Perception-Influenced Design (PID) for Acoustics

Dr. Stephen A. Rizzi
NASA Langley Research Center
s.a.rizzi@nasa.gov

MDAO and Systems Analysis Workshop
NASA Langley Research Center
May 13-14, 2014

Outline

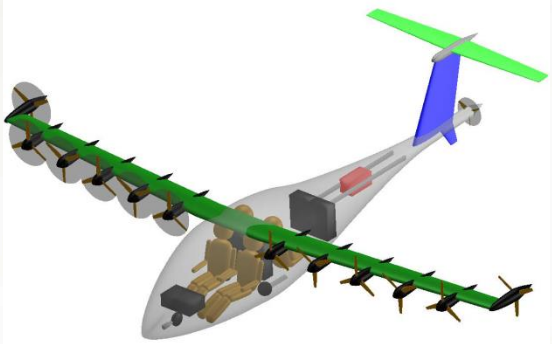
- Perception-Influenced Design: Overview
  - Goals & Objectives
  - PID in MDAO
  - Linkages to new NASA aero programs/projects, FAA, DoD, OGA
- FY14 Activities
  - Validated aircraft acoustics tools and methods for low noise
    - ANOPP2 framework
    - Scattering methods
    - Auralization framework
  - Deployment of PID against other projects
- Roadmap (today to 2017 and beyond)

Perception-Influenced Design

Delivering low noise solutions in operational environments

- NASA and industry acoustic research currently prioritized by source noise rankings based on specific metrics
  - Current noise metrics (e.g. certification metrics) are assumed to fully capture noise annoyance/impact on “community”
- Revolutionary/transformative air vehicles
  - Have unique configurations (from very small to large)
  - Have unique propulsion systems (e.g. electric motors, multi-rotor)
  - Have new missions
    - How and where they operate are different from other aircraft
    - Alternative certification procedures may be required
    - Provide guidance in determining certification metrics, i.e. sonic boom
- Alternative low noise design strategies are <u>critical</u> to support development of new configurations flying in broad range of operational environments

How well does EPNL reflect community noise impact for these systems?



Perception-Influenced Design

Integrating noise perception into multidisciplinary air vehicle design

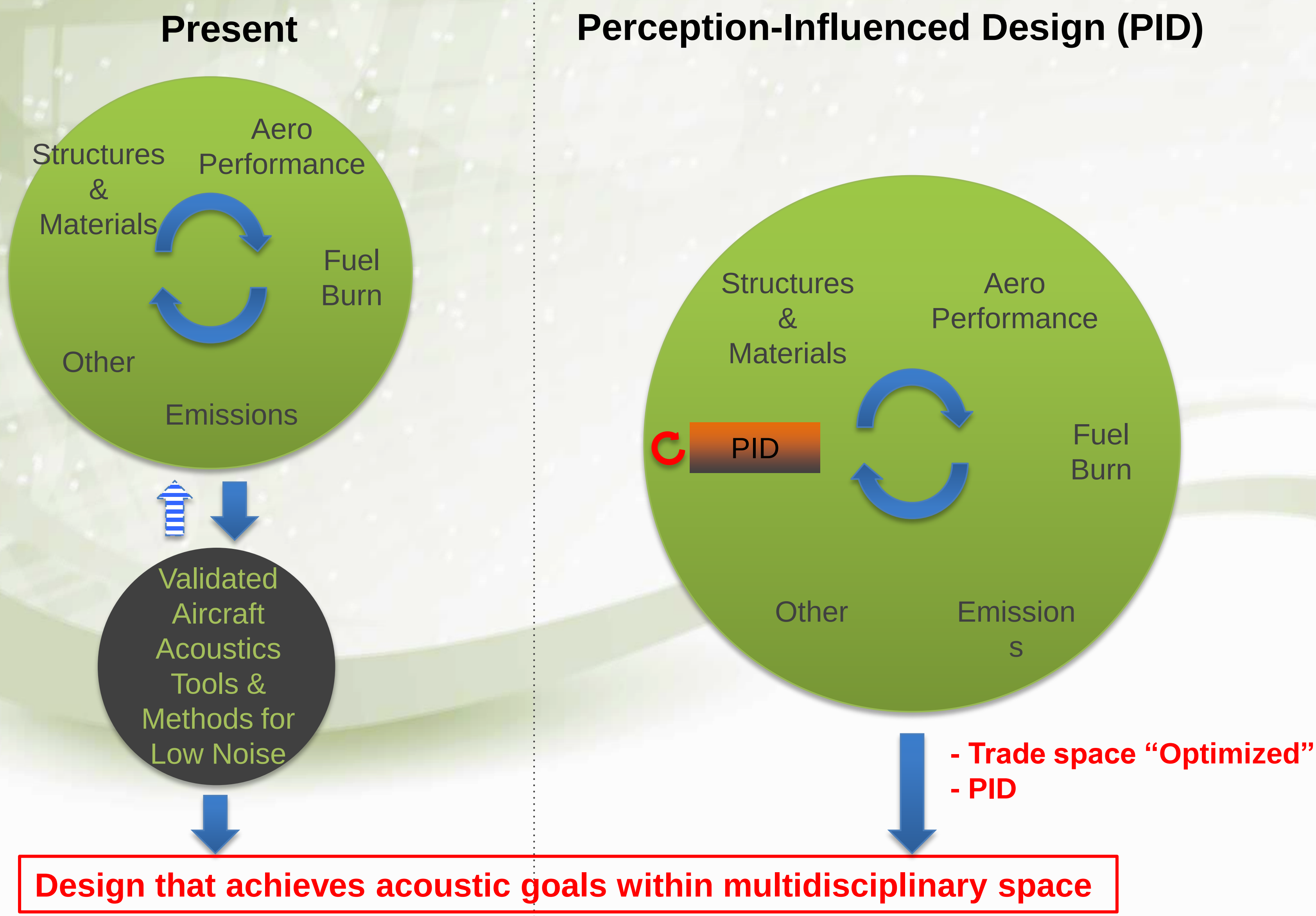
- Objective
  - Enable unconstrained introduction of new air vehicles by reducing undesirable aspects of air vehicle noise through integration of acoustic-defined constraints and noise perception into multidisciplinary air vehicle design
  - Design capability must be cross-cutting and support full range of strategically important flight vehicle classes of national interest (NASA, FAA, OGA & industry)

- Approach
  - Integrate acoustic-defined constraints and noise perception into multidisciplinary air vehicle design: PID
  - Develop comprehensive suite of validated aircraft acoustic tools and methods that permit PID to enable unconstrained introduction of new air vehicles
  - Deploy PID against air vehicle technologies and systems in selected AOSP, AAVP, IASP, TACP projects
  - Demonstrate PID and validate tools/process in relevant environments via laboratory (AAVP) and flight (AOSP & IASP) projects

Increasing TRL

Perception-Influenced Design

A new dimension to a constrained multidisciplinary design space

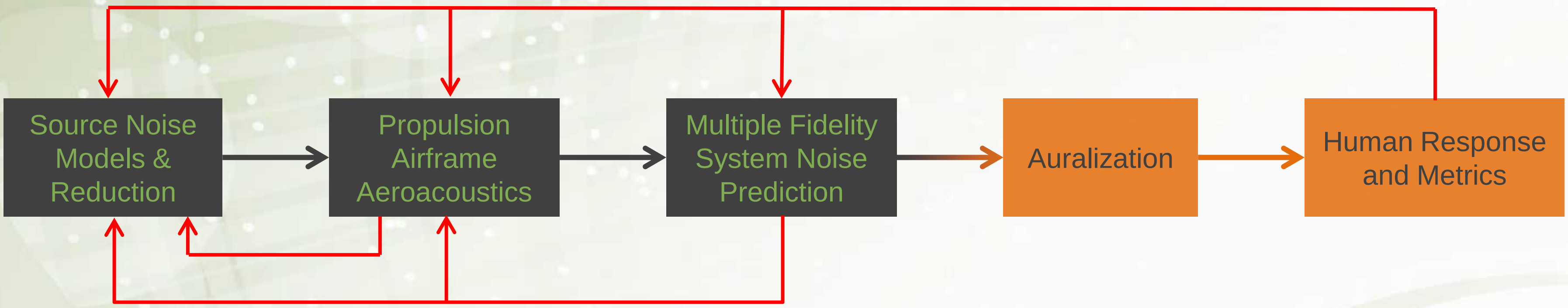


Perception-Influenced Design

A synthesis of validated acoustics tools and methods plus human perception

Validated Aircraft Acoustics Tools & Methods for Low Noise

Human Perception



- Source Noise Models
- Source Noise Reduction Methods
- Measurement Methods
- En Route Noise
- RTM RCA

- Scattering Methods
- Installed Sources

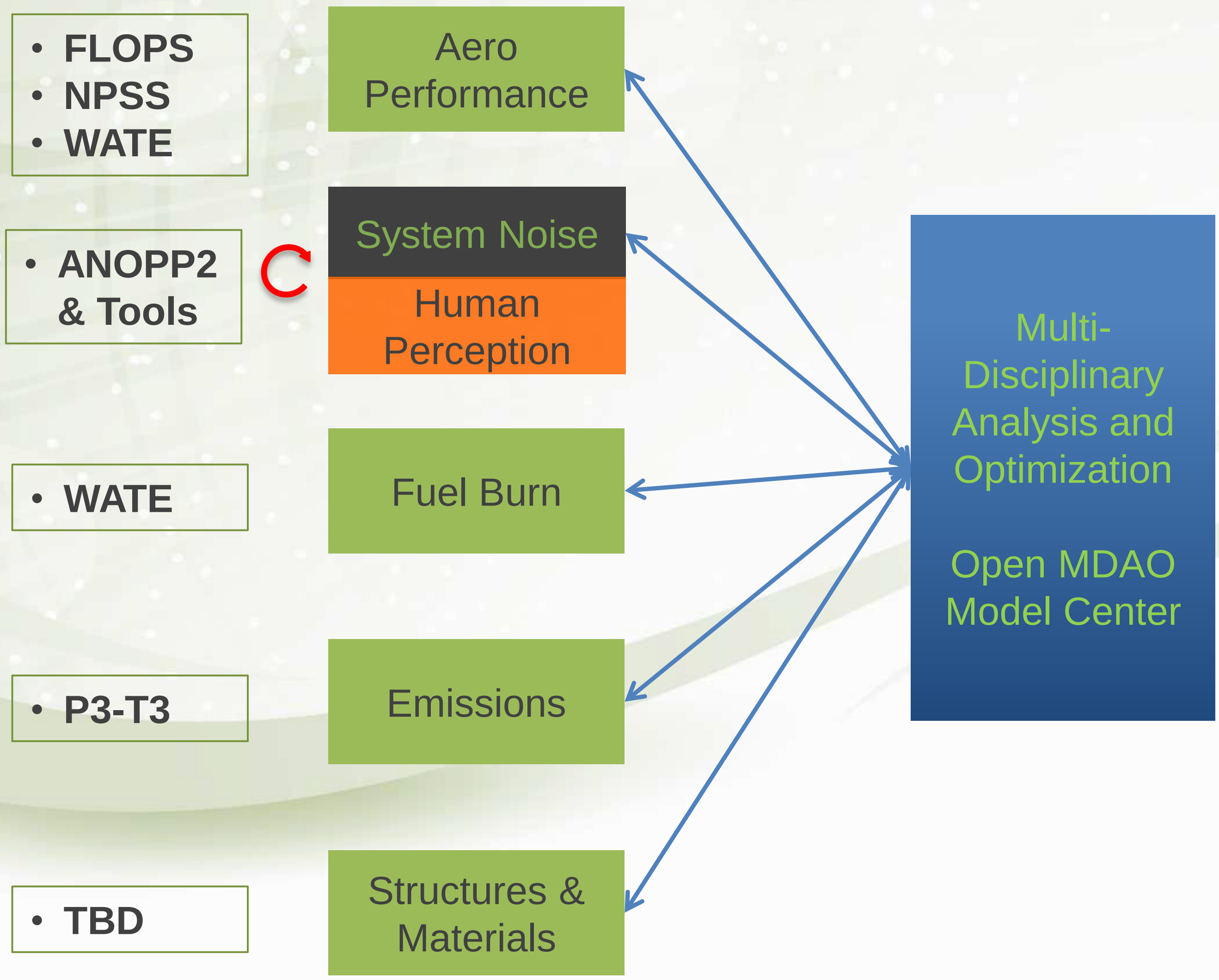
- ANOPP2
- ANOPP
- AAM
- INM
- EDS
- Propagation Models
- Adjoint methods
- Linkages to RTM MDAO

- NAF
- CNoTE

Psychoacoustic Labs
- EER
- IER
- Boom Simulator

Perception-Influenced Design

MDAO with PID



Perception-Influenced Design

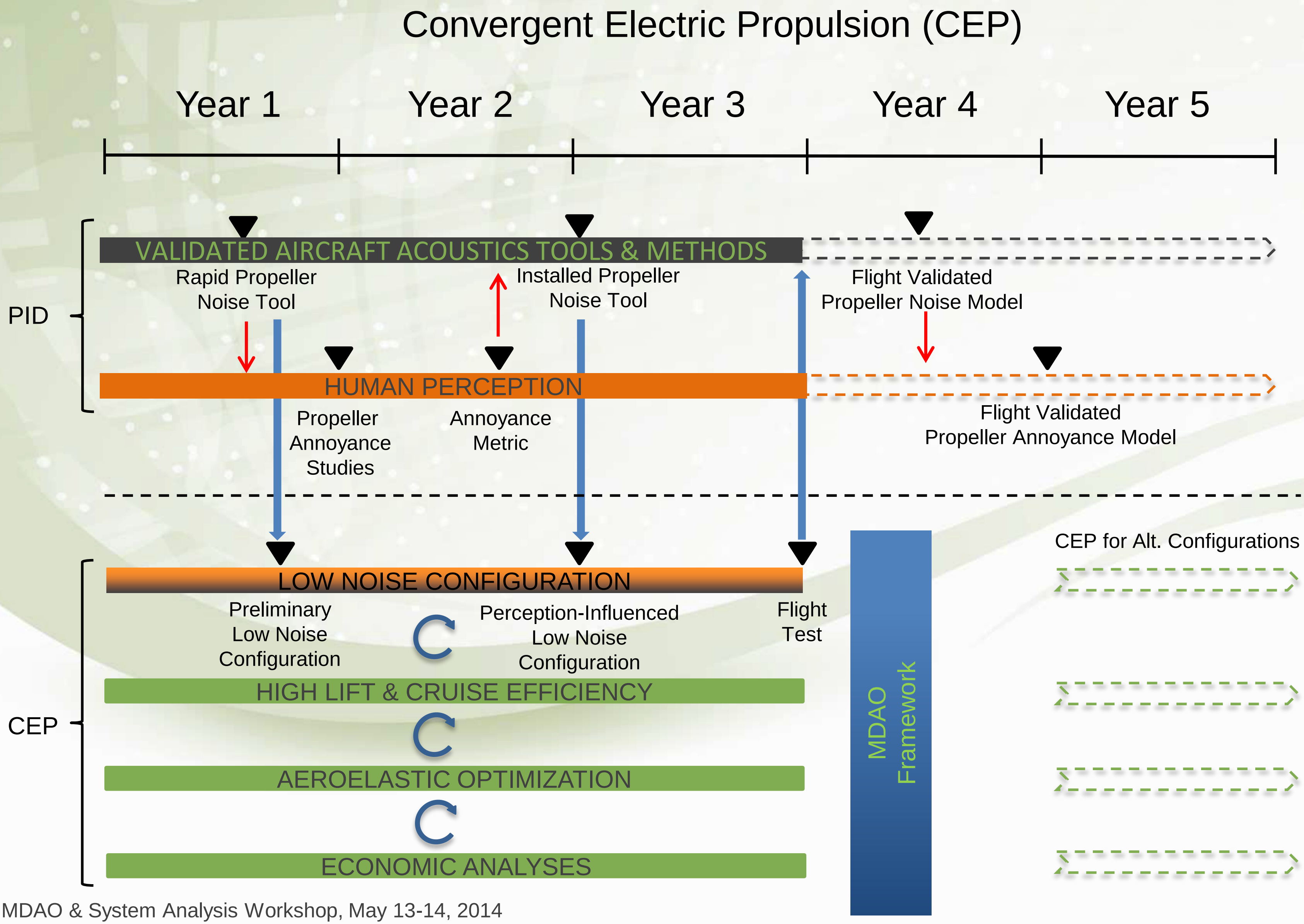
Linkages to Other NASA Aero Programs

- Linkage to RTM CAS Project, AOSP, AAVP, IASP Programs
  - Deploy PID against air vehicle technologies and systems in –
    - AOSP – SMART NAS & SASO projects
    - AAVP – A^2T^2, RVLT, HS & Adv. Comp projects
    - IASP – ERA & UAS in NAS projects
    - TACP – CAS projects
  - Demonstrate PID and validate tools/process in relevant environments –
    - AOSP – Airspace technology demo projects
    - AAVP – AETD facilities
    - IASP – Flight demo projects

- PID can have simultaneous deploy/demonstrate links to any NASA Aero projects having some element of noise. Two notional deployments follow:
  - TACP/CAS – Convergent Electric Propulsion Technology Integration
  - AAVP/A^2T^2 – Double Bubble Boundary Layer Ingestion

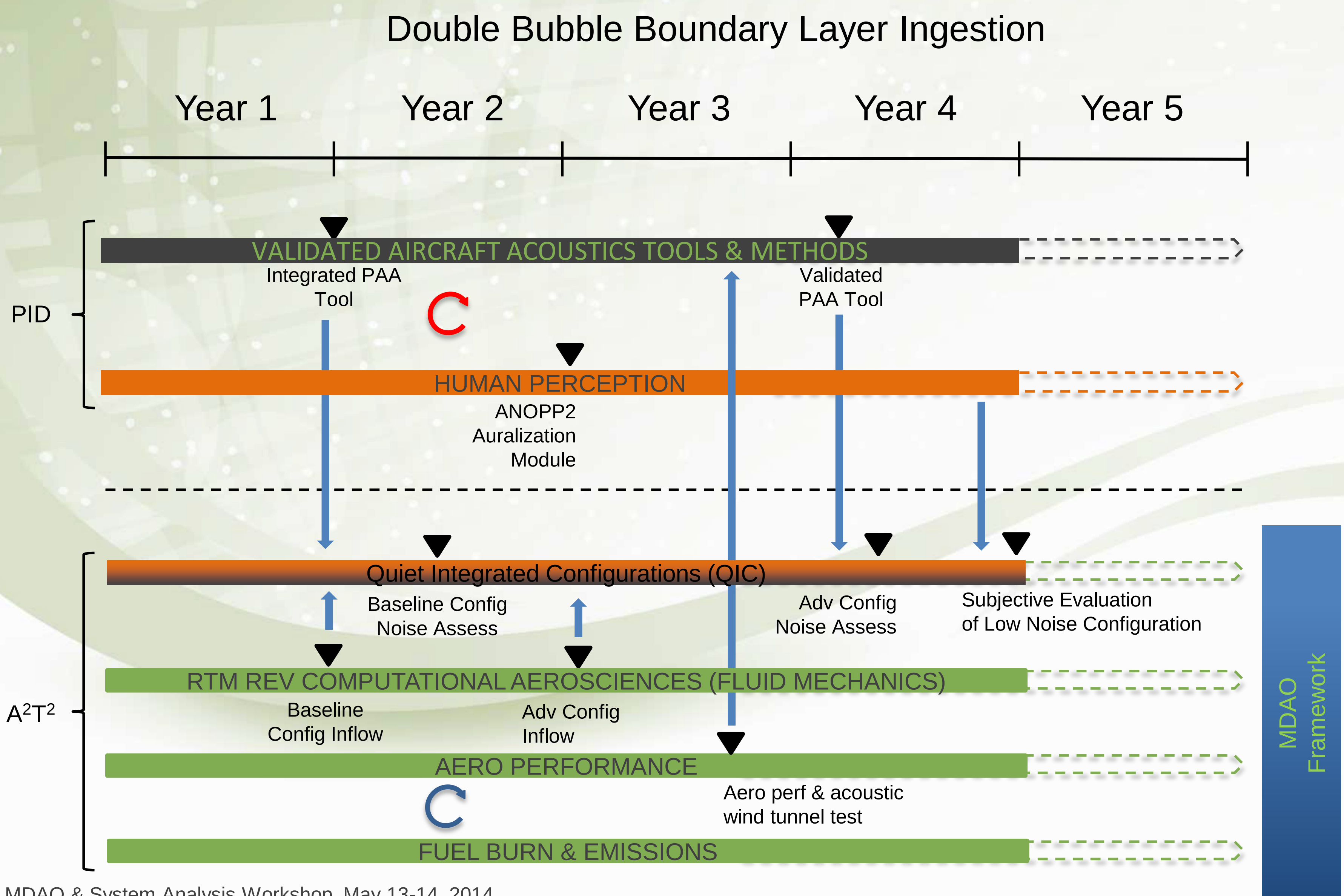
Perception-Influenced Design

RTM/PID – CAS/CEP Deployment [EARLY DRAFT – PLANNING IN PROGRESS]



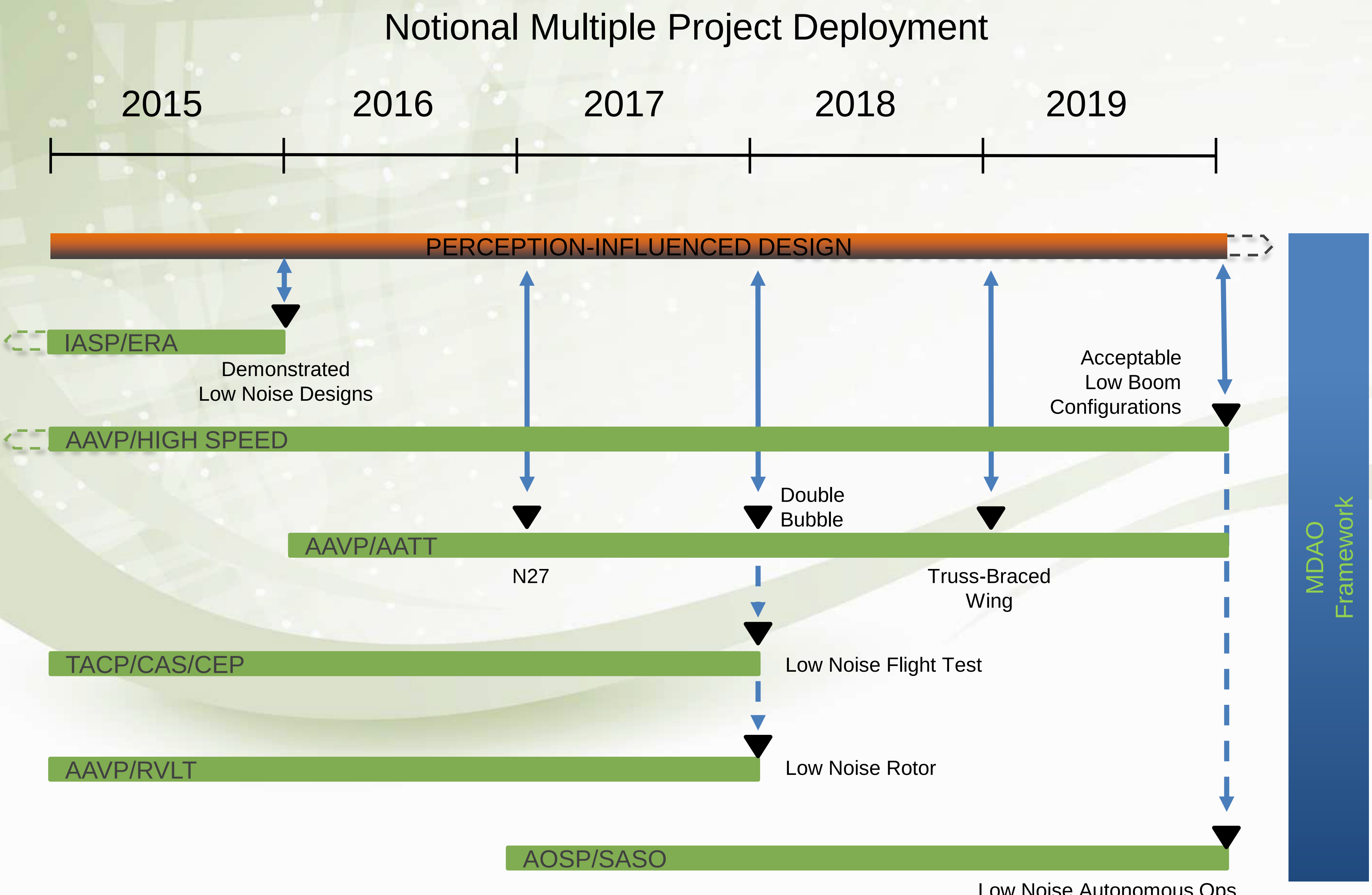
Perception-Influenced Design

Notional RTM/PID – AAVP/A²T² Deployment



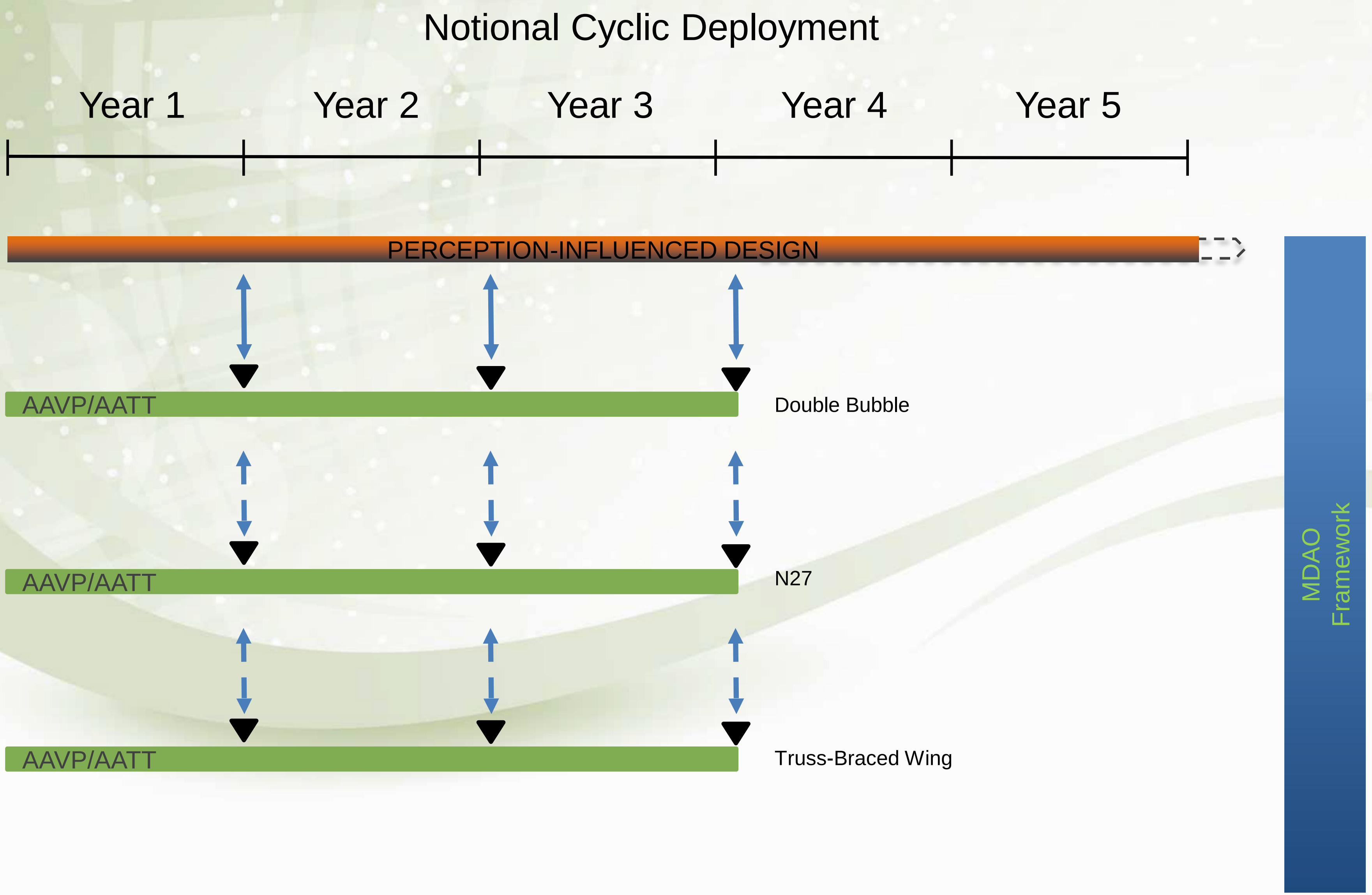
Perception-Influenced Design

Simultaneous deployment across NASA Aero projects



Perception-Influenced Design

Cyclical deployment for project vehicle design



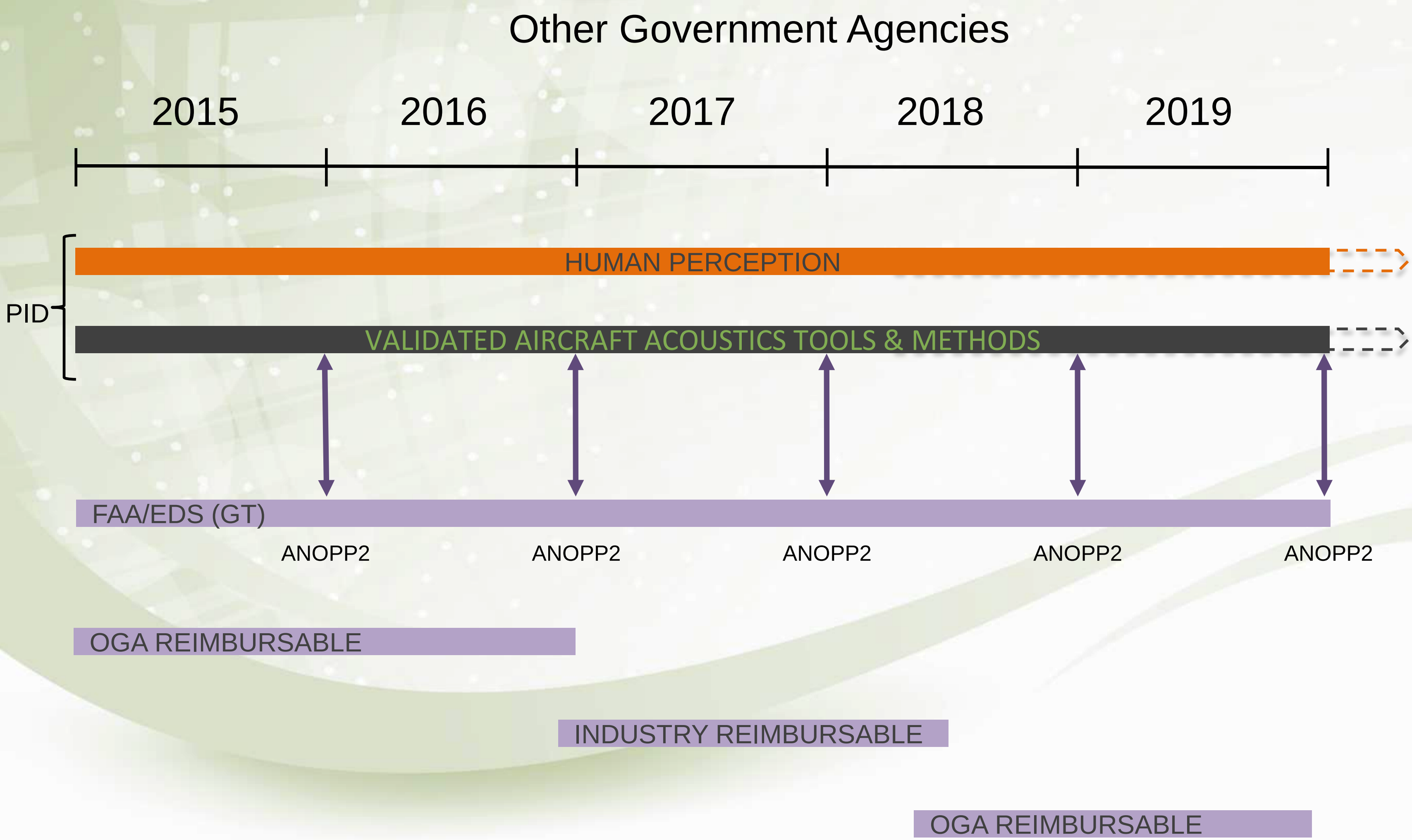
Perception-Influenced Design

Deployment to Other Government Agencies

- DARPA/IARPA and OGA
  - Human detection of advanced vehicles
  - Low noise configurations, components and flight paths
- ARMY
  - Human detection of rotorcraft
  - Low noise configurations, components and flight paths
- Air Force
  - Community noise
- FAA
  - Environment Design Space (EDS) currently uses ANOPP. Need to coordinate migration path to ANOPP2
  - UAV noise certification. Guidance needed to develop applicable metrics.
  - CLEEN, CLEEN II
- Industry
  - Range from large commercial/military transports to general aviation (including rotorcraft), large and small UAVs: example industries include:
    - Boeing, NG, Lockheed, GE, etc.

Perception-Influenced Design

Deployment to Other Government Agencies



Outline

- Perception-Influenced Design: Overview
  - Goals & Objectives
  - PID in MDAO
  - Linkages to new NASA aero programs/projects, FAA, DoD, OGA

- FY14 Activities
  - Validated aircraft acoustics tools and methods for low noise
    - ANOPP2 framework
      - MDAO coupling
      - Cross-cutting tools and solution integration
    - Scattering methods
    - Auralization framework
  - Deployment of PID against other projects

- Roadmap (today to 2017 and beyond)

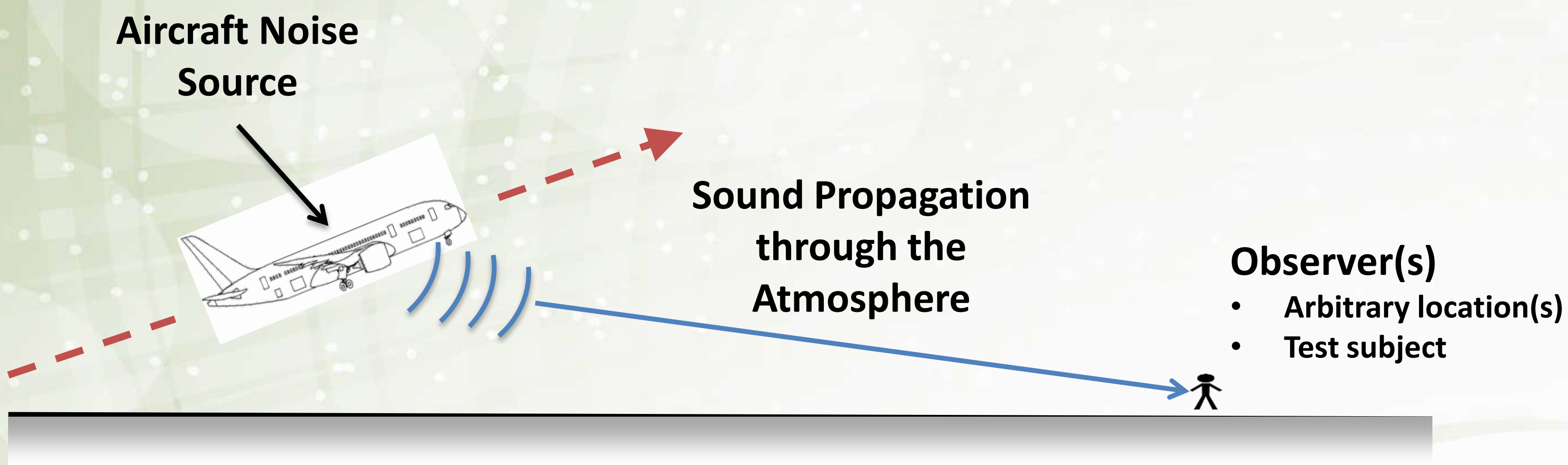
ANOPP2 Objectives/Requirements

- **Provide a 'noise tool' that can be used predict current and future aircraft noise, understand noise physics, and evaluate/explore noise technologies.**

- **Users:**
  - Aeroacoustic research community (NASA, industry, academia)
  - MDAO systems analysis community (NASA, FAA, industry, academia)

- **Key applications and requirements to enable:**
  - Developing noise reduction technologies through **understanding** of noise generation of isolated and installed aircraft components
  - Acoustic prediction capability for **Perception Influenced Design (PID)** and metric evaluation
  - **Evaluating** the potential noise reduction technologies on components, within subsystems and at the aircraft level.
  - **Assessing** aircraft noise during flight and community noise metric determination
  - Results that can be used to **prioritize and focus** aircraft (and components) noise research for NASA and other government agencies (FAA EDS efforts, DoD)
  - A noise framework capability for NASA, OGA, industry and academia
  - Relevance for years to come

Requirements for Aircraft Noise Prediction



- Flight Path
  - Position, time, velocity, orientation angles, throttle setting, flap setting
- Engine Settings
  - Performance (velocities, temperatures, densities) as function of Mach number, throttle setting, altitude
- Airframe Properties
  - Wing properties, body geometry, landing gear configurations, slat/flap configuration
- Additional Information
  - Atmospheric properties, ground specifications, observer locations

ANOPP2 Aircraft Noise Prediction

Outline of *Application* using ANOPP2

Aircraft Definition and Mission
- Atmosphere Data Structure
- Flight Path Data Structure
- Engine System Data Structure
- Geometry Data Structure
- Observer Data Structure

Select 'Functional Modules' (partial list)
- ANOPP
- Flight Effects, Propagation
- PAA Effects
- Surrogate Model
- Farassat's Formulations
- Wind Tunnel Measurements

Predict Noise for Mission
- User defines computational settings
- Results stored on Observer Data Str.

Results: noise, mission, aircraft

ANOPP2 Configuration Files

- Flight Path Configuration ← Externally Computed Flight Path Definition (ex: FLOPS)
- Engine State Data ← NPSS: Engine State
- Measurement Data ← Measured/Predicted Noise
- Flow Data ← Externally Computed Flow Properties
- Plugin Configuration ← External Functional Noise Module

- Acoustics
  - Time histories, 1/3rd-Octaves, Narrowband
    - Auralizations
  - PNL, PNLT vs. emission angle
  - EPNL, SEL (certification point, contour)
- Aircraft/Prediction Information and Metadata
  - Flight Trajectory (Throttle, Mach, Altitude, etc.)
  - Engine State
  - Source Geometric and Flow Properties

Application Programming Interfaces (APIs)

- Communication through 'User Code'
  - User code calls routines defined in ANOPP2 library
  - Routine performs operations or returns information
  - Routines are grouped into APIs
    - Flight Path API, Observer API, Command Executive API, etc.
    - Development of APIs can occur simultaneously and independently
- APIs are stand-alone libraries
  - Do not need to use (or know how to use) entire ANOPP2
  - Use API specific to a certain task
  - Higher level libraries are built upon lower level libraries

```
intSuccess = a2f_aa_epnl (fltTime, fltPNLT, fltEPNL, fltD, fltTimeRange)
```

Essential Steps in ANOPP2 Application

Outline of *Application* using ANOPP2

Aircraft Definition and Mission
- Atmosphere Data Structure
- Flight Path Data Structure
- Engine System Data Structure
- Geometry Data Structure
- Observer Data Structure

Select 'Functional Modules' (partial list)
- ANOPP
- Flight Effects, Propagation
- PAA Effects
- Surrogate Model
- Farassat's Formulations
- Wind Tunnel Measurements

Predict Noise for Mission
- User defines computational settings
- Results stored on Observer Data Str.

Results: noise, mission, aircraft

ANOPP2 Fortran Application

! Include ANOPP2's include file
include "ANOPP2.api.f90"

! Initialize ANOPP2
intSuccess = **a2f_exec_init_api** ()

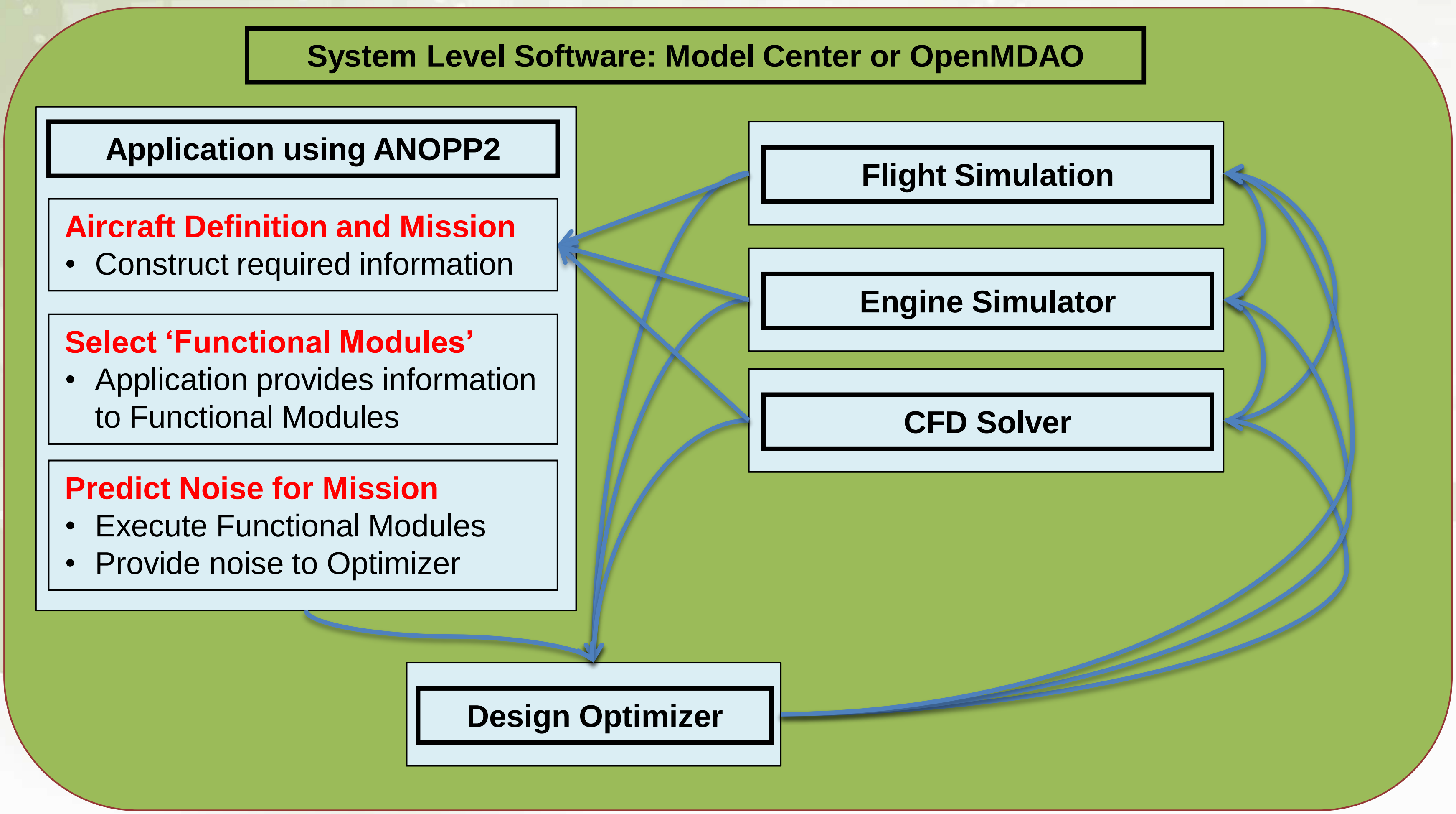
! Define Data Structures
intSuccess = **a2f_obs_create** (intObserver Tag, 'Observer.config')

! Create Functional Module
intSuccess =
a2f_exec_create_functional_module
(intAnoppTag, 'Anopp.config', [intObserverTag], intResultTag)

! Create and Execute Mission
intSuccess =
a2f_exec_create_mission (intMissionTag, [intAnoppTag])
intSuccess = **a2f_exec_execute_mission** (intMissionTag)

! Export Results
intSuccess =
a2f_obs_export
(intObserverTag, intResultTag, 'Results.dat', a2_aa_epnl)
intSuccess =
a2f_obs_get_epnl (intObserverTag, intResultTag, fltEpnl)

ANOPP2 in System Level Environment



ANOPP2 within Model Center and OpenMDAO

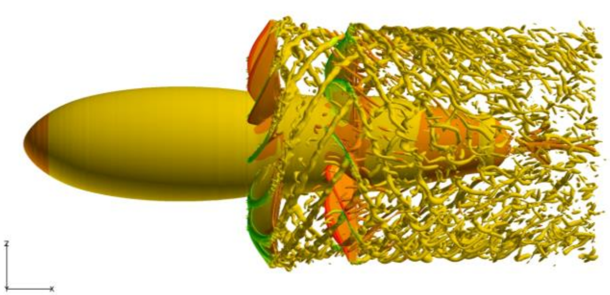
- 2014 Focus: Model Center Coupling
  - Achieve Loose Coupling
    - Reduce the information required to be passed between Model Center and ANOPP2
      - Provide some acoustic feedback to optimizer using ANOPP2's framework
      - Utilize methods within ANOPP2 that require less information (lower resolution)
    - Focus on proof of concept, plan follow on activities for tighter coupling with higher resolution methods
    - Derivatives and sensitivity
  - Status
    - Hooks identified and effort started
  - Exit Criteria
    - Demonstration for 737 using ANOPP within ANOPP2. (Sept 2014)
    - Demonstration for HWB with scattering method (FSC, DIM3) (Sept 2015)

- 2015 Focus: OpenMDAO Coupling
  - 2014: Python interfaces for ANOPP2 being developed
  - Build upon lessons learned in 2014 with Model Center
  - ANOPP2 python interface defined and tested with 2012 version of OpenMDAO
  - Investigating/implementing adjoint solutions

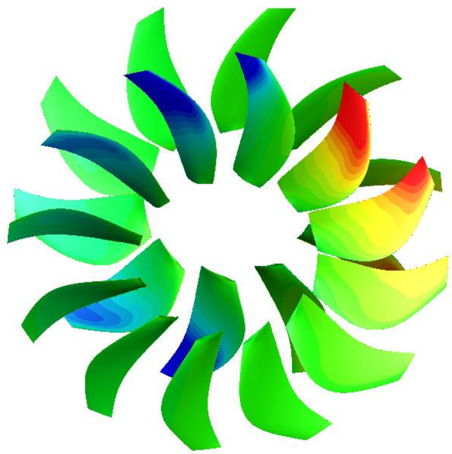
Cross-Cutting Capability Under AS

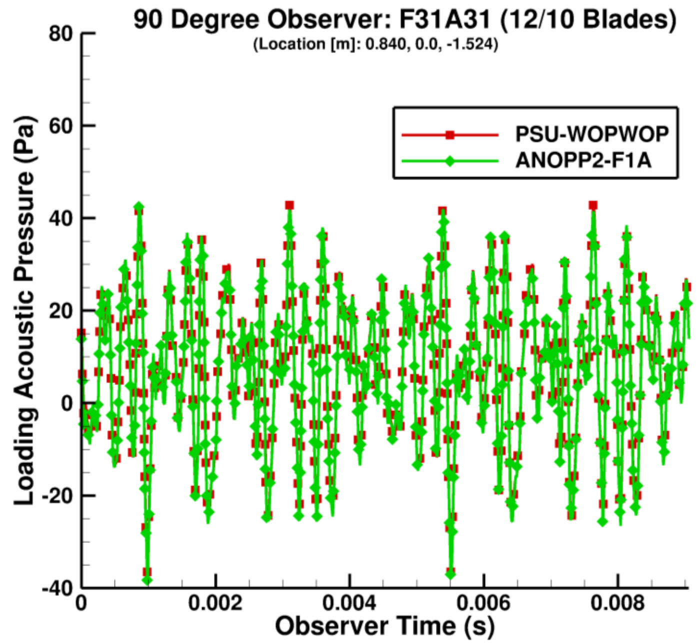
- Development of CFD based prediction methodology
- Implementation of Farassat's Formulations (F1A, F1, G1A, etc.)
  - Free-space Green's function solution to Ffowcs-Williams and Hawkings equation
- AS funded due to cross-cutting nature
- Applicable to several different projects
  - Currently utilized in RW and FW

Overflow Solution



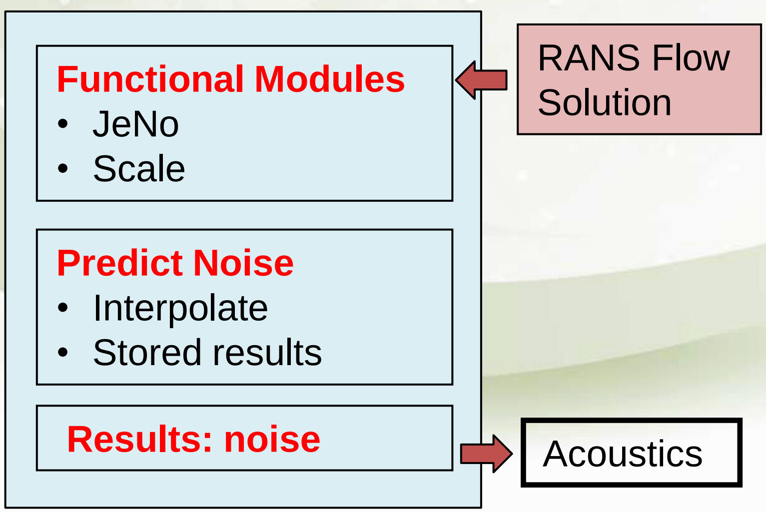
ANOPP2-F1A Metadata

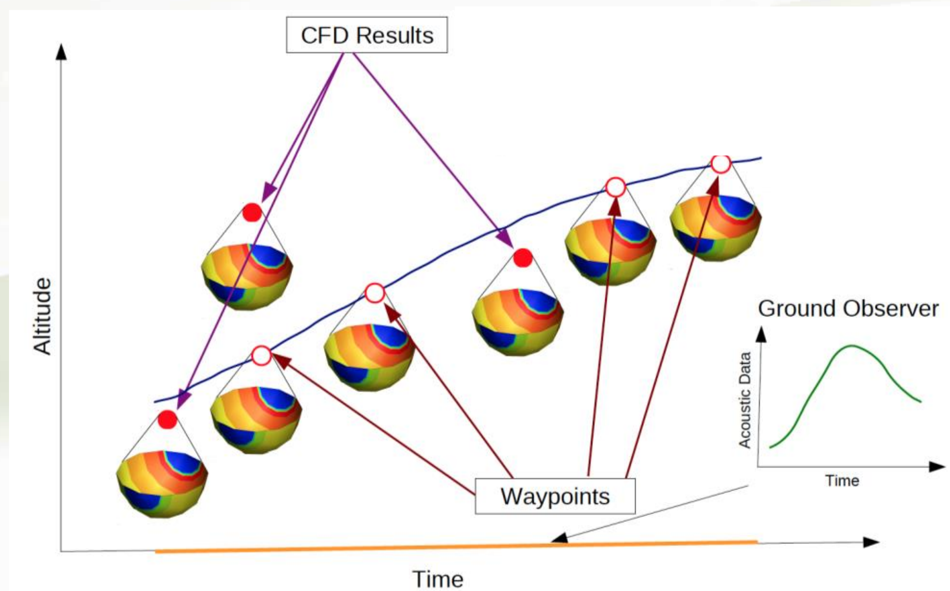




Project Supported Tool Development

- Incorporation of jet noise code (JeNo)
  - HS funded implementation due to project specific requirements
  - Coupling of CFD based prediction method into ANOPP2 framework
    - Tackle method specific speed bumps such as restart files, optimized computations (reduce repeated calculations between different flight paths)
- Required AS support for additional ANOPP2 tools that are cross-cutting
  - Macro to interpolate noise hemispheres from predictions using several CFD datasets onto flight path specific flight conditions
  - Macro's for user defined scaling laws





Outline

- Perception-Influenced Design: Overview
  - Goals & Objectives
  - PID in MDAO
  - Linkages to new NASA aero programs/projects, FAA, DoD, OGA

- FY14 Activities
  - Validated aircraft acoustics tools and methods for low noise
    - ANOPP2 framework
    - Scattering methods
      - Time domain (NRA)
      - FSC, DIM3 integration in ANOPP2
    - Auralization framework
  - Deployment of PID against other projects

- Roadmap (today to 2017 and beyond)

Scattering/Shielding Methods

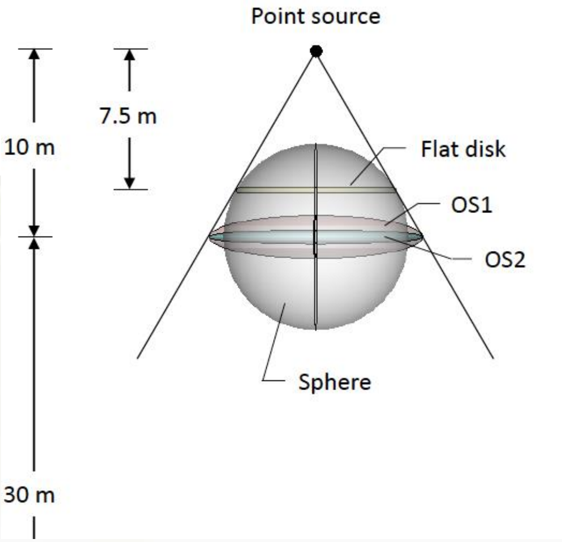
- **ANOPP: WING module**
  - Based on semi-infinite diffraction edge theory (Maekawa & Beranek)
  - Limited geometries ("wings" represented as quadrilateral), No phase information retained

- **DIM3 (based on MIT diffraction integral method)** (ERA: PI: Spakovszky, POC: Burley)
  - Based creeping ray effect modeled using Geometrical Theory of for deep shadow region & wedge diffraction potential (transition region), no frequency restrictions
  - 3-D geometry input effects for edge curvature and reflections modeled
  - Fast (~1 min), no frequency restrictions

- **Fast Scattering Code (FSC)** (SFW NRA (ended 2012): PI: Dunn, POC: Nark)
  - Can handle geometric details: i.e. edges, 'corners'
  - No frequency restrictions other than resource limitations
  - Application/validation on HWB: Broadband Engine Simulator (BENS) predictions

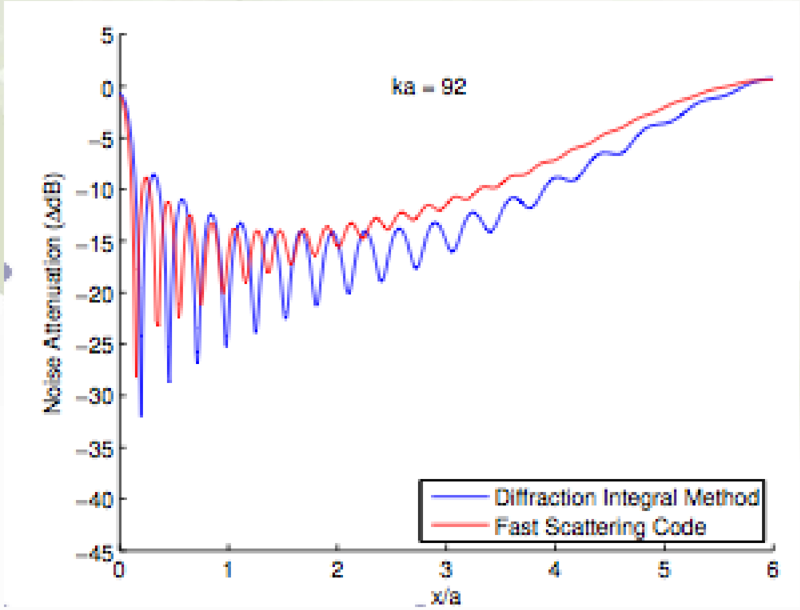
- **Time Domain BEM : TDBEM** (AS NRA (Ongoing): PI: Fang Hu, POC: Nark)
  - Scattering solutions at all frequencies are obtained within one single computation
  - Broadband noise sources and time dependent transient signals directly studied
  - Inversion of a large linear system is avoided

DIM predictions:
with & without edge effect

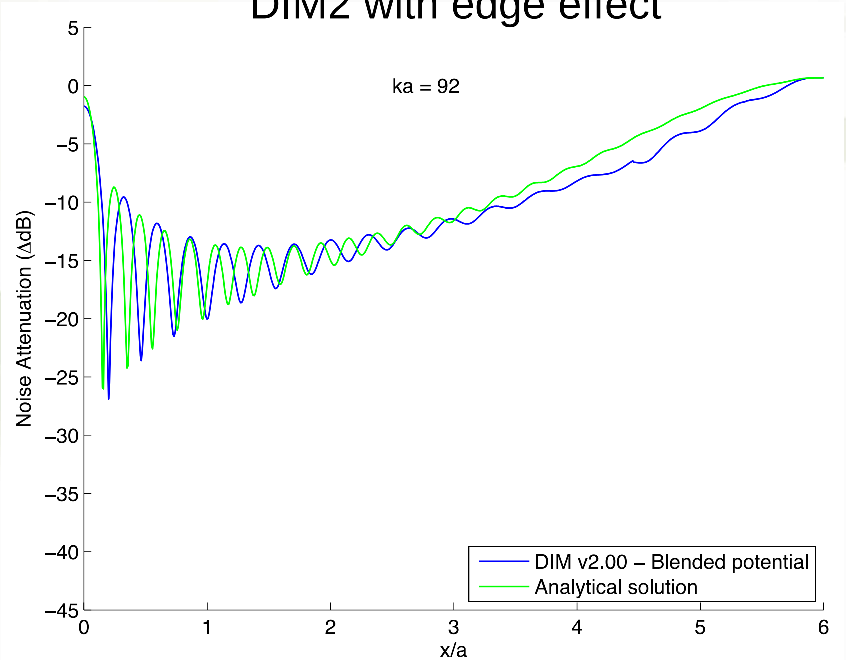


- MIT Diffraction Integral Method: DIM (Spakovszky)
  - Babinet's Principle with wedge potential for edge modeling
  - Beam tracing for reflections
  - directional sources (e.g., ANOPP, measurement, analytical)
- Comparison: analytical solution, FSC and DIM
  - Sphere radius: a = 5 m
  - ka=92

DIM without edge effect

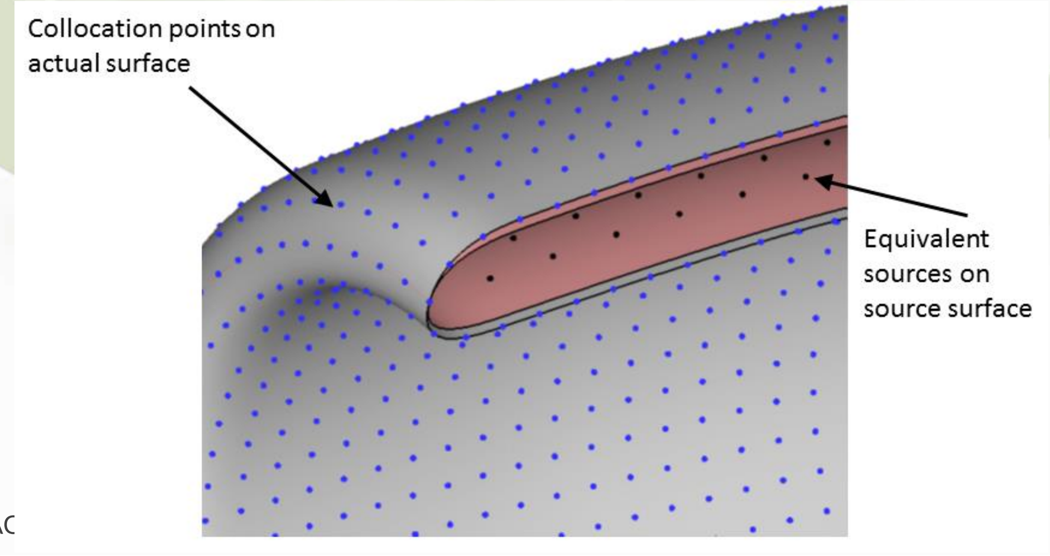


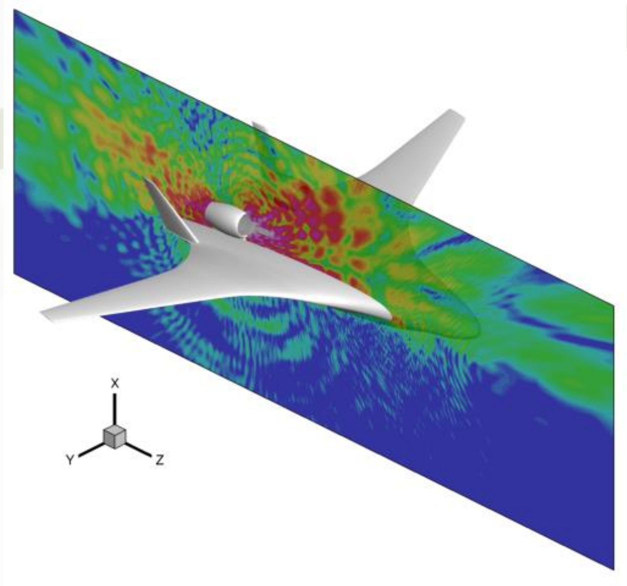
DIM2 with edge effect



Fast Scattering Code (FSC)

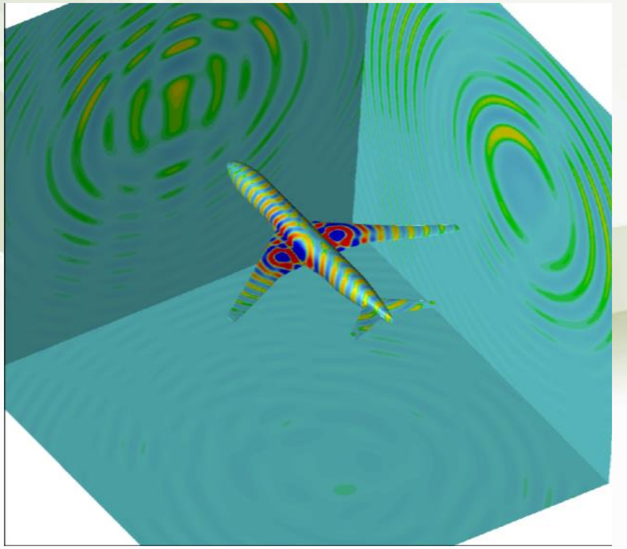
- Frequency domain solve of a 3-D Helmholtz boundary value problem via the equivalent source method (ESM)
- Scattered acoustic pressure field expanded into a series of point sources (Ns) distributed on a fictitious surface placed inside the actual scattering surface
- Scattering surface is discretized into collocation points (Nc) to produce a dense, over-determined system of linear equations of size Nc x Ns.
- Source strengths are adjusted to satisfy surface boundary condition using least squares methods

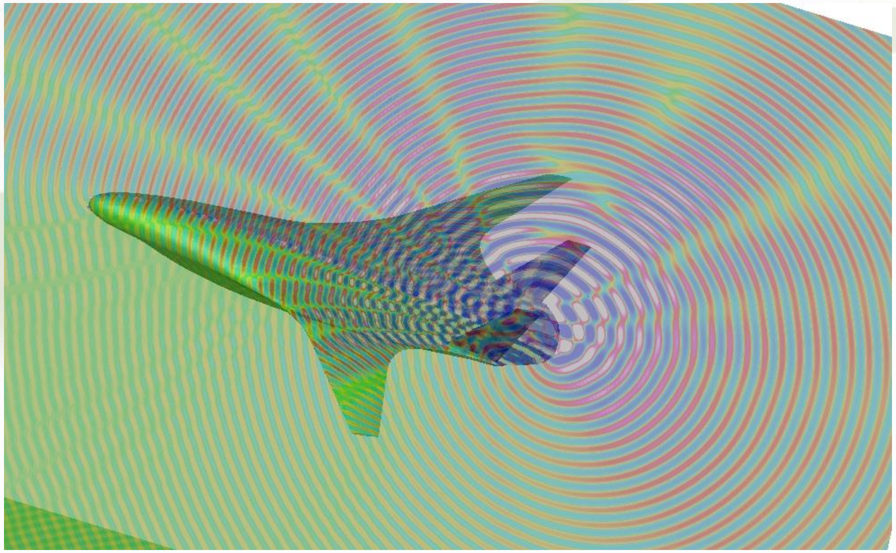




Time Domain BEM

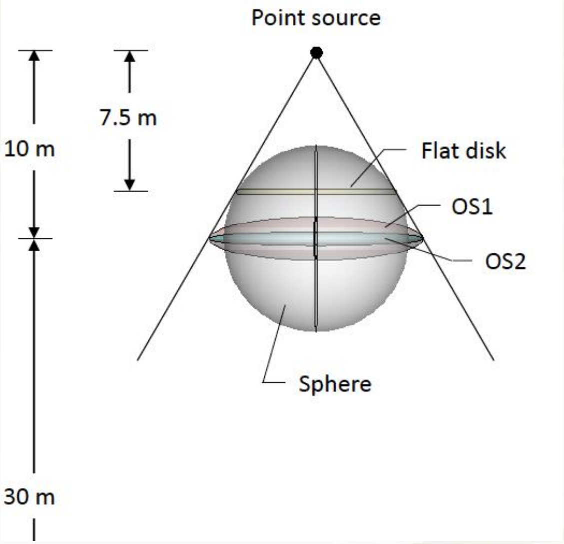
- **Time domain boundary integral equation (TDBIE) reformulated for the convective wave equation**
- **Numerical instability in time marching stages addressed via Burton-Miller type formulation**
- **Computational Cost of direct solution addressed via**
  - **High-order basis functions, reducing N**
  - **Multi-level Fast Methods**
- **Utilize muti-core CPU and GPU architectures**

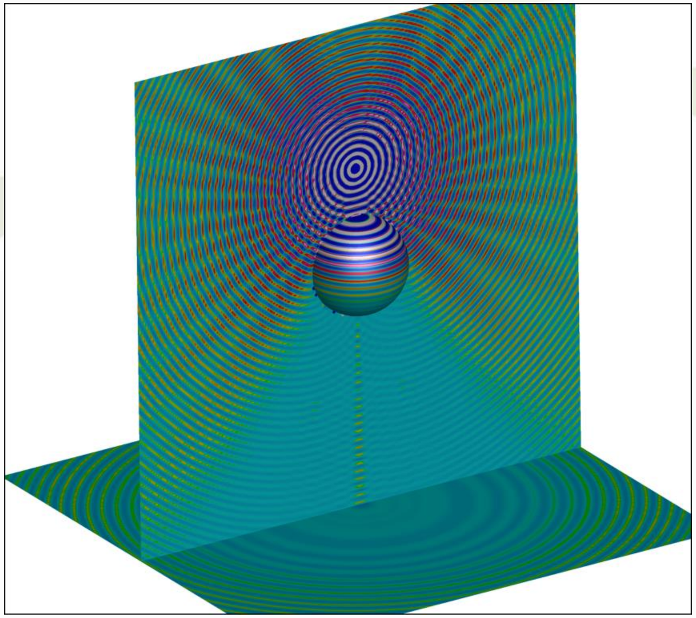




Validation Studies

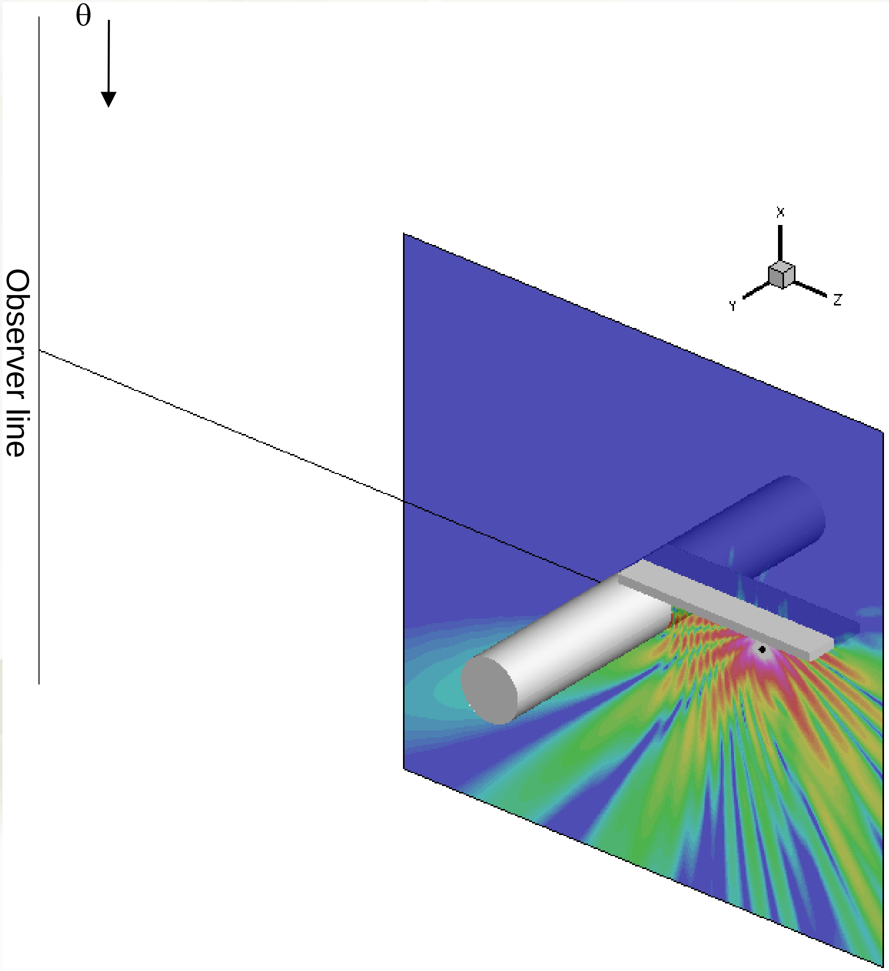
- **Source projects geometrically similar shadow zone**
- **Spheroids (centered at origin)**
  - Sphere: *r* = *a* = *b* = 5.0 m
  - OS1: *a* = 5.77 m, *b* = 1.147 m
  - OS2: *a* = 5.77 m, *b* = 0.38 m
- **Flat disk**
  - Rounded edges
  - *r* = 4.33 m, *t/D* = 0.035
- **Sound Source**
  - Monopole of unit strength
  - Frequencies: 1 < *ka* < 400
- **Observer fields**
  - Bisecting plane, plane at z = -30 m
  - Line at z = -30 m
  - Ring, *r* = 7.5 m, centered at origin





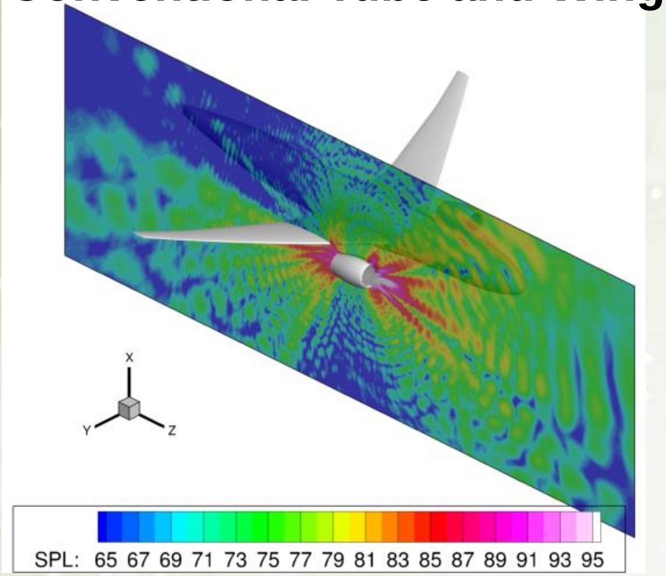
Validation Studies

- **Configuration geometry/data from NASA TP 1004**
- **Cylinder (centered at origin)**
  - Diameter: d = 0.48 m
  - Length: L = 3.05 m
- **Flat plate**
  - Square edges
  - W= 0.5 m, L = 1.6 m, t = 0.07m
- **Sound Source**
  - Monopole of unit strength
  - Location: (0.0, 0.0, 0.9936) m
  - Excitation frequencies: 9 < kd < 69
- **Observer fields**
  - Bisecting plane
  - Line at z = -5.04 m
  - Sphere: r = 2.5 m, centered at origin

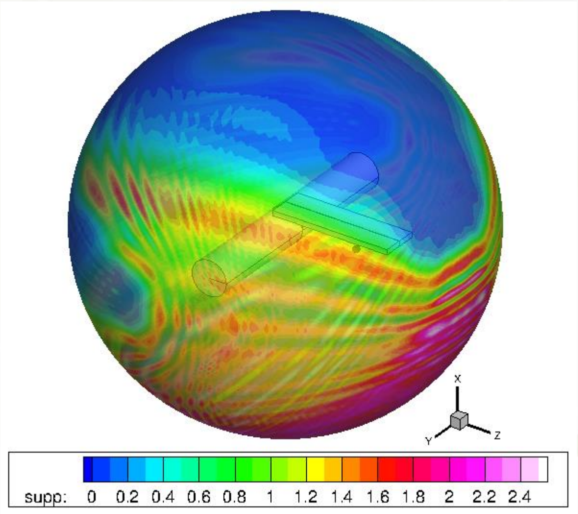


Applications

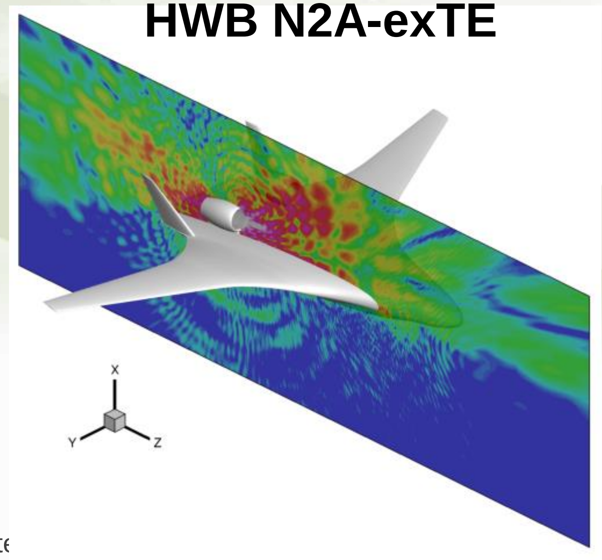
Conventional Tube and Wing



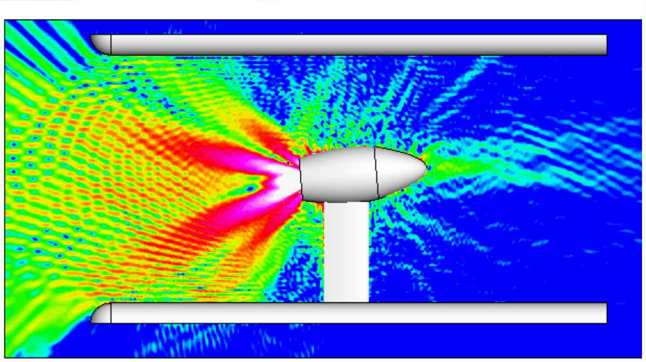
Suppression Table Creation



HWB N2A-exTE



Installation Effects



Outline

- Perception-Influenced Design: Overview
  - Goals & Objectives
  - PID in MDAO
  - Linkages to new NASA aero programs/projects, FAA, DoD, OGA
- FY14 Activities
  - Validated aircraft acoustics tools and methods for low noise
    - ANOPP2 framework
    - Scattering methods
    - Auralization framework
      - Propeller noise auralization
  - Deployment of PID against other projects
- Roadmap (today to 2017 and beyond)

Auralization Framework

Current tool set is limited

- Auralization of aircraft flyover noise consists of source-path-receiver modeling
  - Source noise synthesis based on prediction (ANOPP, ANOPP2), flight-scaled wind tunnel data, flight test data
  - Propagation of synthesized noise generates pseudo-recording at ground receiver and accounts for spreading loss, atmospheric absorption, Doppler simulation, and ground plane effects
    - Pseudo-recording demonstrated to obtain same integrated metrics as those obtained from system noise prediction
  - Receiver modeling takes pseudo-recording to a subjective test environment for evaluation

- Current auralization tool set developed over past 10 years
  - Reliant on specialized hardware for propagation and receiver modeling
  - All processing steps uncoupled
    - Source noise directivity not integrated with prediction codes
    - Synthesis uses C++ code or Matlab
    - Propagation processing limited by capabilities of real-time processor used for receiver modeling. New capabilities difficult to add.
  - Need integrated framework to permit auralization of advanced concepts without compromise -> NASA Auralization Framework (NAF)

NASA Auralization Framework (NAF)

New API permits advanced configurations to be considered

Host Environment

(Executable, GUI, MATLAB, LabView, etc.)
[C/C++, VisualBasic, Java, MATLAB, etc.]

Executive/Scheduler

Manages threads, optimization, message-passing, memory

API

Object Definitions

Component
Source
SourceFrame
Sink
Receiver
Atmospec
Path
PolySampleBuf
GTF
GTFSeries

SceneGen

Defines a "simulation frame" at block boundary by traversing and interpolating trajectories, and reading live sensors

Trajectory

PathFinder

Connects sinks back in time to sources through multi-path algorithms, maintaining at least source x sink paths at each frame

Terrain

SynthEngine

Creates new block of time pressure history from each component for each different emission angle for each frame

GTFEngine

Applies Gain-Time-Filter to TPH at fractional samples for each path

- NAF is extensible
  - Each bold-border box is a DLL. All DLL's are dependent on the API DLL.
  - The yellow-boxes are major Activities and are implemented as inheritable classes.
  - The Executive is dependent on all DLL's.
  - Any DLL can be replaced in whole or in part by user defined routines

Propeller Noise Auralization

Defining the source noise

Steady

Propeller Performance ⇒ **Acoustics** - Gutin

Periodic Unsteady

Geometry - ASP_Tools ⇒ **Aerodynamics** - ANOPP: PAS ⇒ **Acoustics** - ANOPP: PAS - ASSPIN

⇩ ANOPP: WING

Scattered Field

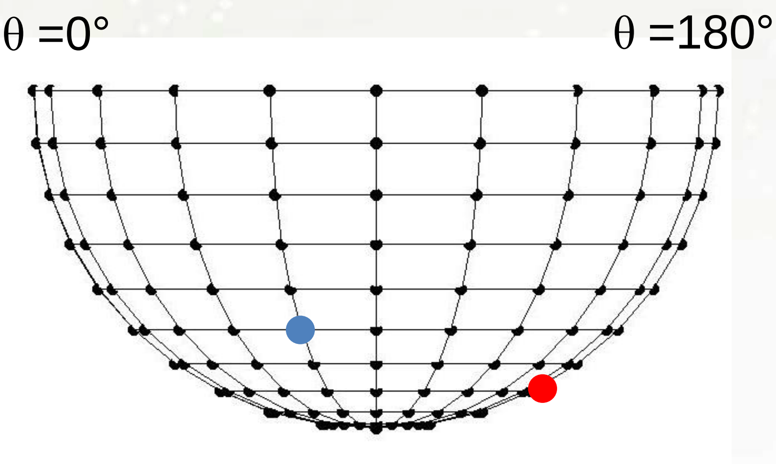
⇧ FSC, TDBIM, DIM

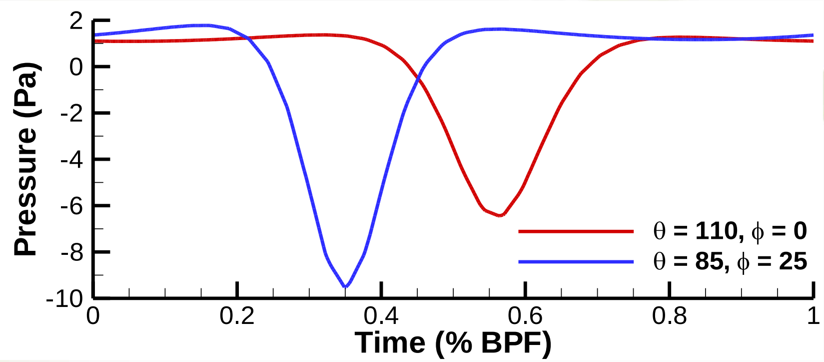
Fully Unsteady

Geometry - ASP_Tools ⇒ **Aerodynamics** - OVERFLOW - FUN3D ⇒ **Acoustics** -FW-H

Propeller Noise Synthesis

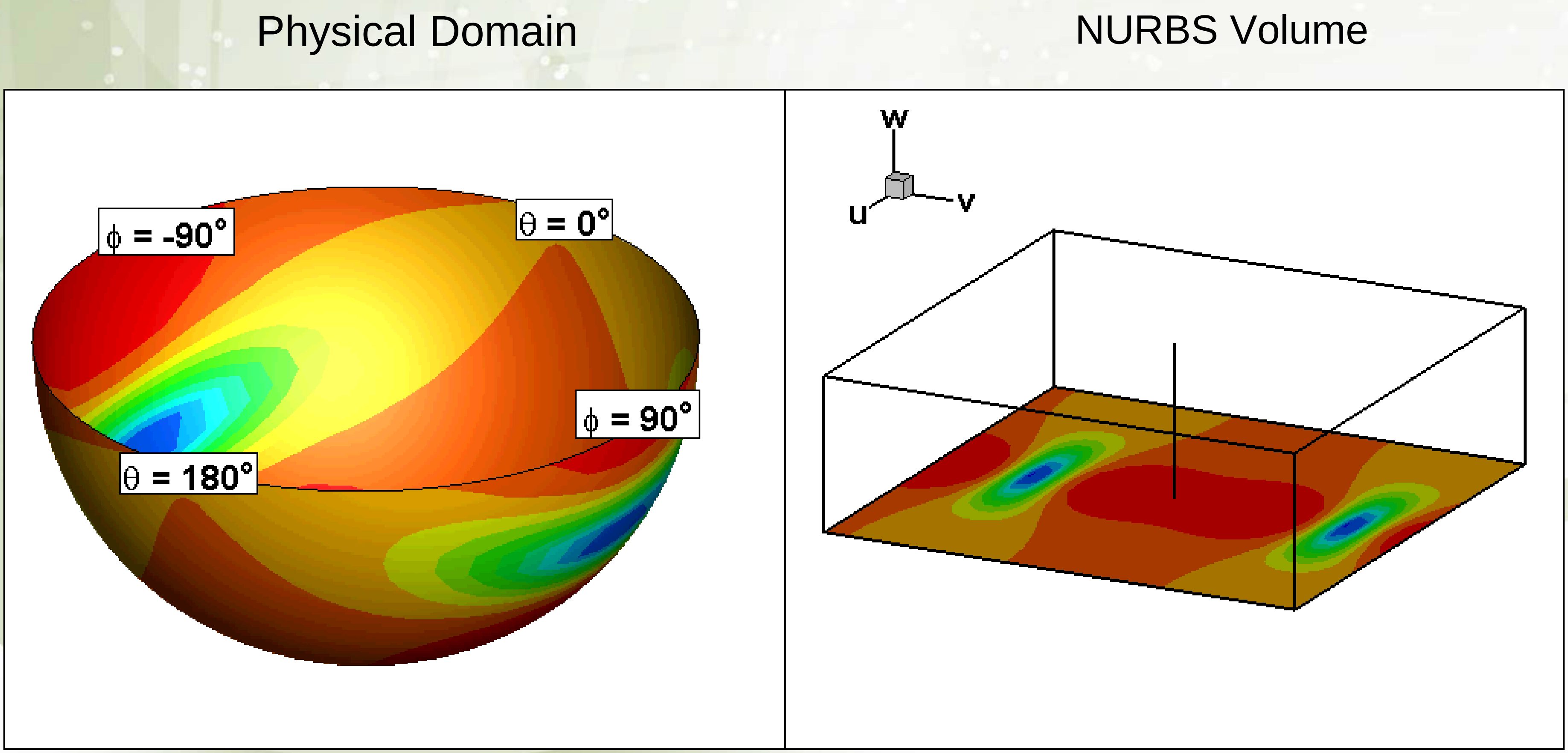
- Start with time domain source noise prediction at discrete directivity angles
  - Polar angle: $0 \le \theta \le 180^\circ$
  - Azimuth angle: $-90^\circ \le \phi \le 90^\circ$
  - Time:
    - Long (1-shot) e.g. entire flyover
    - Short (loop) e.g. 1 blade passage
- Construct non-uniform rational B-spline (NURBS) volume at control points
- Evaluate NURBS volume at points corresponding to instantaneous emission time and angles
  - Forms continuous pressure time history on hemisphere





Need to compute pressures off prediction points.

Synthesis of 3-blade propeller



- Prediction: Single blade passage of thickness source noise at 5º spacing
- Emission time and angles correspond to straight and level overhead flyover (ϕ = 0): 400 ft altitude, 60 MPH

Outline

- Perception-Influenced Design: Overview
- FY14 Activities
  - Validated aircraft acoustics tools and methods for low noise
    - ANOPP2 framework
    - Scattering methods
    - Auralization framework
  - Deployment of PID against other projects
    - AS: Distributed electric propulsion
    - FW: Open rotor predictions
    - RW: Prediction/propagation of helicopter noise using ANOPP2 tools
    - HS: Utilization of model scale CFD based jet noise prediction
- Roadmap (today to 2017 and beyond)

Deployment of PID

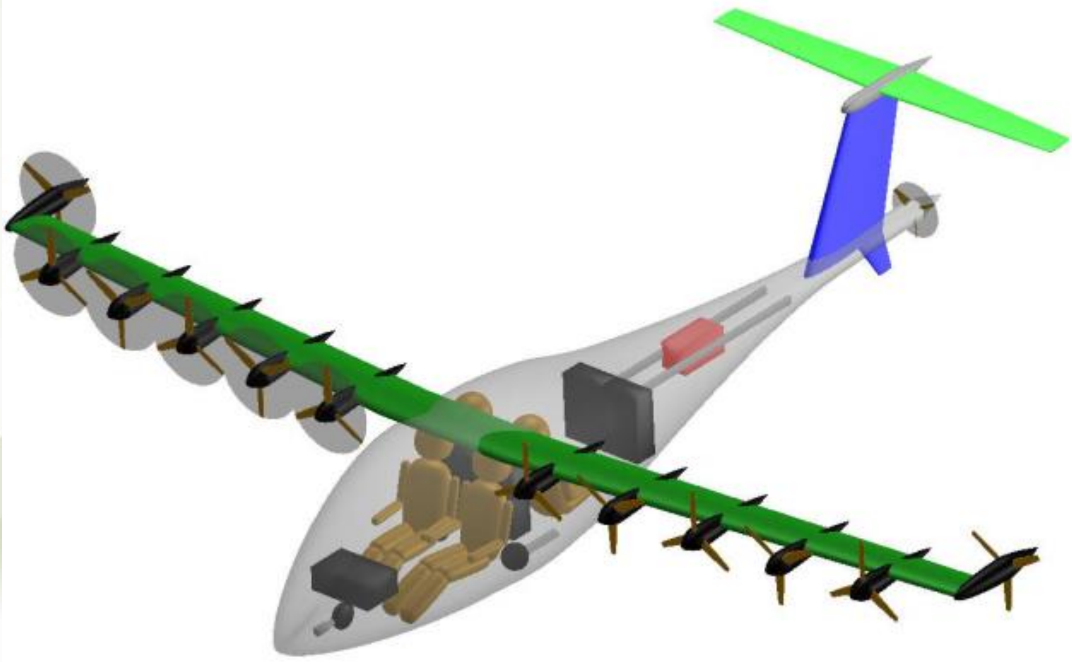
Distributed Electric Propulsion

Motivation

- Large potential noise reduction possible with Distributed Electric Propulsion Aircraft (DEP)
- Influence early design process using noise metrics developed through human perception of auralized noise.

Approach

- Use quick look auralization based on combined effect of multiple isolated propellers
- Investigate effect of tip speed and source synchronization on generated sound

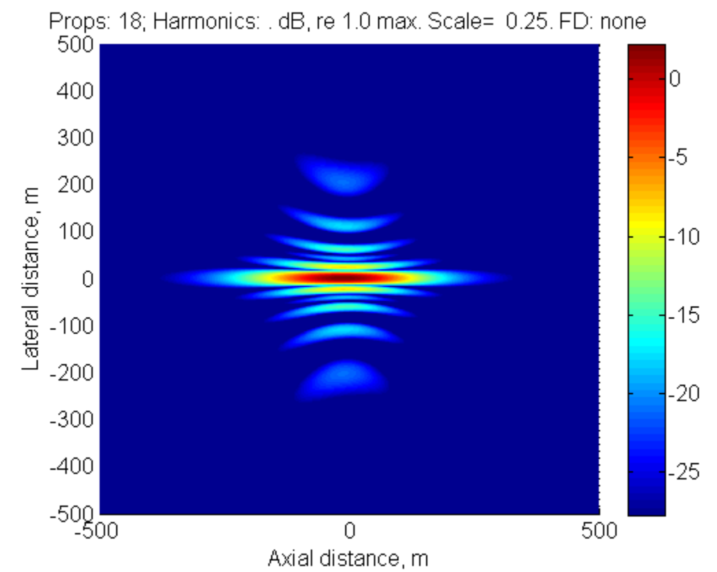


Early Results

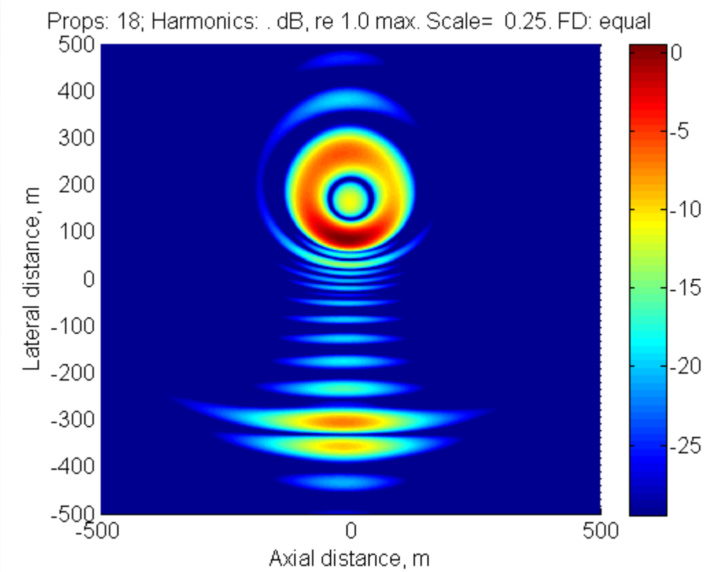
- To be presented at AVIATION 2014 special session on Transformational Flight - DEP

Deployment of PID on DEP

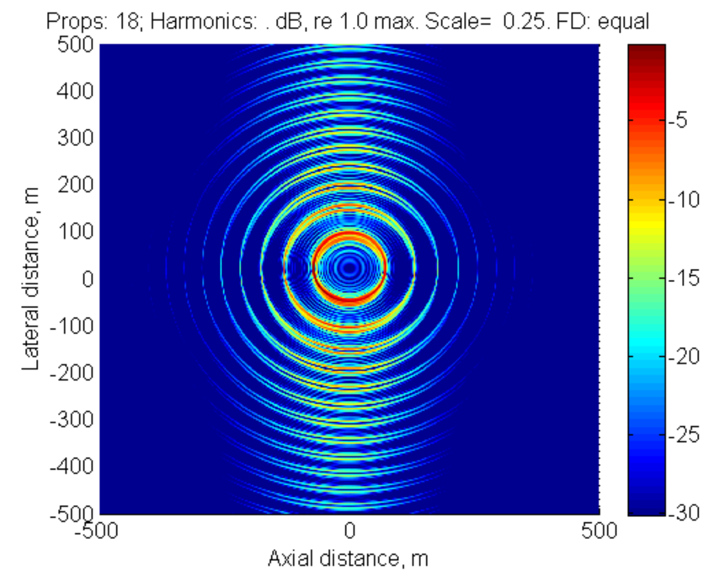
18 stationary, 1st harmonic sources @ BPF=325 Hz; Altitude=150 m



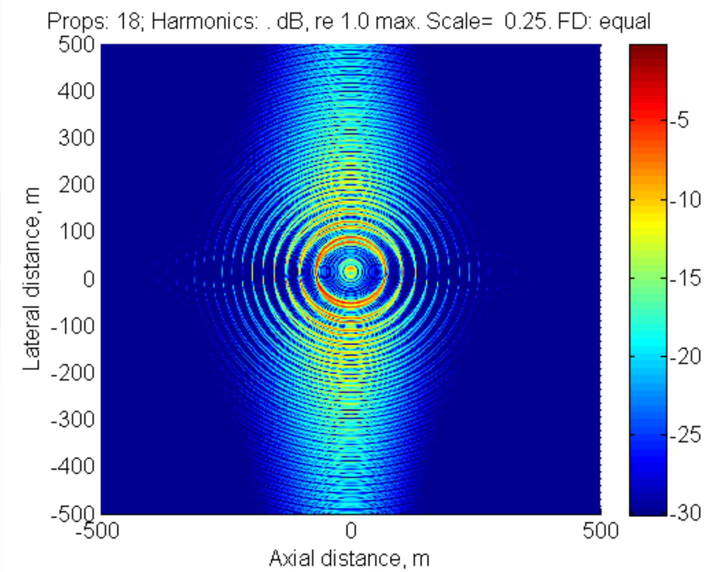
Coherent



Spread Δf=0.5Hz



Spread Δf=10Hz



Spread Δf=20Hz

Outline

- Perception-Influenced Design: Overview
  - Goals & Objectives
  - PID in MDAO
  - Linkages to new NASA aero programs/projects, FAA, DoD, OGA
- FY14 Activities
  - Validated aircraft acoustics tools and methods for low noise
    - ANOPP2 framework
    - Scattering methods
    - Auralization framework
  - Deployment of PID against other projects
- Roadmap (today to 2017 and beyond)

Perception-Influenced Design

FY15 Plan

- FY15 – PID transitional year (enabling required-critical capabilities)
  - Continue development of ANOPP2 framework and linkages to MDAO tools
    - ANOPP2 coupling with CFD/CAD packages: Developing hooks for ANOPP2 to couple with CFD and CAD packages
    - ANOPP2 coupling with OpenMDAO: Developing hooks for ANOPP2 to couple with OpenMDAO (python hooks)
  - Continue development of NAF API
    - Core framework functional modules
    - Auralization of reference vehicles
  - Case study
    - Initial deployment against proposed TACP/CAS/Convergent Electric Propulsion Technology Integration project

Perception-Influenced Design

Roadmap

- FY16+
  - Consolidate cross-cutting acoustics research under RTM/PID Acoustics project
  - Further develop comprehensive suite of validated aircraft acoustic tools and methods that permit PID to enable unconstrained introduction of new air vehicles consistent with NASA Aeronautics Six Strategic Thrusts and that of other government agencies
  - Further deploy PID against air vehicle technologies and systems in selected AOSP, AAVP, IASP, TACP projects
  - Demonstrate PID and validate tools/process in relevant environments via laboratory (AAVP) and flight (AOSP & IASP) projects

Questions