Sept 2011	Characterize lightning resilience of SansEC sensors. Evaluate differential resistance sensor designs / *G. Szatkowski, S. Woodard*
AEST4.4.36	June 2012	Demonstrate1 meter standoff distance between interrogation antenna and SansEC / *K. Dudley, C. Wang*
AEST4.3.13	Sept 2012	Develop Lightning SansEC Sensor designs to resonate at frequencies permeable in composite materials / *K. Dudley, S. Woodard*
AEST4.3.14	June 2013	Demonstrate Lightning SansEC sensors meet FAA certification requirements / *K. Dudley*
AEST4.2.13	Sept 2013	Demonstrate the ability to detect damage in composite aircraft skins. */K. Dudley, S. Woodard*

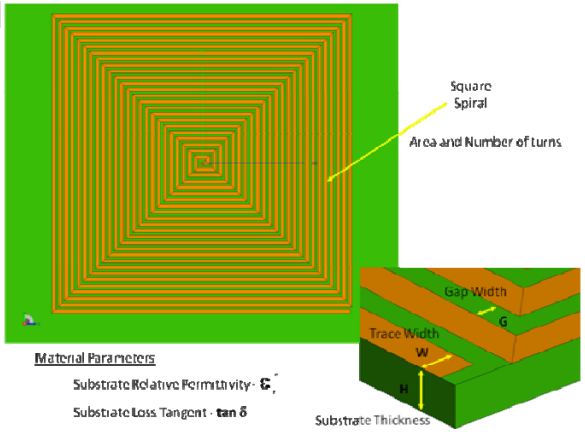
AEST4.4.33 SansEC Sensors Shielding Effectiveness FY11Q3

Develop computational EM tools to predict shielding effectiveness characteristics of lightning SansEC sensors and the experimental test methods for validation

FY11				FY12				FY13				FY14				FY15			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4



Demonstrate computational EM predictions compare within 4 dB of experimental measurement results.

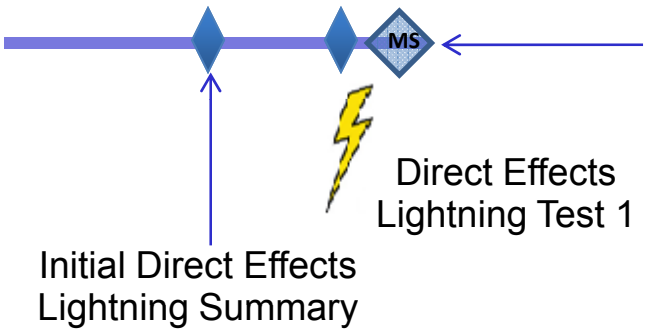


- Justification: Reliable computational tools and solutions will support sensor designs and shielding effectiveness optimizations.
- Discoveries So Far: Preliminary shielding characteristic detected for SansEC Sensors.
- Challenges To Come: Parallel Computational Electromagnetic (CEM) shielding effectiveness (SE) methodology development and Experimental SE/EMI Validation measurements in HIRF Chamber.
- Partnerships: None planned at this time.
- Publications: FY11Q2 CEM paper for the Applied Computational Electromagnetics Society Conference (ACES), FY11Q3 SansEC Shielding Effectiveness Paper, FY11Q4 CEM Shielding Effectiveness Paper.

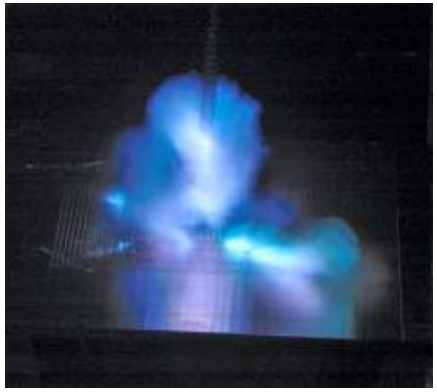
AEST4.4.34 SansEC Sensors Lightning Strike Protection FY11Q4

Conduct direct effect lightning test investigations on Lightning SansEC Sensors to characterize lightning resilience and to evaluate differential resistance sensor designs.

FY11				FY12				FY13				FY14				FY15			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4



Demonstrate Lightning SansEC Sensor withstands 100KA direct strike and remains operational. Demonstrate lightning current propagation can be directed along pathways using sensor geometry shaping and differential resistance and/differential capacitive designs.

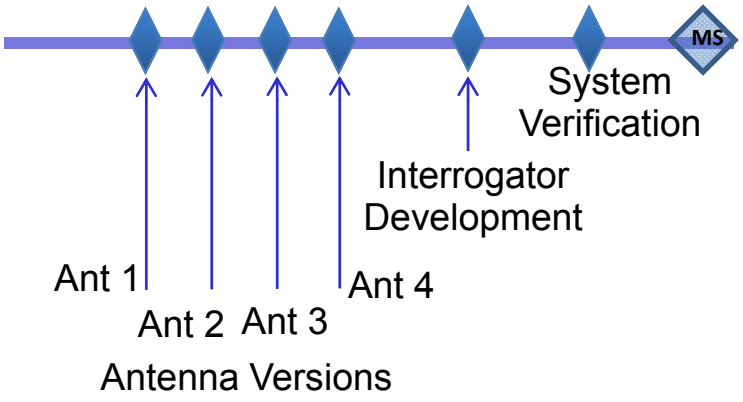


- Justification: Composite aircraft require enhanced lightning protection. This research will lead to new understanding of the direct effects of lightning on composite airframes and new multifunctional sensor/protection concepts for a more resilient composite aircraft.
- Discoveries So Far: Individual SansEC Sensors offer lightning protection to dielectric composites at the 30KA level. Sensor Geometry directs the energy of the strike.
- Challenges To Come: Integrating arrays of SansEC sensors on both dielectric and composite materials for direct effects lightning tests to 100KA level.
- Partnerships: None planned at this time.
- Publications: FY11Q2. Results will be published in journal and/or conference papers..

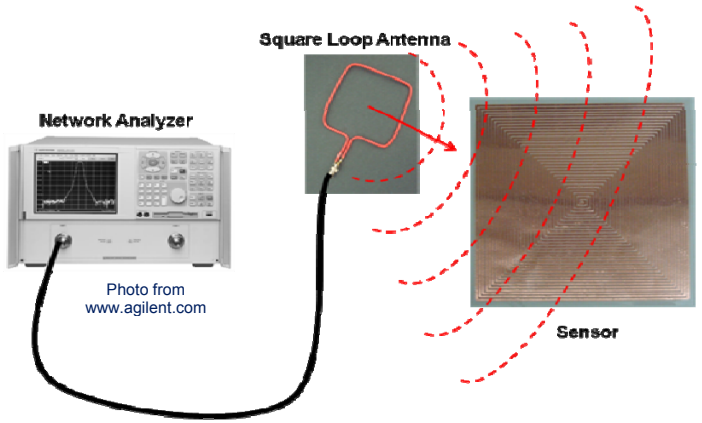
AEST4.4.36 SansEC Sensors 1 meter Interrogation Standoff FY12Q3

Investigate antenna concepts for powering and interrogating SansEC sensor arrays at a distance of 1 meter.

FY11				FY12				FY13				FY14				FY15			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4



Develop technology required to increase separation distance between interrogation antenna and sensor.

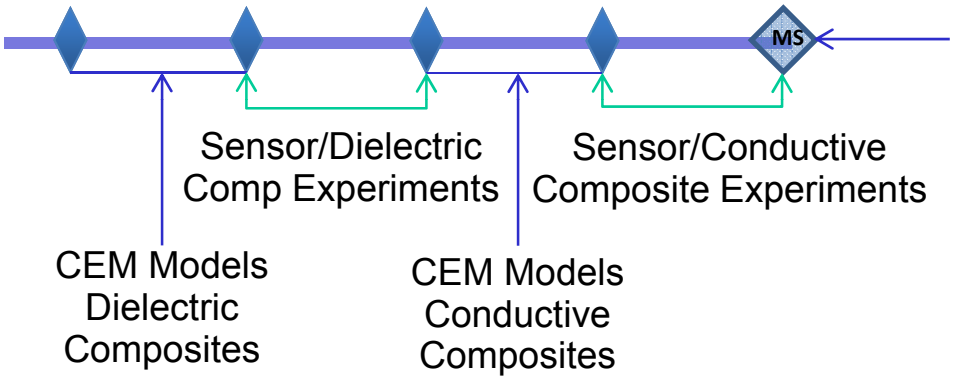


- Justification: 1 meter standoff distance between interrogation antenna and sensor would provide robust design space for aircraft applications.
- Discoveries So Far: Present interrogation antennas require < 0.6m proximity to passive SansEC Sensors for effective resonance detection. Even closer proximity is required for carbon composite materials due to their higher conductivity.
- Challenges To Come: Developing new or enhancing present antenna technology and/or measurement systems in order to increase read-range for passive SansEC sensors.
- Partnerships: None planned at this time.
- Publications: FY12Q2. Results will be published in journal and/or conference papers.

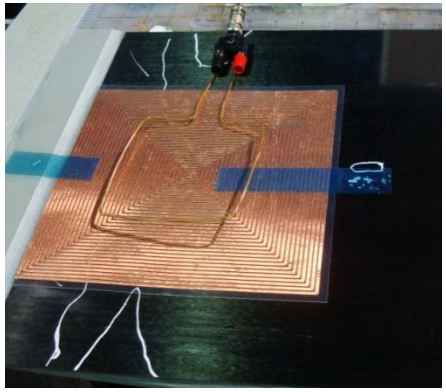
AEST4.3.13 SansEC Signal Penetration of Carbon Composites FY12Q4

Develop Lightning SansEC Sensor designs to resonate at frequencies permeable in composite materials. Develop computational EM tool to predict lightning SansEC sensors frequency resonance.

FY11				FY12				FY13				FY14				FY15			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4



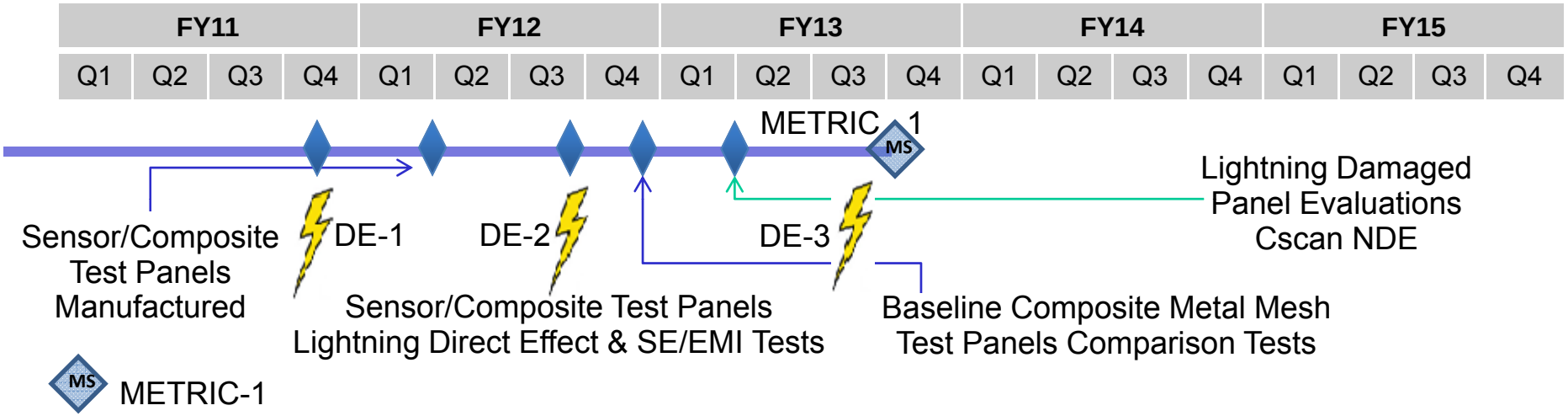
Demonstrate Lightning SansEC Sensor can detect and identify delamination, punctures and rips in composite materials.



- Justification: Successful completion of this research will provide new capability in composite damage diagnosis.
- Discoveries So Far: Recent experiments and preliminary modeling show that SansEC sensors can detect punctures and rips in dielectric composite materials.
- Challenges To Come: There is expected to be great challenge in developing SansEC sensors with electromagnetic fields that penetrate conductive carbon composites.
- Partnerships: None planned at this time.
- Publications: FY12Q4. Results will be published in journal and/or conference papers.

AEST4.3.14 SansEC FAA Lightning Certification Demonstration FY13Q3

Demonstrate Lightning SansEC sensors can adequately protect composite aircraft and expect to meet FAA certification requirements. Perform experimental evaluations to support validation of FAA certification.



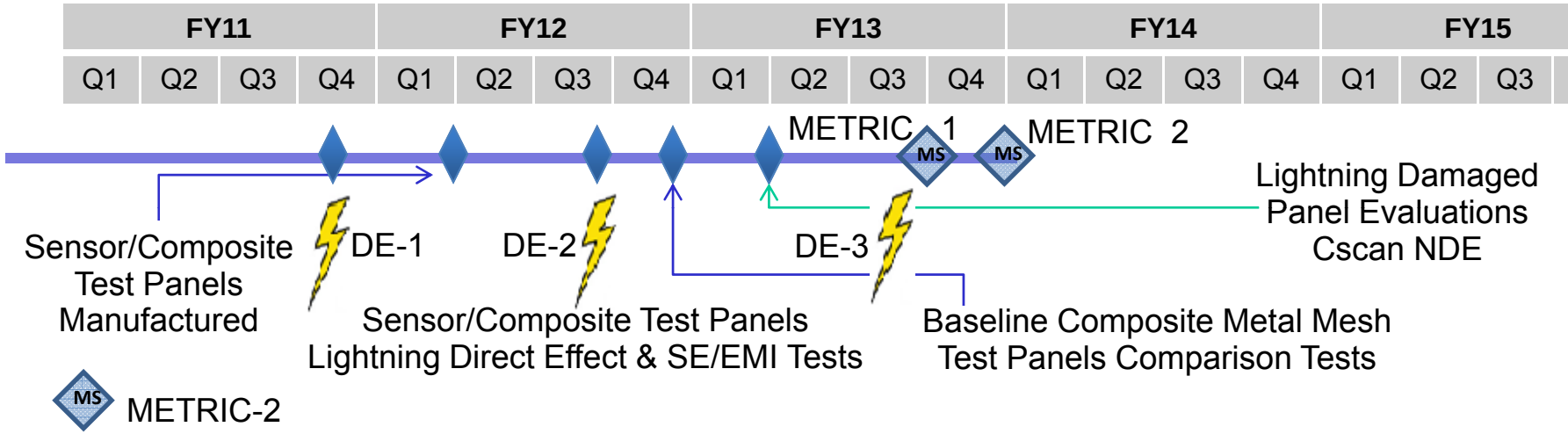
MS METRIC-1

Demonstrate Lightning SansEC Sensor will provide lightning strike protection comparable to metal mesh currently in use in composite aircraft. Direct effect tests will be conducted based on test requirements defined in the SAE ARP5412A (Aircraft Lightning Environment and Related Test Waveforms) document used to show FAA certification compliance.

- Justification: Successful completion of this research will show that SansEC technology can provide an equivalent level of lightning protection as present mesh technology.
- Discoveries So Far: promising feasibility
- Challenges To Come: Conductive Carbon Composite Panels
- Partnerships: None at this time. TBD
- Publications: FY13Q4. Results will be published in journal and/or conference papers.

AEST4.2.13 SansEC Multi-Functional Lightning Demonstration FY13Q4

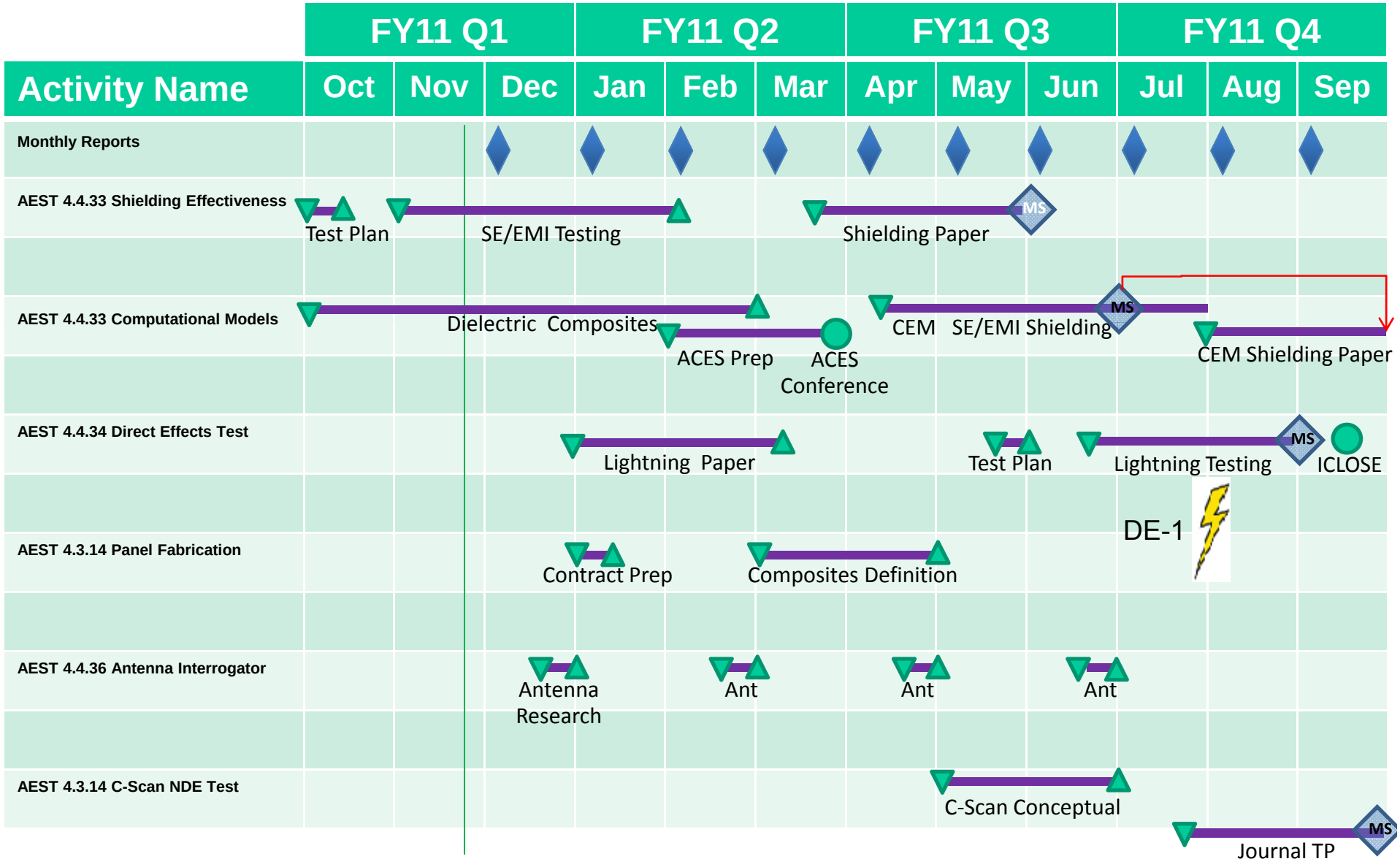
Ground-based demonstration of SansEC sensor that can detect damage in composite structures and provide the EMI shielding and lightning protection to replace the conductive mesh skin currently used on composite aircraft.

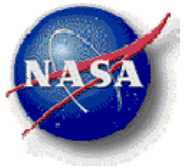


Lightning SansEC Sensors will demonstrate similar lightning strike protection and electromagnetic shielding performance as metal meshes used to protect composite aircraft. The sensors will further demonstrate the ability to detect delamination, moisture absorption, punctures and rips in composite aircraft skins.

- Justification: As a result of a successful demonstration, the SansEC technology can be considered a preferred alternative to the present mesh technology.
- Challenges To Come: Advanced work can be pursued to improve and optimize the technology for practical application
- Partnerships: None at this time. TBD
- Publications: FY13Q4. Results will be published in journal and/or conference papers.

SansEC Sensor Research



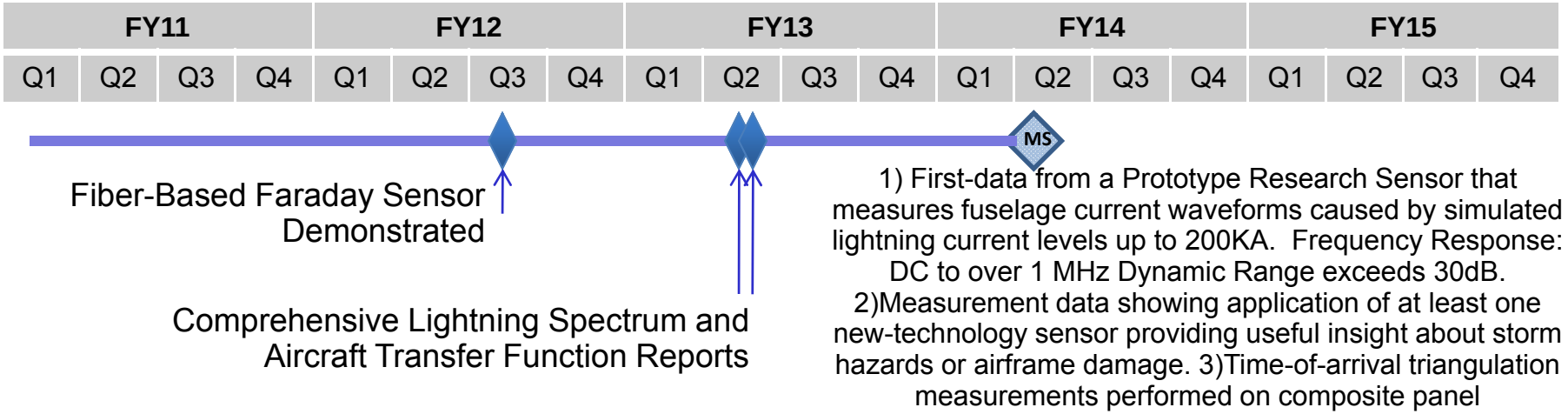


Lightning Environment Milestones

Milestone	Due Date	Milestone Title / *FTE POC*
AEST4.4.35	Mar. 2012	Fiber-Based Faraday Effect Sensor Research for Lightning Current Measurements / *T. Nguyen*
AEST4.4.39	Mar. 2013	Comprehensive Lightning Spectrum Data / *J. ELY*
AEST4.4.40	Mar. 2013	Comprehensive Aircraft Transfer Function Data / *J. ELY*
AEST4.3.17	Dec. 2013	Demonstrate new-technology sensors for lightning measurement / *T. Nguyen*
AEST4.3.18	Dec. 2013	Instrumentation & Flight Integration/ *J. ELY*
AEST4.2.12	Oct. 2015	Demonstrate prototype Lightning Strike Measurement System to capture in-flight lightning events / *J. ELY*

AEST4.3.17 New-Technology Sensors FY14Q1

Demonstrate fiber optic sensor of direct lightning current via polarization rotation caused by Faraday Effect. Leverage novel new sensing approaches becoming available for measuring X-Rays, Γ-Rays, millimeter, skin-depth leakage current, and other emissions from lightning and its attachment to airframes. Use of capacitive sensors, located inside an aircraft fuselage, locate lightning attachments using triangulation.

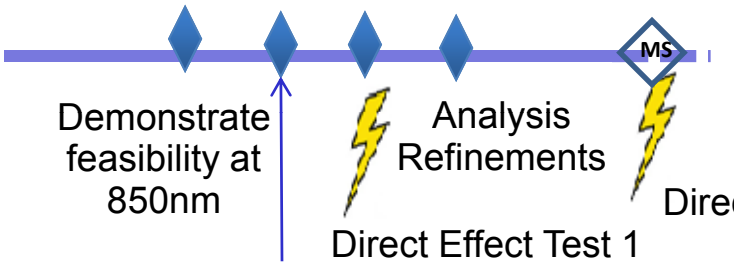


- Justification: New Optical Faraday technology sensor provides data suitable for determining total energy transfer, duration and waveform of entire lightning strike, is light-weight, and is immune to electromagnetic interference. Other new technology sensors allow small number of sensors to localize and assess airframe damage.
- Partnerships: USRP, GSRP, SBIR
- Publications: TBD

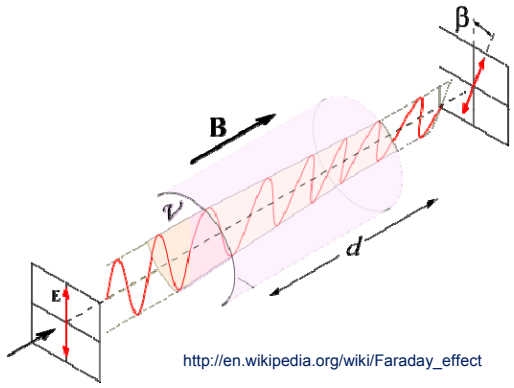
AEST4.4.35 Fiber-Based Faraday Optical Sensing FY12Q2

Design and implement a laboratory demonstration of 850nm, 1550nm and other (light wavelength) low-birefringent fiber and Faraday Mirror, used to sense lightning current waveforms in the LaRC HIRF Laboratory.

FY11				FY12				FY13				FY14				FY15			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4



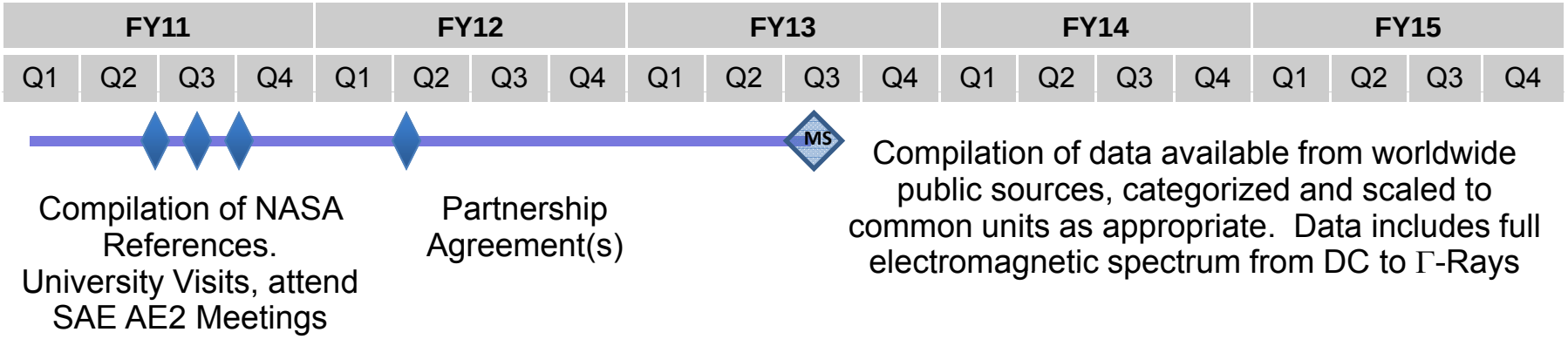
Laboratory Demonstration using spun or twisted fiber at reduced lightning threat level



- Justification: Will enable practical measurement of aircraft fuselage current waveforms and amplitudes. Capabilities not possible with existing sensors.
- Discoveries So Far: Wideband Source, Faraday Mirror, Light Wavelength Band, Twisted vs. Spun Fiber, Reduced Measurement Sensitivity
- Challenges To Come: Specialty Spun Fibers, High Detector Noise, 1310 or 1550 nm Setups, EMI, Packaging, Environmental Testing, Temperature Sensitivity, Data Acquisition, Software.
- Partnerships: None planned at this time.
- Publications: 2011 International Conference on Lightning and Static Electricity (ICOLSE). Truong Nguyen

AEST4.4.39 Lightning Spectrum FY13Q2

Compile lightning radio emissions data from available sources. Add new data for X-Ray and Γ-Ray, as well as millimeter and other spectrum. Categorize according to parameters such as cloud-to-ground, cloud-to-cloud, geographic location, atmospheric conditions, etc. Convert to common units as appropriate (i.e. E (f) at a common distance). Evaluate for correlation between lightning radiated emissions and storm hazards.



- Justification: Lightning emissions occur in radio, microwave, millimeter, terrahertz, optical, X-Ray and Γ–Ray spectrum. Comprehensive resource is needed as a basis for sensor technologies used for lightning strike damage assessment and avoidance of storm hazards.
  - Damage Assessment: Determine severity of lightning attachments to aircraft
  - Damage Avoidance: New, multispectral data provide significantly improved understanding of electric field, leader formation, lightning flash characteristics and how they relate to storm hazards.
- Partnerships: GSRP, SAE AE2 Committee, Universities
- Publications: TBD

AEST4.4.40 Composite Aircraft Transfer Function FY13Q2

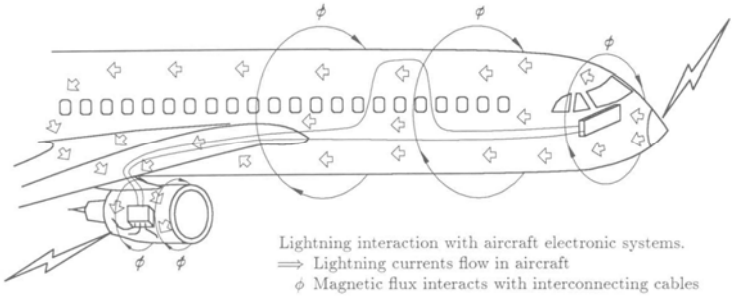
Compile existing aircraft transfer function data available from the FAA, industry and universities. Space Act agreements and/or Annexes executed, allowing new transfer function measurement data and comparison of aluminum and composite airplanes.

FY11				FY12				FY13				FY14				FY15			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

Compile existing aircraft transfer function data available from the FAA, industry and universities

Partnership Agreement(s)

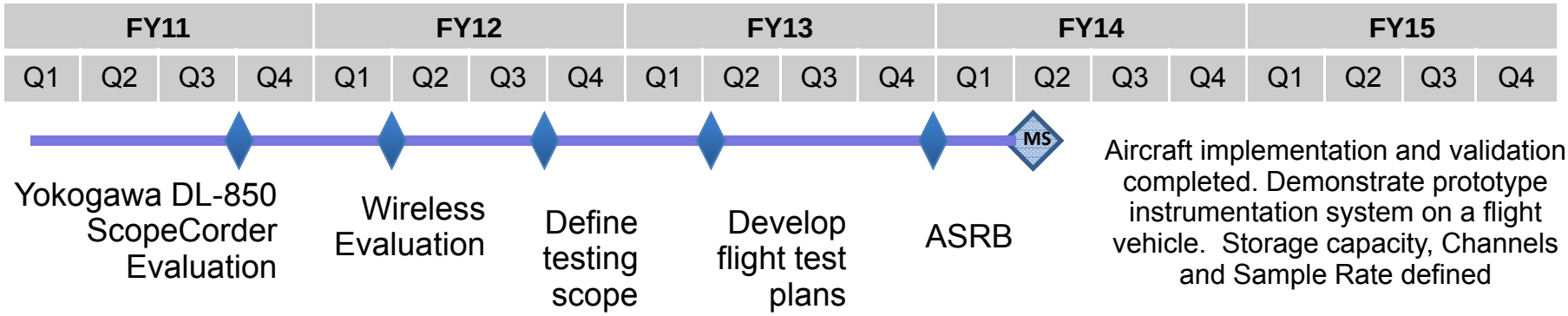
Publicly accessible update of aircraft lightning coupling data, including composite aircraft



- Justification: Estimation of external lightning environment may be determined from on-board sensor data. New certification test standard waveforms for indirect effects can be developed for composite airframes.
- Publications: TBD

AEST4.3.18 Instrumentation & Flight Integration FY14Q1

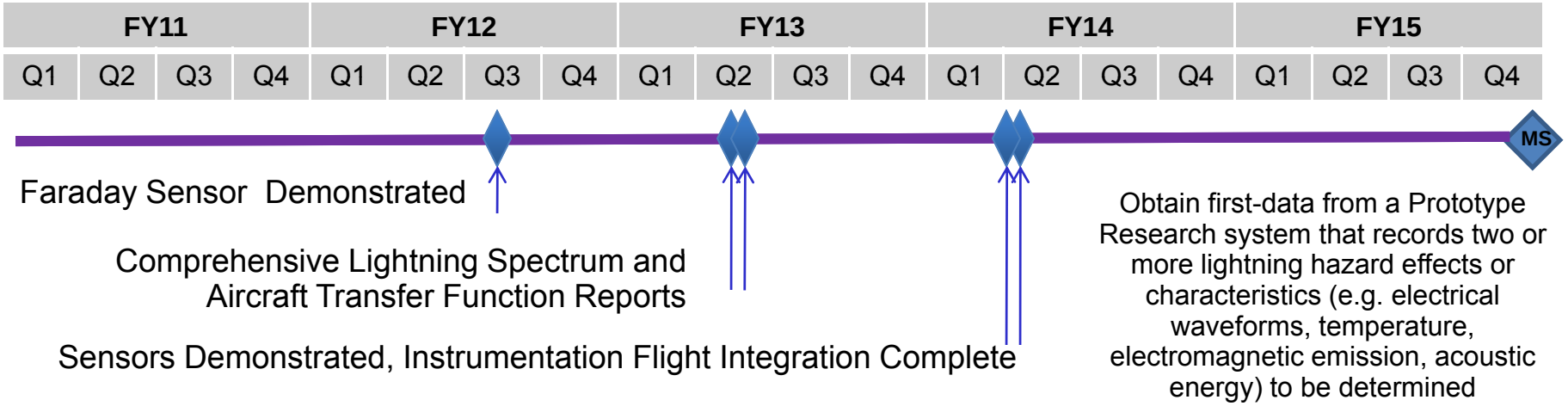
System design, fabrication and demonstration of prototype instrumentation system. Define testing scope, develop flight test plans, and address flight-test safety review board requirements. Develop and ground test LSMS instrumentation and data acquisition package. Leverage existing flight resources with NASA, NOAA, NSF, etc.



- Justification: Instrumentation system performance needs to be acceptable for lightning sensors, and suitable for flight.
- Publications: TBD

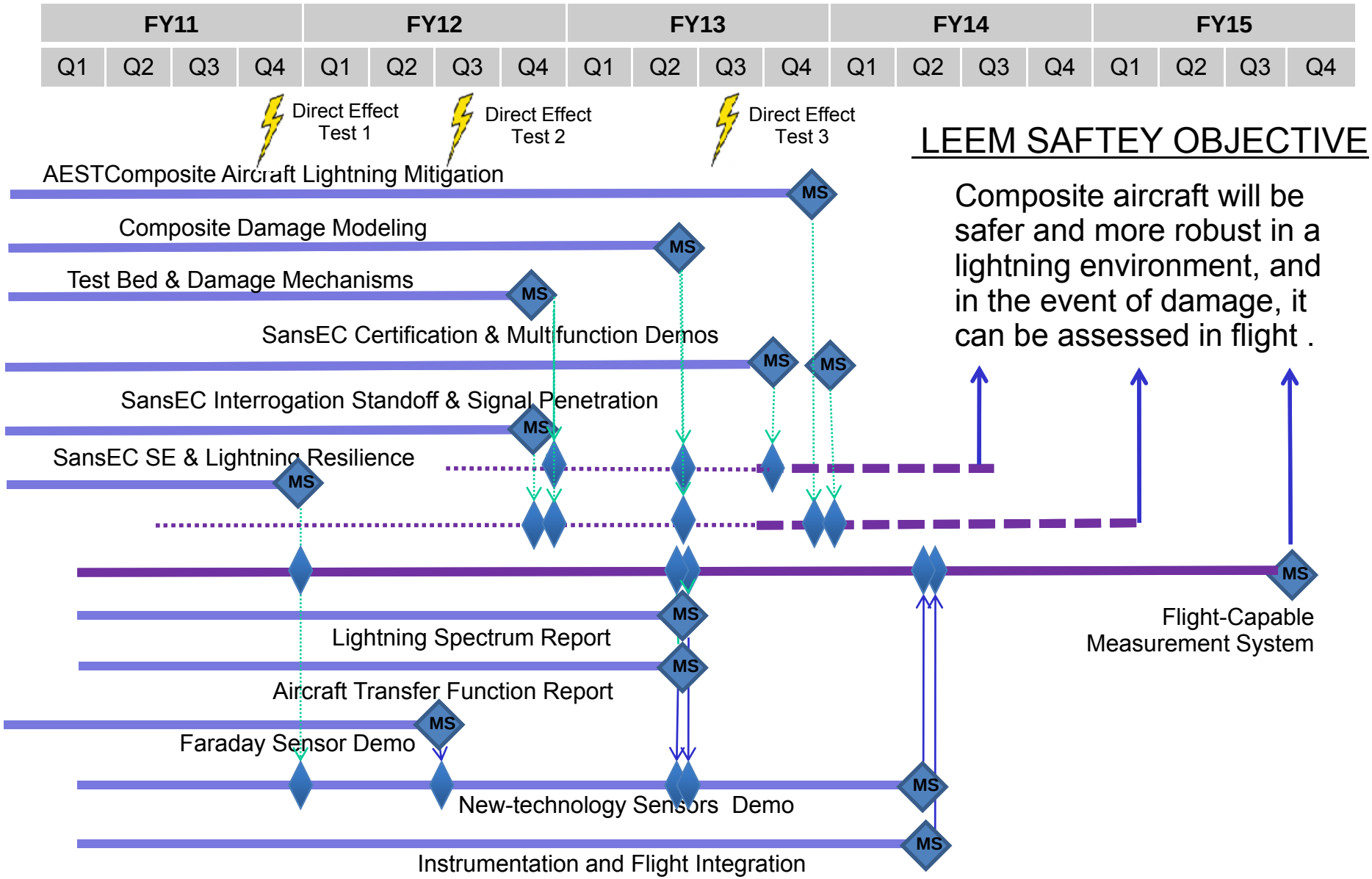
AEST4.2.12 Flight Demonstration FY15Q4

Demonstrate a prototype Lightning Strike Measurement System to capture in-flight lightning events which pose risk to flight safety. Prototype shall be suitable for installation into existing research vehicles operating in lightning environments.



- Justification: Improved lightning certification test standards can be developed that better represent the statistical lightning environment. An on-board lightning measurement system can be developed and deployed in aircraft to simplify inspections and support damage severity safety assessments after a strike.
- Publications: TBD

LEEM Milestone Roadmap



LEEM SAFTEY OBJECTIVE

Composite aircraft will be safer and more robust in a lightning environment, and in the event of damage, it can be assessed in flight .

Direct Effect Test 1 Roadmap