

Commercial Space Operations Noise Modeling

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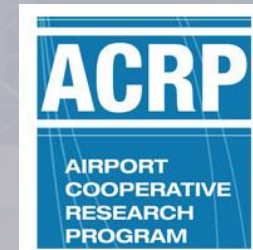


Blue Ridge Research and Consulting

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Alexandria Salton, M.S.

Micah Downing, Ph.D.



Work funded by the
Airport Cooperative
Research Program (ACRP)

Background



Commercial
Space

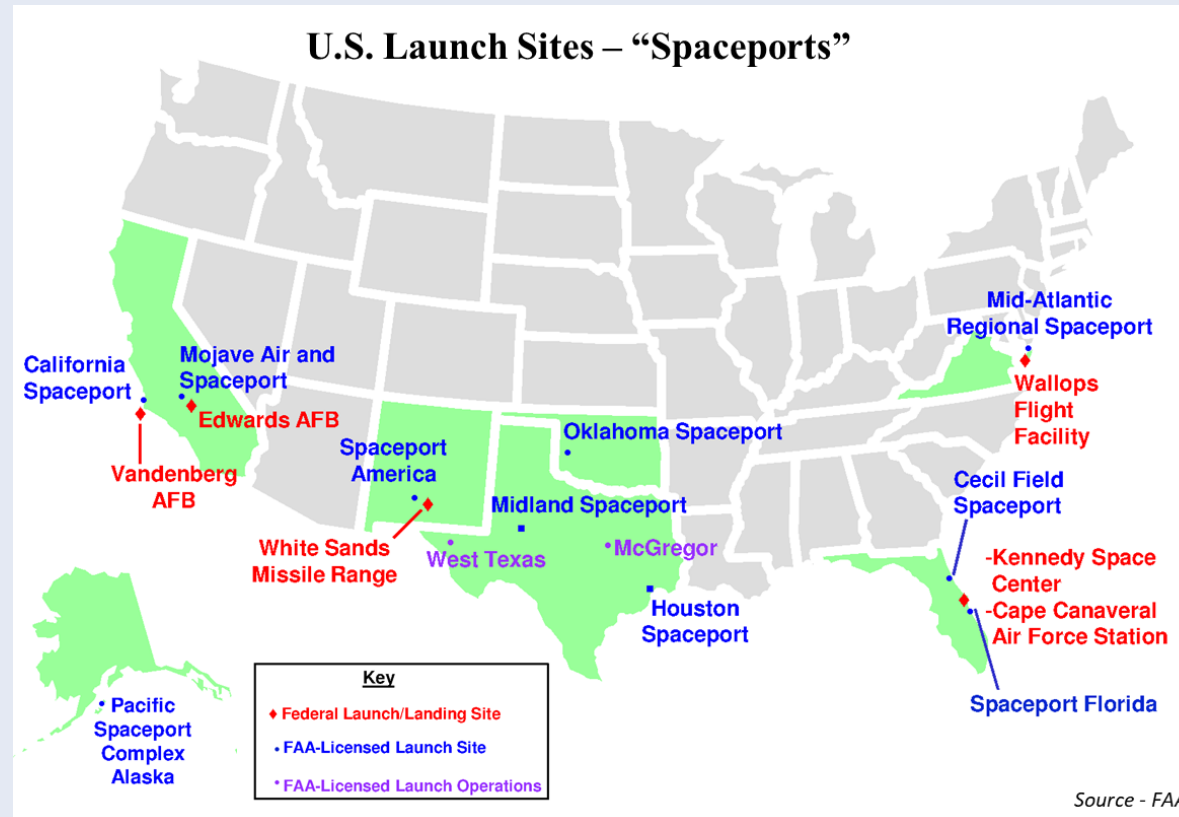


Vehicle
Types



Noise
Modeling

Acquisition of a site/vehicle license or experimental permit is a Federal Action subject to environmental review



Background



Commercial
Space



Vehicle
Types



Noise
Modeling

Conventional



Concept Z
Carrier Aircraft



Concept X



Concept Y



Vertical
Takeoff/Landing



Background



Commercial
Space

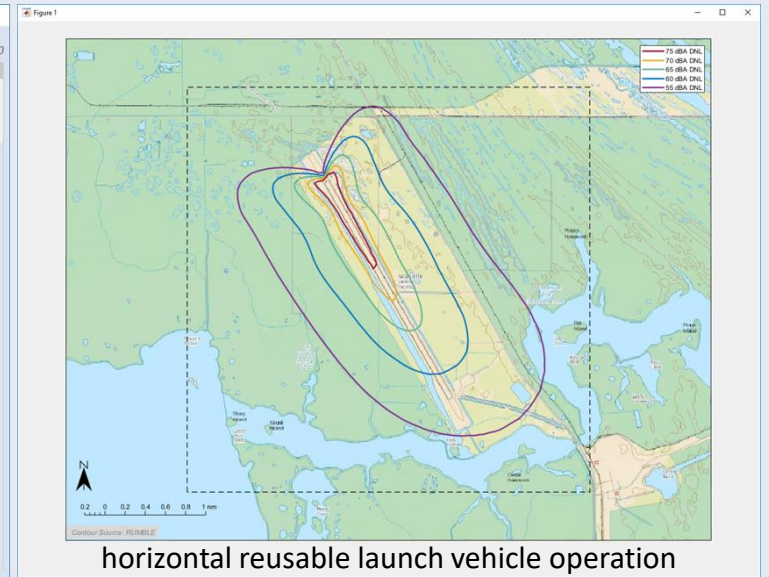
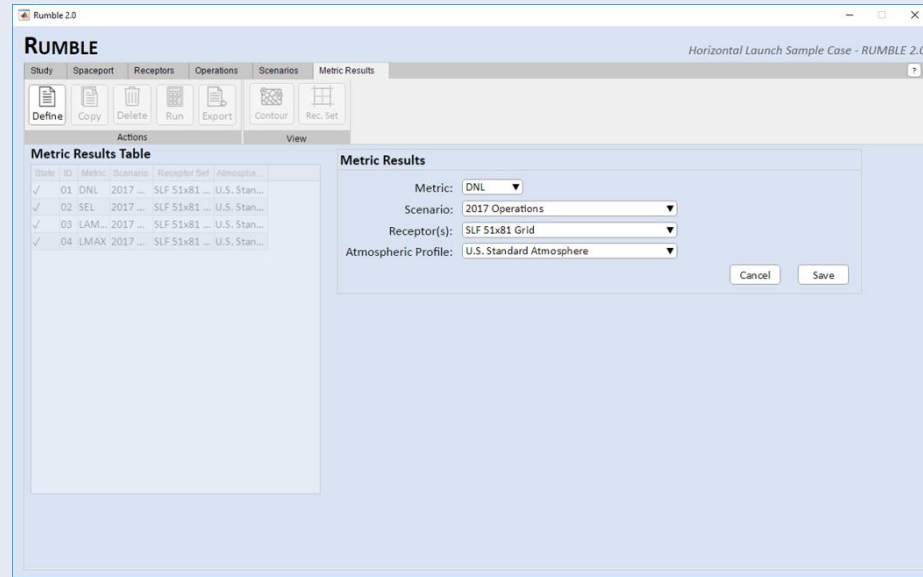


Vehicle
Types



Noise
Modeling

RUMBLE : BRRC's Launch Vehicle Acoustic Simulation Model



- Relevant to environmental analysis of commercial space operations
- Efficient/accurate noise model
- Database of vehicle and engine/motor parameter

Background



Commercial
Space



Vehicle
Types



Noise
Modeling

AEDT Integration

- **Workflow** – Modified RUMBLE program workflow to be more closely linked with AEDT. Adopted relevant names and element order prescribed by ASIF format.
- **User model input** – Transitioning to xml file format (open source) to benefit from hierarchical structure, simplicity to read/edit (plain text), and data identification capabilities.
- **Model output** – Noise Model ASCII Grid Format (NMAGF) files have been modified to ensure users can import and combine RUMBLE NMAGF files and AEDT metric results within the AEDT user interface.
- **Database management** – Adopted database organization used by AEDT so that rocket elements can easily be integrated into the existing database.
- **User-interface** – Developed a RUMBLE graphical user interface to allow users to run the tool in a simplified mode and view results.

Background



Commercial
Space



Vehicle
Types



Noise
Modeling

Interim AEDT Integration

DATABASE

```
1 <?xml version="1.0" encoding="utf-8"?>
2 <DATABASE>
3   <aircraft>
4   </aircraft>
5   <engine>
6   </engine>
7 </DATABASE>
```

INPUT (XML)

```
1 <?xml version="1.0" encoding="utf-8"?>
2 <RocketNoiseModelInputXml>
3   <case>
4     <veh>
5     </veh>
6     <tr>
7     </tr>
8     <op>
9     </op>
10    <cat>
11    </cat>
12    <rec>
13      <name>KSC 50x50 Grid</name>
14      <type>Cartesian Grid</type>
15      <xcount>50</xcount>
16      <ycount>50</ycount>
17      <xspc>1215.224</xspc>
18      <yspc>1215.224</yspc>
19      <h0>5</h0>
20      <latitude>28.8263200291838</latitude>
21      <longitude>-80.696948022122</longitude>
22      <altitude>0</altitude>
23      <reference>LowerLeft</reference>
24    </rec>
25    <met>
26    </met>
27  </case>
28 </RocketNoiseModelInputXml>
```

OUTPUT (GRD or SHP)

```
1 [TITL Grid Vers 2 3]
2 [CART -80.728615 28.522218 0 0 FEET 0]
3 [MTRC "DNL" "dBA"]
4 [DPAL 2500]
5 [-80.728615,28.522218] 29.809186
6 [-80.724831,28.522218] 30.089225
7 [-80.721047,28.522218] 30.368087
8 [-80.717263,28.522218] 30.647154
9 [-80.713479,28.522217] 30.927786
10 [-80.709695,28.522217] 31.205843
11 [-80.705910,28.522216] 31.483105
12 [-80.702126,28.522215] 31.759119
13 [-80.698342,28.522215] 32.036023
14 [-80.694558,28.522214] 32.310791
15 [-80.690774,28.522213] 32.582487
16 [-80.686990,28.522212] 32.851297
17 [-80.683206,28.522210] 33.117441
```

RUMBLE

RUMBLE 2.0

Horizontal Launch Sample Case - RUMBLE 2.0

Study Spaceport Receptors Operations Scenarios Metric Results

Define Copy Delete Run Export Contour Rec. Set

Metric Results Table

State	ID	Metric	Scenario	Receptor Set	Atmosphere
✓	01	DNL	2017	SLF 51x81	U.S. Stan...
✓	02	SEL	2017	SLF 51x81	U.S. Stan...
✓	03	LAM	2017	SLF 51x81	U.S. Stan...
✓	04	LMAX	2017	SLF 51x81	U.S. Stan...

Metric Results

Metric: DNL

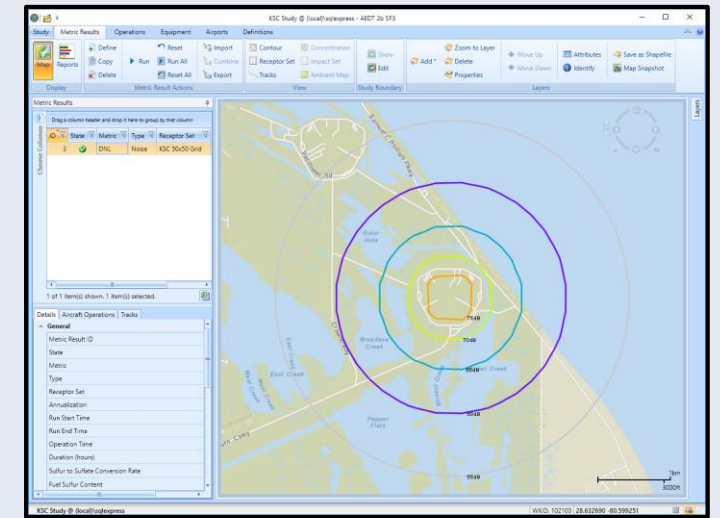
Scenario: 2017 Operations

Receptor(s): SLF 51x81 Grid

Atmospheric Profile: U.S. Standard Atmosphere

Cancel Save

AEDT



Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface

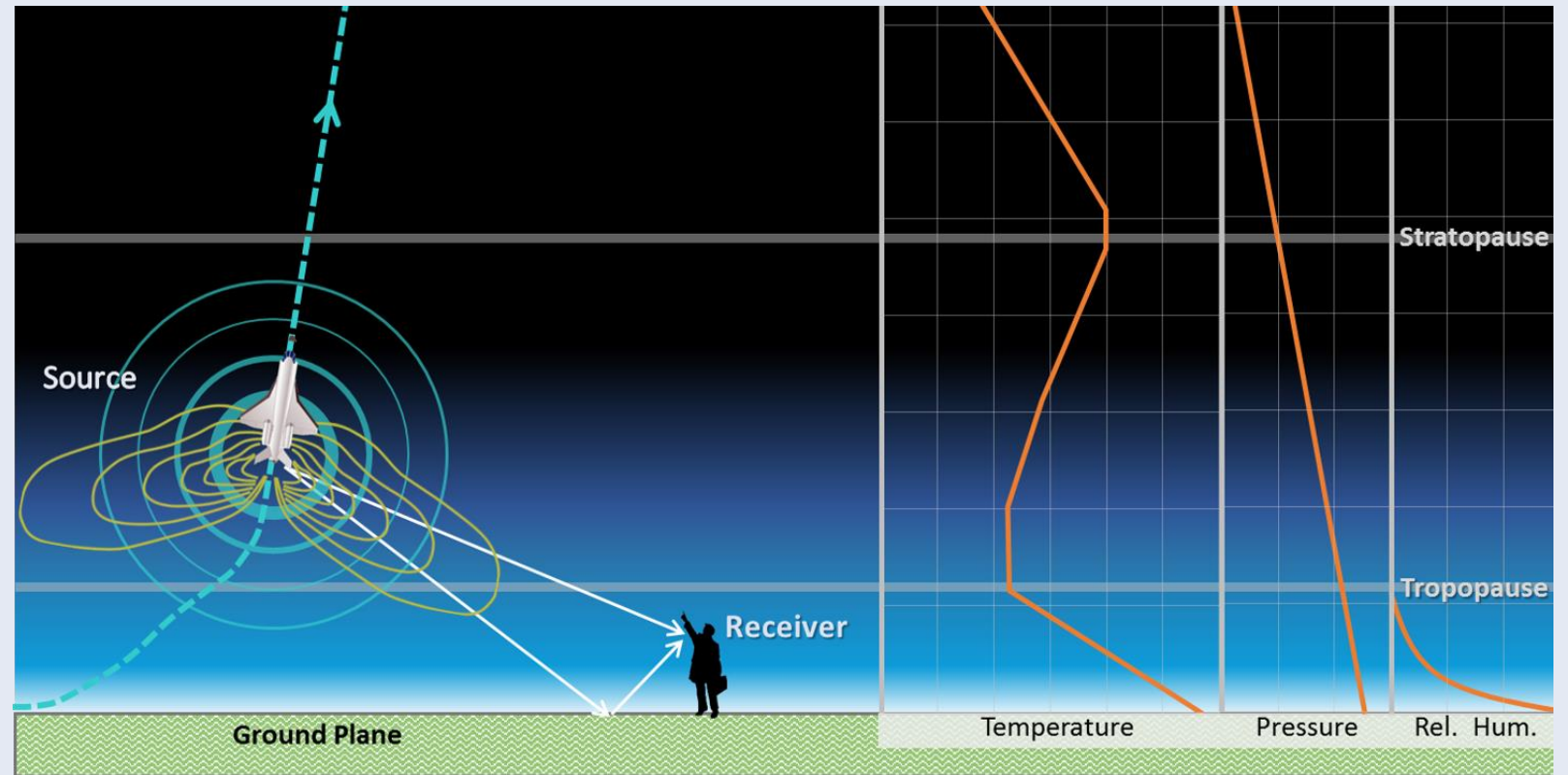


Map Results



Simulation

$$SPL = \underbrace{L_w + A_{ffe} + A_{dir} + A_{dop}}_{\text{Source}} + \underbrace{A_{spread} + A_{atm} + A_{gnd}}_{\text{Propagation}}$$



Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results

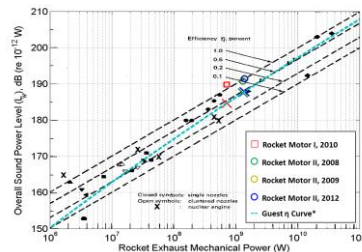


Simulation

$$SPL = \underbrace{L_w + A_{ffe} + A_{dir} + A_{dop}}_{\text{Source}} + \underbrace{A_{spread} + A_{atm} + A_{gnd}}_{\text{Propagation}}$$

Acoustic Power

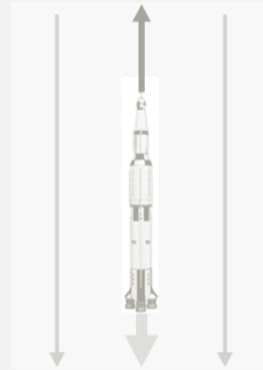
Overall sound power based on rocket-specific parameters



Forward Flight Effect

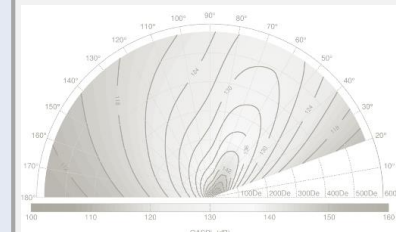
Rocket exhaust and ambient airflow travel in the same direction

- Decreased relative velocity
- Decreased jet mixing and resultant noise



Directivity

Acoustic power is concentrated in specific directions and the sound pressure observed will depend on the angle from the source to the receiver.



Doppler Effect

Doppler Effect changes the frequency of a wave for an observer moving relative to its source



Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results

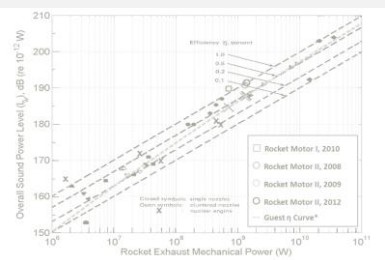


Simulation

$$SPL = L_w + \underbrace{A_{ffe}}_{\text{Source}} + A_{dir} + A_{dop} + \underbrace{A_{spread} + A_{atm} + A_{gnd}}_{\text{Propagation}}$$

Acoustic Power

Overall sound power based on rocket-specific parameters



Forward Flight Effect

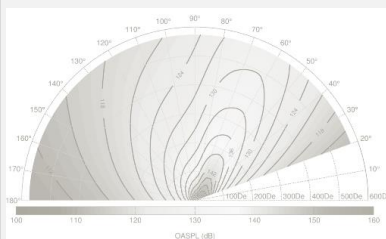
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Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results

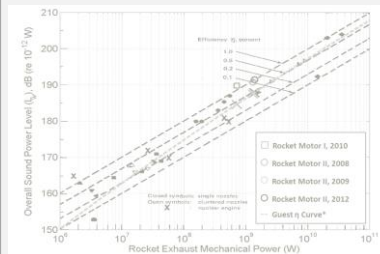


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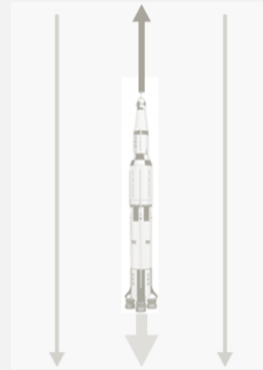
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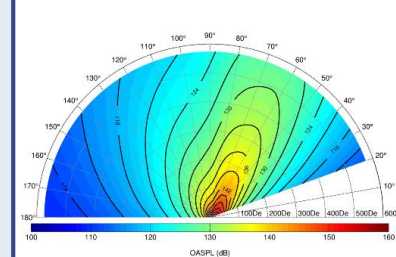
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Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results

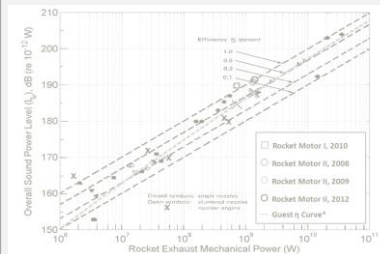


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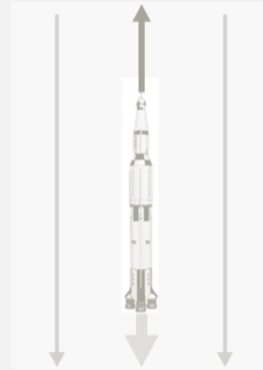
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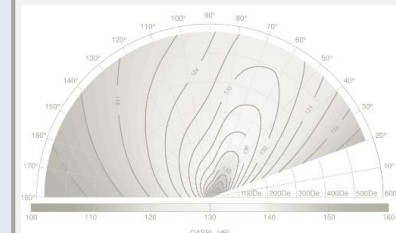
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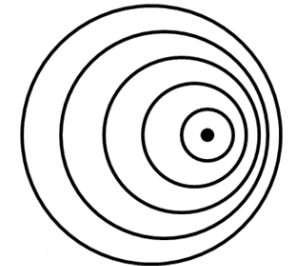
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Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

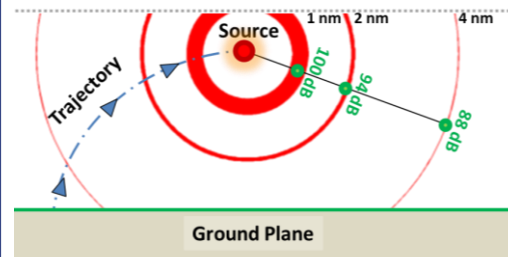
$$SPL = \underbrace{L_w + A_{ffe} + A_{dir} + A_{dop}}_{\text{Source}} + \underbrace{A_{spread} + A_{atm} + A_{gnd}}_{\text{Propagation}}$$

Geometric Spreading

Assumes a point source that radiates with a spherical field.

$$SPL_{b,p} = L_{w,b} - 10 \log(4\pi R^2) + DI(b, \theta)$$

R : distance from source to receiver location

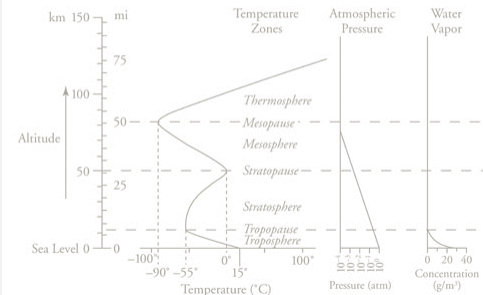


Atmospheric Absorption

Sound attenuation as a function of the temperature, humidity, and pressure of the atmosphere.

- Method: ANSI S1.26-1995
- Sum of attenuation through each layer

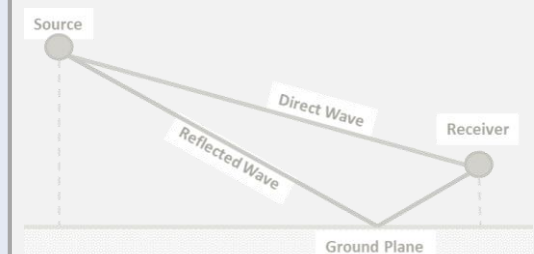
Selected Properties of Earth's Atmosphere



Ground Interference

Accounts for the combination of a direct wave (source to receiver) and a reflected wave (source to ground to receiver)

- Includes atmospheric turbulence



Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

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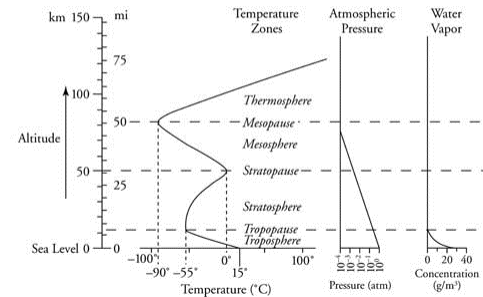


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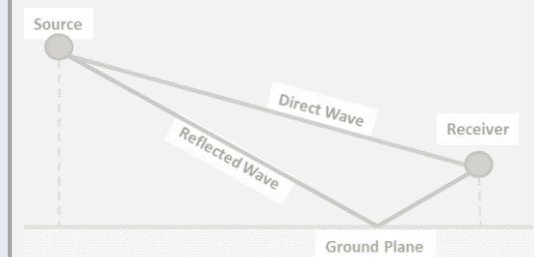
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Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



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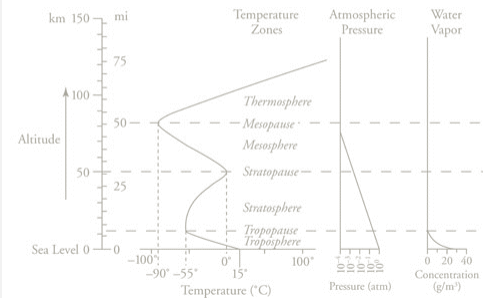


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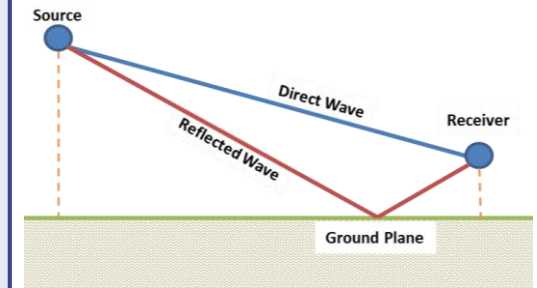
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Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



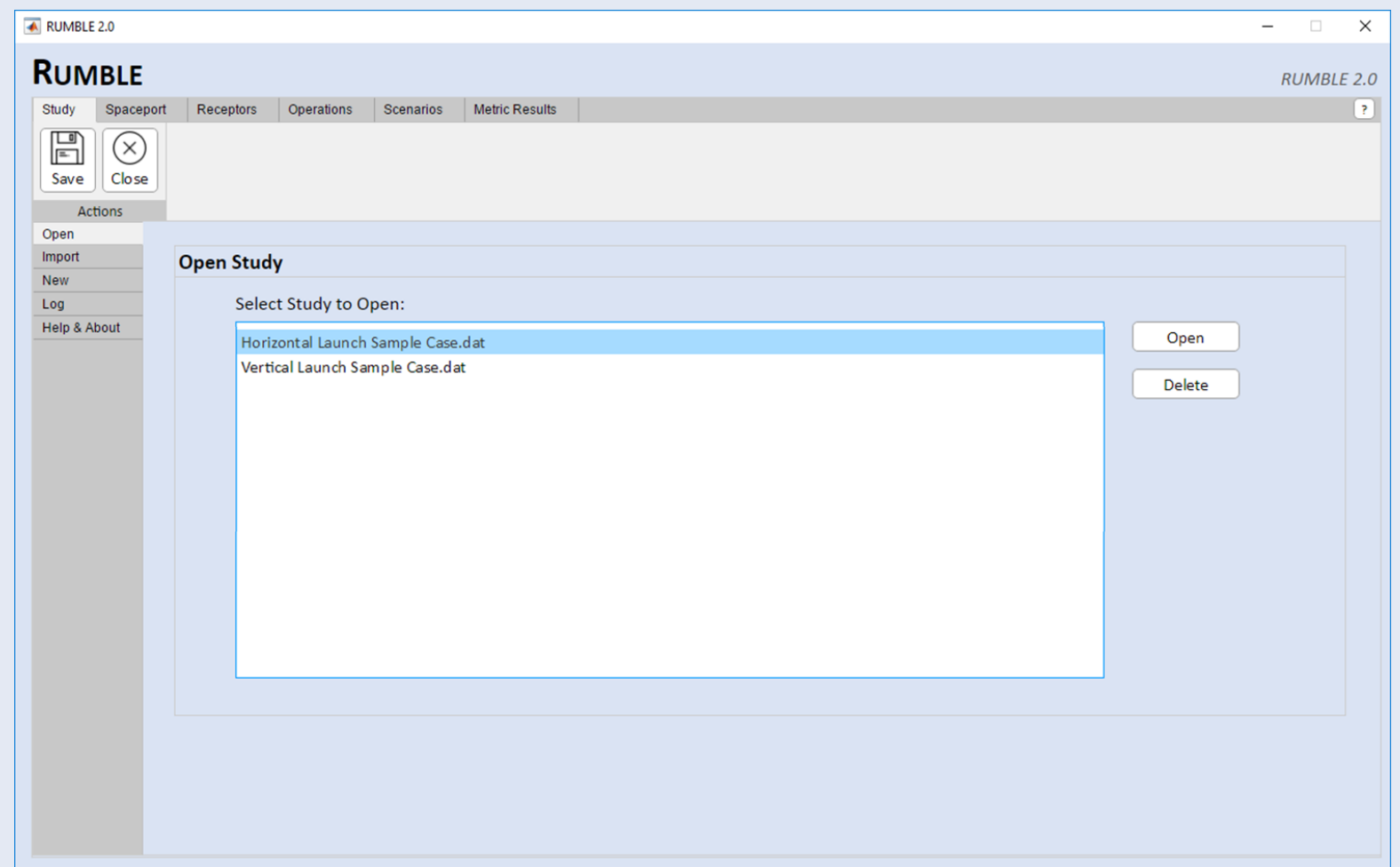
User Interface



Map Results



Simulation



Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE Horizontal Launch Sample Case - RUMBLE 2.0

Study | **Spaceport** | Receptors | Operations | Scenarios | Metric Results

New Edit

Actions

Spaceport

Spaceport Name:

Latitude (deg):

Longitude (deg):

Elevation MSL (ft):

Cancel Save

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE

Horizontal Launch Sample Case - RUMBLE 2.0

Study

Spaceport

Receptors

Operations

Scenarios

Metric Results

New

Copy

Delete

Edit

Actions

Table of Receptors

ID	Name	Receptor Type
01	SLF 81x81 Grid	Grid

Receptor Details

Name:

SLF 81x81 Grid

Type:

Grid

X Count:

81

(X Distance: 4 nmi)

Y Count:

81

(Y Distance: 4 nmi)

X Spacing (nmi):

0.05

Y Spacing (nmi):

0.05

Grid Origin Info

South-West corner of the grid location in nautical miles from the X-Y origin

X Offset (nmi):

-2

Y Offset (nmi):

-2

Location Info

The X-Y Projection Origin in Lat/Long. Usually set to the spaceport origin.

Latitude (deg):

28.614894

Longitude (deg):

-80.694373

Elevation MSL (ft):

0

Cancel

Save

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE

Horizontal Launch Sample Case - RUMBLE 2.0

Study

Spaceport

Receptors

Operations

Scenarios

Metric Results

New

Copy

Delete

Edit

Actions

Table of Receptors

ID	Name	Receptor Type
01	SLF 81x81 Grid	Grid

Receptor Details

Name:

SLF 81x81 Grid

Type:

Grid

Grid

Point

X Count:

(Distance: 4 nmi)

Y Count:

81

(Y Distance: 4 nmi)

X Spacing (nmi):

0.05

Y Spacing (nmi):

0.05

Grid Origin Info

South-West corner of the grid location in nautical miles from the X-Y origin

X Offset (nmi):

-2

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The X-Y Projection Origin in Lat/Long. Usually set to the spaceport origin.

Latitude (deg):

28.614894

Longitude (deg):

-80.694373

Elevation MSL (ft):

0

Cancel

Save

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE Horizontal Launch Sample Case - RUMBLE 2.0

Study | Spaceport | Receptors | **Operations** | Scenarios | Metric Results

New | Copy | Delete | Edit

Actions

Table of Operations

ID	Operation Type	User ID	Spacecraft	Day	Evening	Night	Trajectory Name
01	Launch	SLF Launch	Notional Suborbital Spacecraft 1	1170	0	390	Notional Suborbital Trajectory 1

Operation Details

Operation Type: Launch

User ID: SLF Launch

Choose Spacecraft: Notional Suborbital Details

Number of Daily Periods: ☒ 2 ☐ 3

Trajectory: Notional Suborbital Trajectory 1

Annual Operations: 1560 Total

1170	Daytime (7:00 am - 10:00 pm)
390	Nighttime (10:00 pm - 7:00 am)

Cancel Save

Commercial Space Noise Modeling: RUMBLE



Modeling Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE

Horizontal Launch Sample Case - RUMBLE 2.0

Study

Spaceport

Receptors

Operations

Scenarios

Metric Results

New

Copy

Delete

Edit

Actions

Table of Operations

ID	Operation Type	User ID	Spacecraft	Day	Evening	Night	Trajectory Name
01	Launch	SLF Launch	Notional Suborbital Spacecraft 1	1170	0	390	Notional Suborbital Trajectory 1

Operation Details

Operation Type: Launch

User ID: Launch

Choose Spacecraft: Landing

Static Fire

Details

Number of Daily Periods: 2

Annual Operations: 1560

1170 Daytime (7:00 am - 10:00 pm)

390 Nighttime (10:00 pm - 7:00 am)

Trajectory: Notional Suborbital Trajectory 1

Cancel

Save

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

Horizontal Launch Sample Case - RUMBLE 2.0

Study | Spaceport | Recentors | Operations | Scenarios | Metric Results

New | Copy | Delete

Actions

Table of Operation

ID	Operation Type
01	Launch

Operation Details

Operation Type: Notional Suborbital Spacecraft 1

User ID: Browse...

Choose Spacecraft: Notional Suborbital

Details

Number of Daily Periods: ☒ 2 ☐ 3

Trajectory: Notional Suborbital Trajectory 1

Annual Operations: 1560 Total

1170	Daytime (7:00 am - 10:00 pm)
390	Nighttime (10:00 pm - 7:00 am)

Cancel Save

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE Horizontal Launch Sample Case - RUMBLE 2.0

Study | Spaceport | Receptors | **Operations** | Scenarios | Metric Results

New | Copy | Delete | Edit

Actions

Table of Operations

ID	Operation Type	User ID	Spacecraft	Day	Evening	Night	Trajectory Name
01	Launch	SLF Launch	Notional Suborbital Spacecraft 1	1170	0	390	Notional Suborbital Trajectory 1

Operation Details

Operation Type: Launch

User ID: SLF Launch (Copy)

Choose Spacecraft: Notional Suborbital

Details

Number of Daily Periods: ☒ 2 ☐ 3

Trajectory: Notional Suborbital Trajectory 1

Annual Operations: 1560 Total

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390 Nighttime (10:00 pm - 7:00 am)

Cancel Save

Commercial Space Noise Modeling: RUMBLE



Modeling
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User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE

Horizontal Launch Sample Case - RUMBLE 2.0

Study

Spaceport

Receptors

Operations

Scenarios

Metric Results

New

Copy

Delete

Actions

Table of Scenarios

ID	Name
01	2017 Operations

Scenario Details

Name: 2017 Operations

Assign Weighting

Weighting	Name
1	Scenario: 2017 Operations
1	Op Group: SLF Launch Op Group

Cancel

Create

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE Horizontal Launch Sample Case - RUMBLE 2.0

Study | Spaceport | Receptors | Operations | Scenarios | Metric Results

Define | Copy | Delete | Run | Export | Contour | Rec. Set

Actions | View

Metric Results Table

State	ID	Metric	Scenario	Receptor Set	Atmospheric Profile
✓	01	DNL	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	02	SEL	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	03	LAM...	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	04	LMAX	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...

Metric Results

Metric: **DNL**

Scenario: **2017 Operations**

Receptor(s): **SLF 81x81 Grid**

Atmospheric Profile: **U.S. Standard Atmosphere**

Cancel Save

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE

Horizontal Launch Sample Case - RUMBLE 2.0

Study

Spaceport

Receptors

Operations

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Metric Results

Define

Copy

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Actions

View

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✓	03	LAM...	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	04	LMAX	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...

Metric Results

Metric:

DNL

Scenario:

DNL

Receptor(s):

SEL

Atmospheric Profile:

LMAX

CNEL

Cancel

Save

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE

Horizontal Launch Sample Case - RUMBLE 2.0

Study

Spaceport

Receptors

Operations

Scenarios

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Define

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View

Metric Results Table

State	ID	Metric	Scenario	Receptor Set	Atmospheric Profile
✓	01	DNL	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	02	SEL	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	03	LAM...	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	04	LMAX	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...

Metric Results

Metric: DNL

Scenario: 2017 Operations

Receptor(s): SLF 81x81 Grid

Atmospheric Profile: U.S. Standard Atmosphere

U.S. Standard Atmosphere

Browse...

Cancel

Save

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



User Interface



Map Results



Simulation

RUMBLE 2.0

RUMBLE

Horizontal Launch Sample Case - RUMBLE 2.0

StudySpaceportReceptorsOperationsScenariosMetric Results

DefineCopyDeleteRunExport

ContourRec. Set

ActionsView

Metric Results Table

State	ID	Metric	Scenario	Receptor Set	Atmospheric Profile
✓	01	DNL	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	02	SEL	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	03	LAM...	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...
✓	04	LMAX	2017 Operations	SLF 81x81 Grid	U.S. Standard Atm...

Metric Results

Metric: LMAX

Scenario: 2017 Operations

Receptor(s): SLF 81x81 Grid

Atmospheric Profile: U.S. Standard Atmosphere

CancelSave

Viewing Options

Contour Settings:

Minimum (dB): 100

Maximum (dB): 125

Increment (dB): 5

Basemap Layer:

Select GeoTIFF map layer to add (optional).

Horizontal Launch Sample Basemap

CancelView

Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



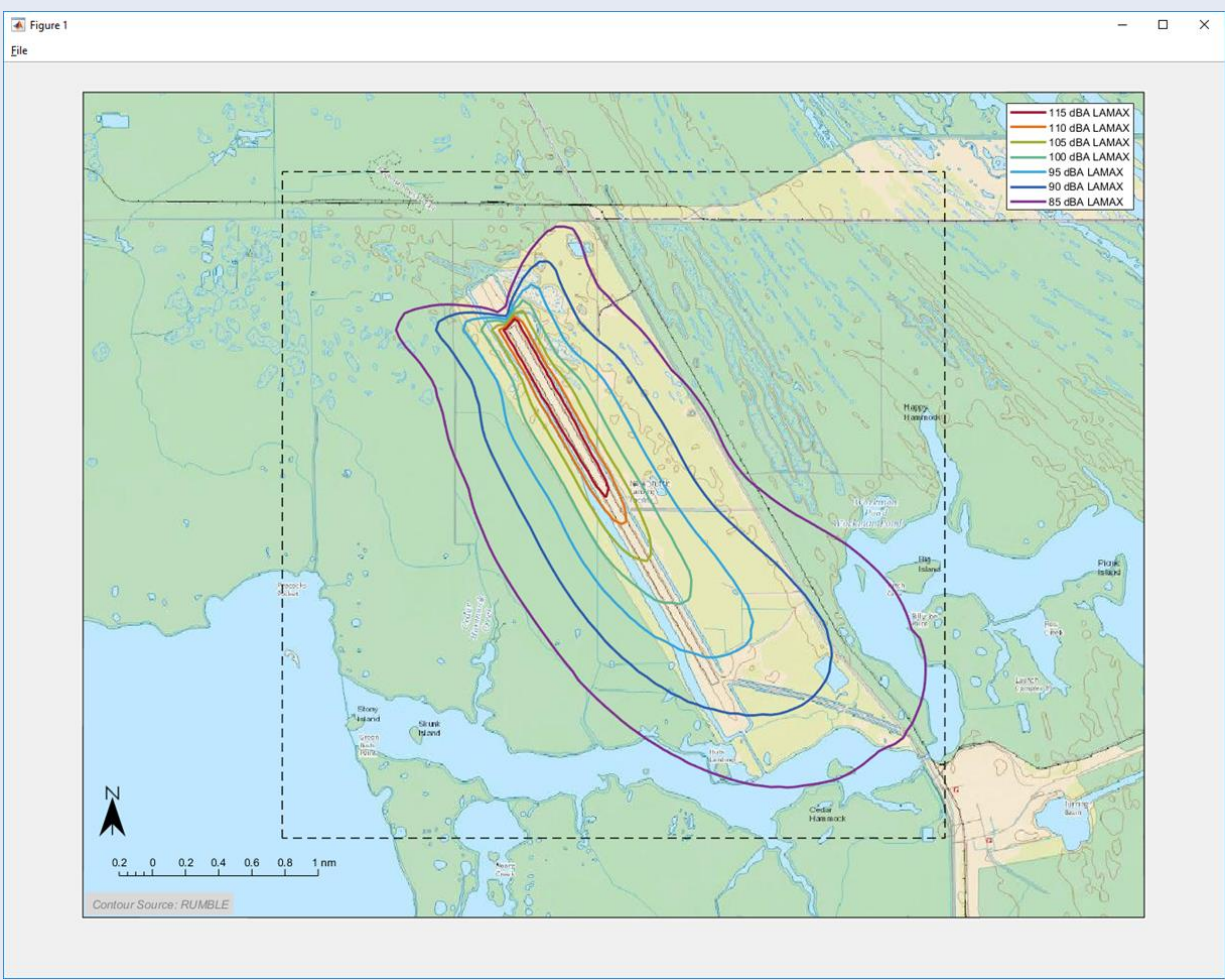
User Interface



Map Results



Simulation



Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



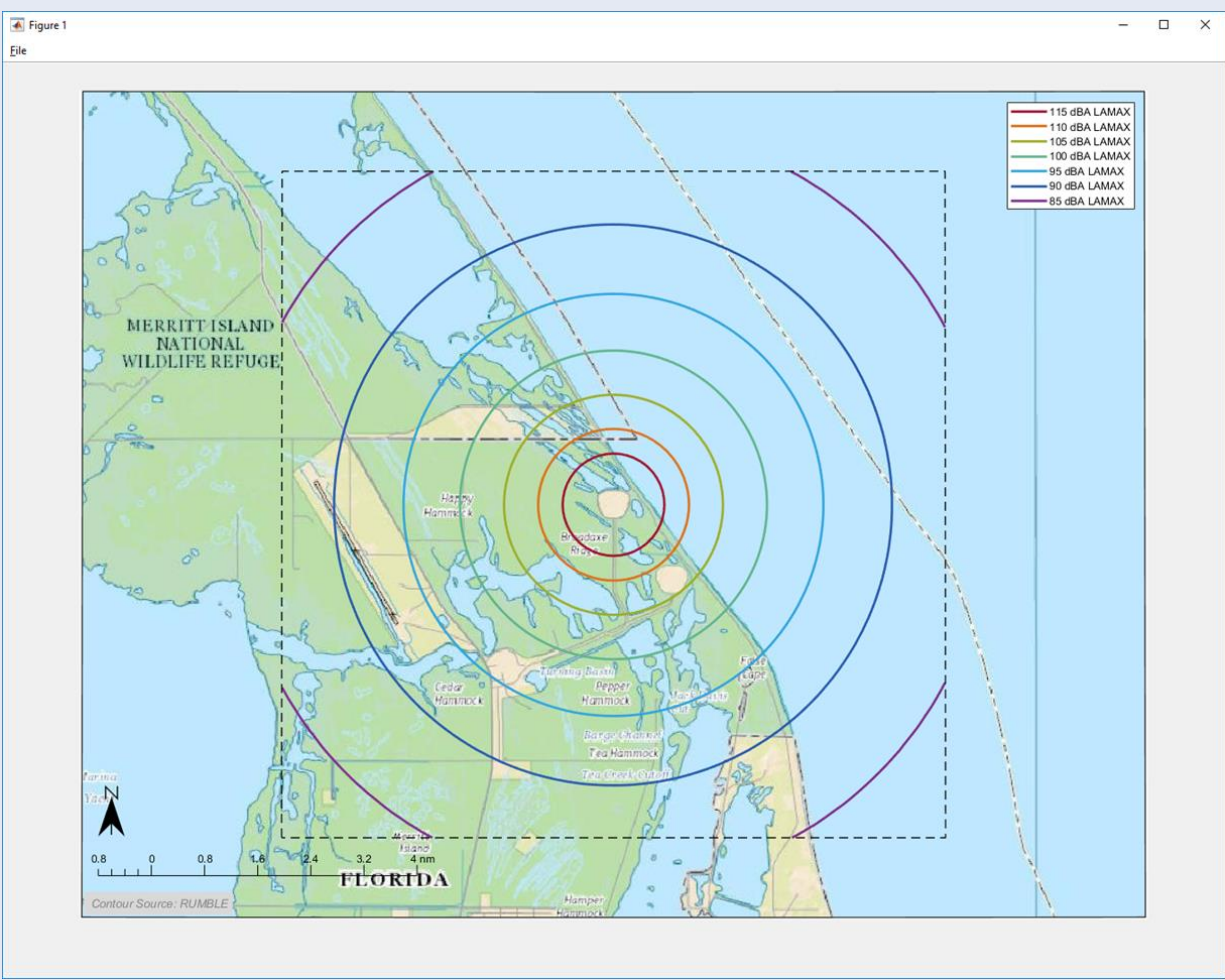
User Interface



Map Results



Simulation



Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



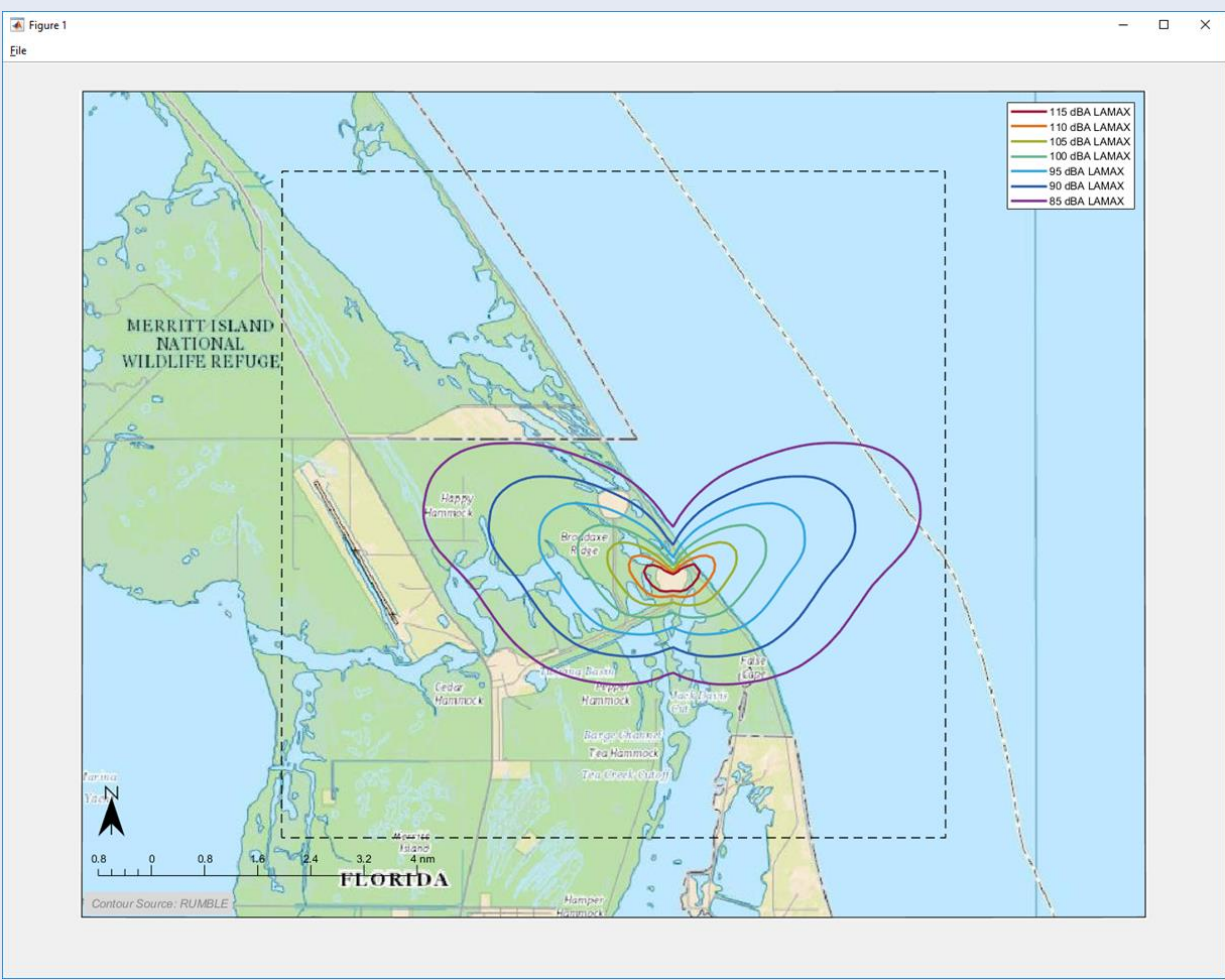
User Interface



Map Results



Simulation



Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



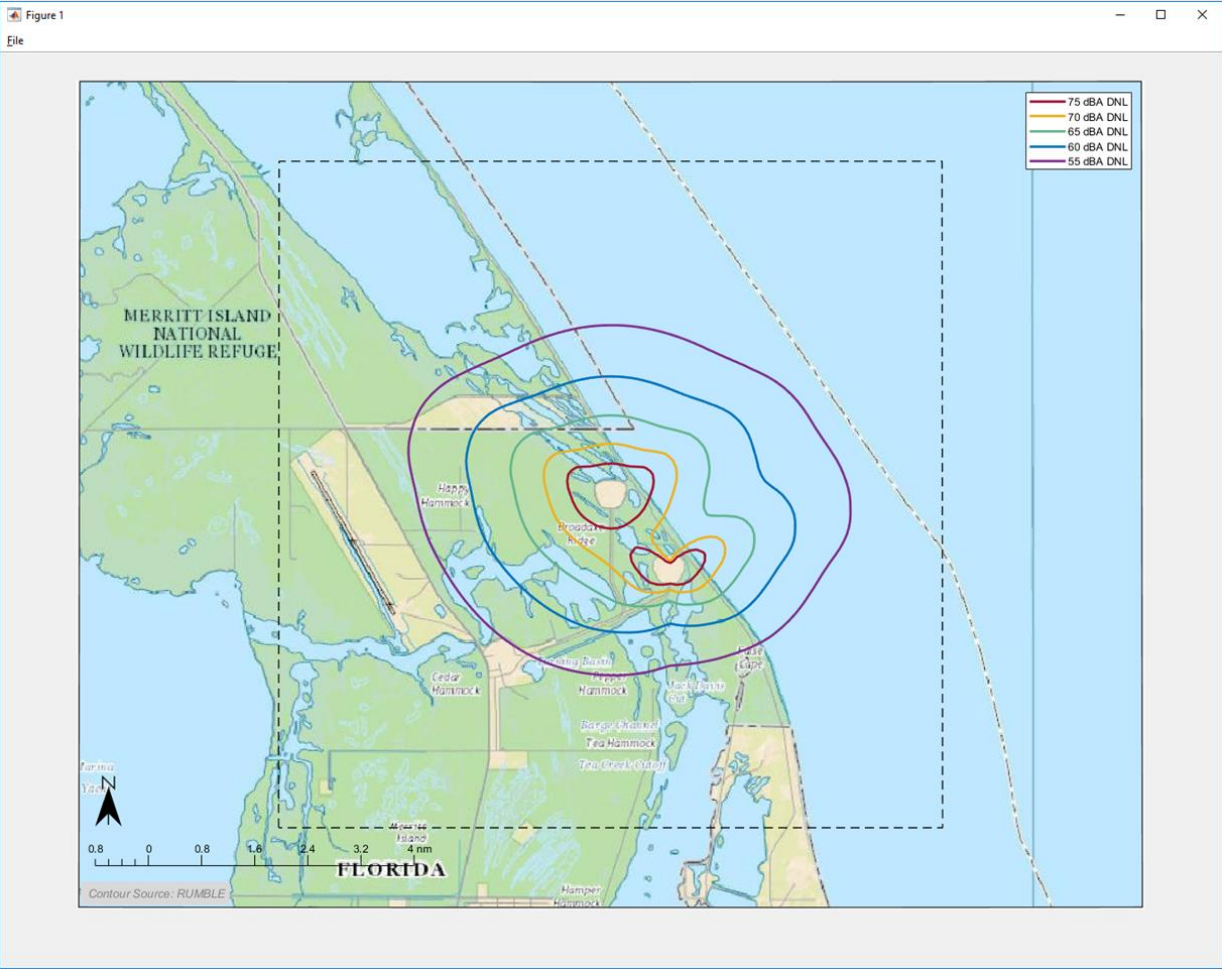
User Interface



Map Results



Simulation



Commercial Space Noise Modeling: RUMBLE



Modeling
Methodology



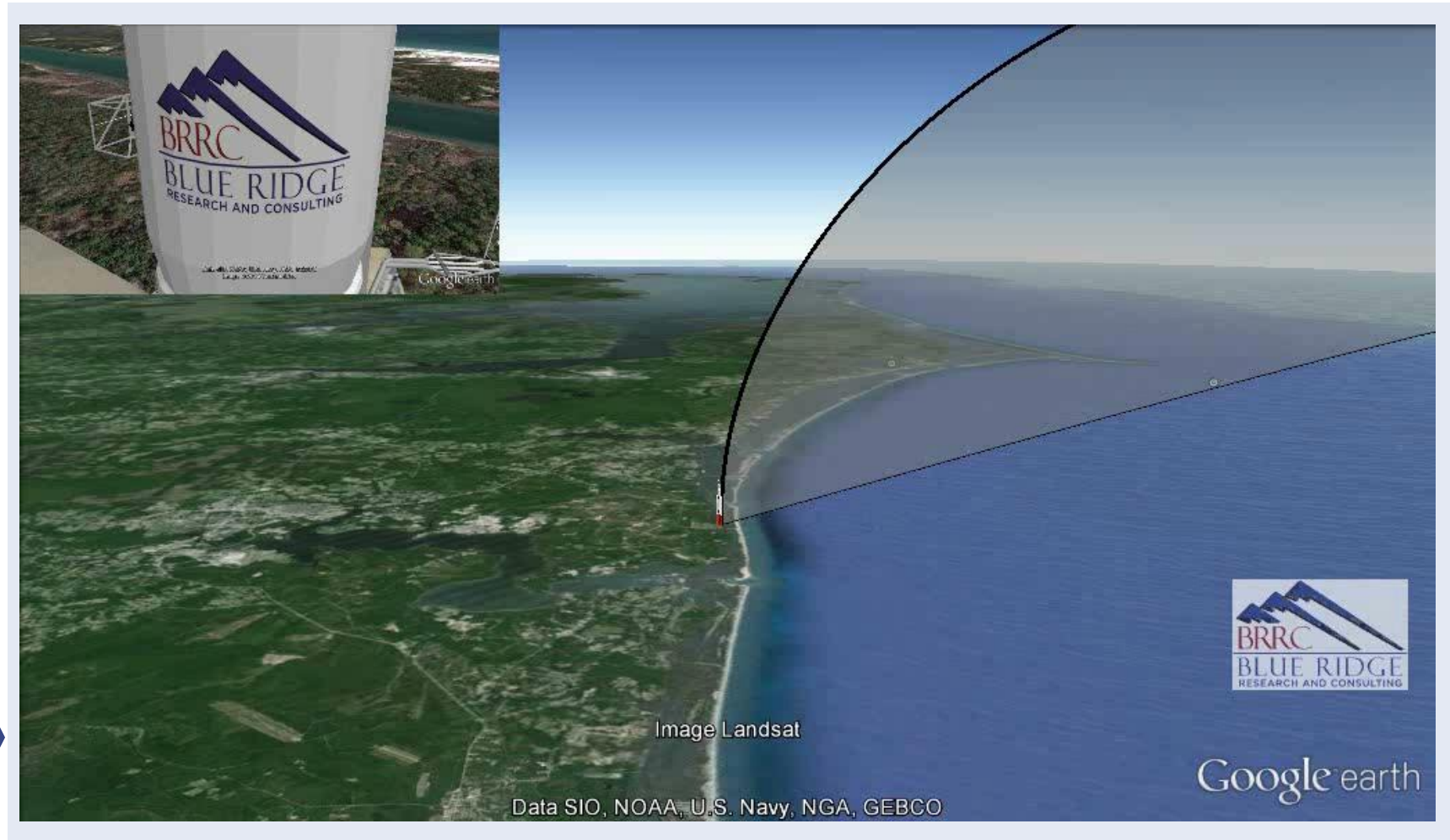
User Interface



Map Results



Simulation



Current/Future Commercial Space Efforts



Noise
Measurements



Noise Model
Validation



Emissions
Modeling

Commercial Space Noise Measurements Objectives

- Develop community noise measurement protocol
- Conduct a measurement campaign
- Compile database of rocket propulsion noise



Credit: Michael Deep

Antares 230



Credit: SpaceX

Falcon 9



Credit: NASA HQ

Delta IV Heavy

Current/Future Commercial Space Efforts



Noise
Measurements



Noise Model
Validation



Emissions
Modeling

- Antares 230
- 2 x RD-181 engines - LOX/Kerosene
- 12 Nov 2017, 7:19 AM
- MARS Pad 0A
- CYGNUS CRS 0A-8E
- ISS Re-supply



Credit: Michael James



Current/Future Commercial Space Efforts



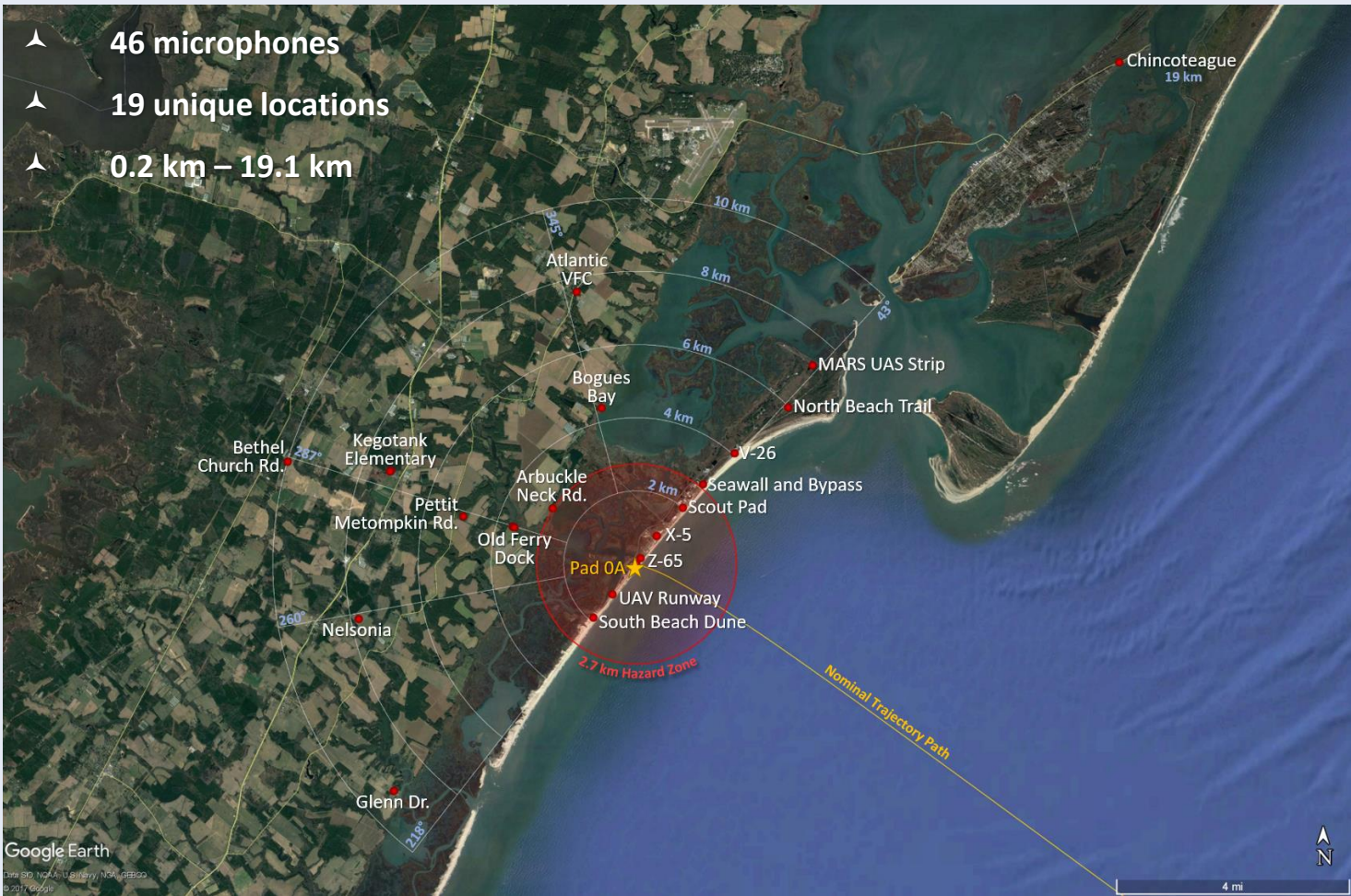
Noise
Measurements



Noise Model
Validation



Emissions
Modeling



Current/Future Commercial Space Efforts



Noise
Measurements



Noise Model
Validation



Emissions
Modeling

Z-65



Arbuckle Neck Rd



Bogues Bay



Old Ferry Dock



Pettit-Metompkin Rd



Kegotank Elementary



Current/Future Commercial Space Efforts



Noise Measurements



Noise Model Validation



Emissions Modeling



Current/Future Commercial Space Efforts



Noise
Measurements

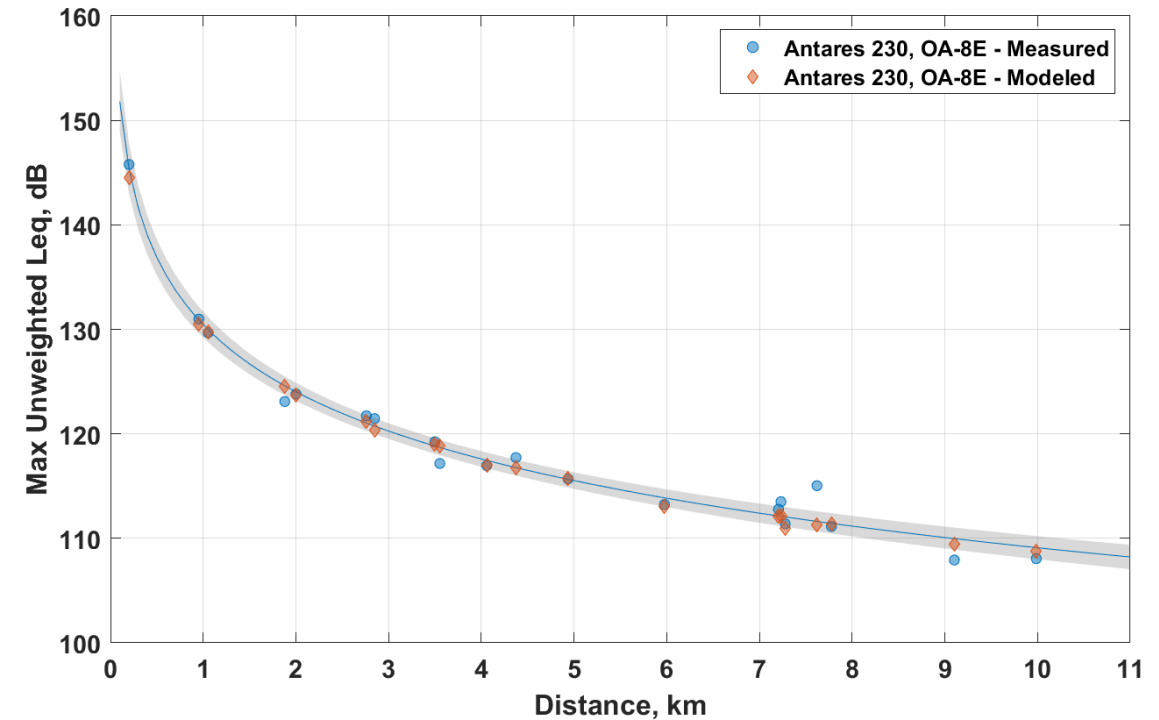


Noise Model
Validation



Emissions
Modeling

- Measured vs Modeled maximum unweighted L_{eq}
 - As-flown trajectory
 - Atmospheric profile
- Note, locations are at different azimuthal angles
- Blue line and grey area represents logarithmic fit of measured data and its 95% confidence intervals
- **Good agreement between measured and modeled max unweighted L_{eq}**



Current/Future Commercial Space Efforts



Noise
Measurements

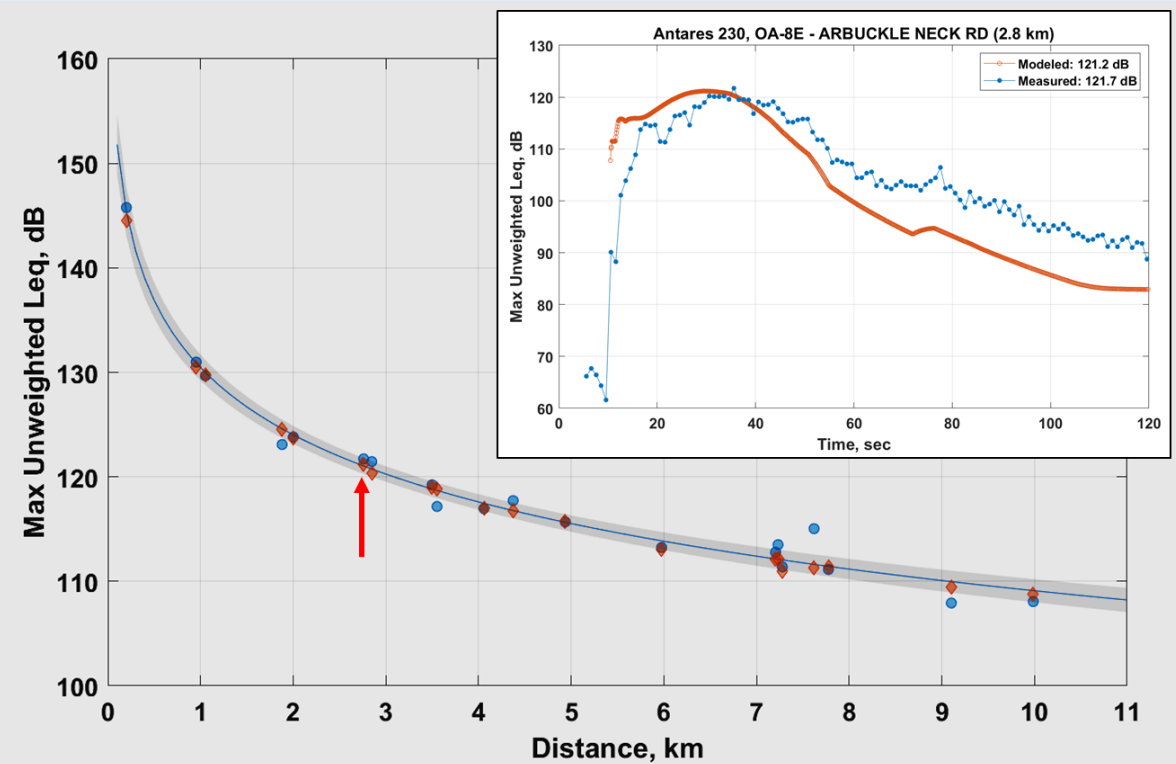


Noise Model
Validation



Emissions
Modeling

- Predicts overall maximum correctly but time of peak directivity is off
- Time history comparison shows that model does not accurately predict
 - Initial ramp up
 - Fall off



Current/Future Commercial Space Efforts



Noise
Measurements

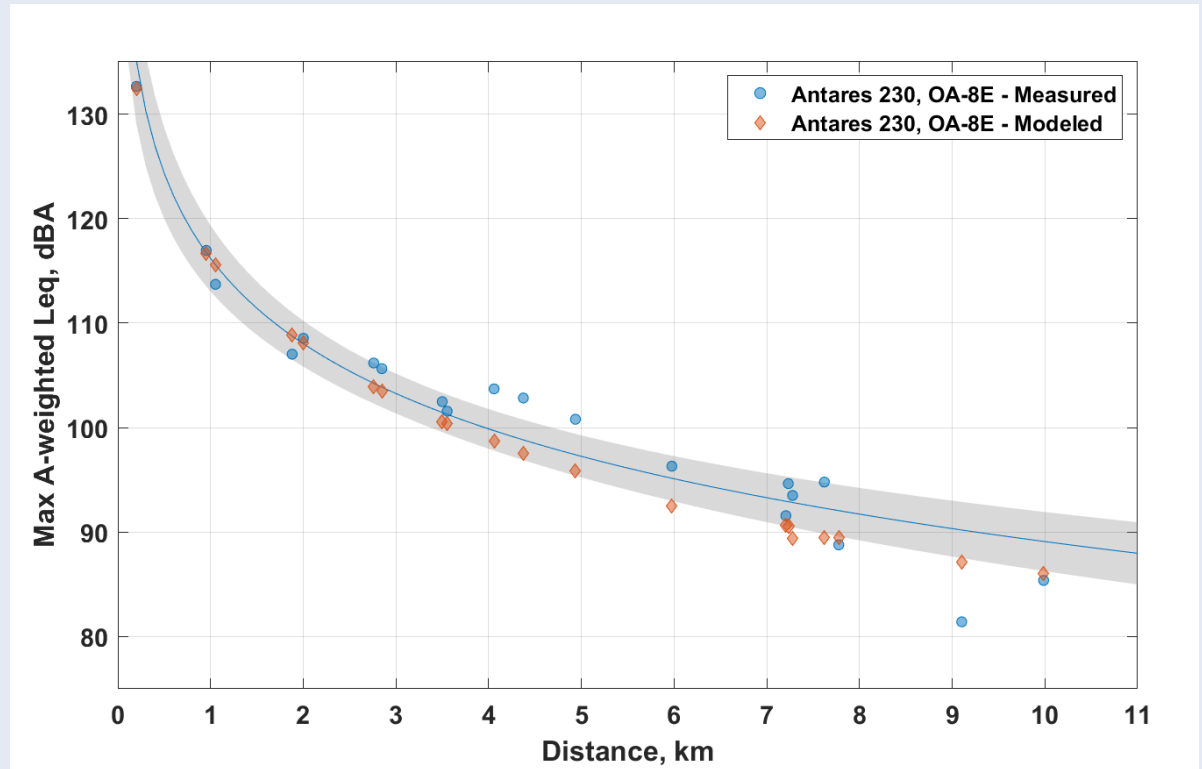


Noise Model
Validation



Emissions
Modeling

- Measured vs Modeled maximum A-weighted L_{eq}
 - As-flown trajectory
 - Atmospheric profile
- Note, locations are at different azimuthal angles
- Blue line and grey area represents logarithmic fit of measured data and its 95% confidence intervals
- **Model underpredicts the maximum A-weighted L_{eq} for measurement locations between 2.5 and 8 km**



Current/Future Commercial Space Efforts



Noise
Measurements

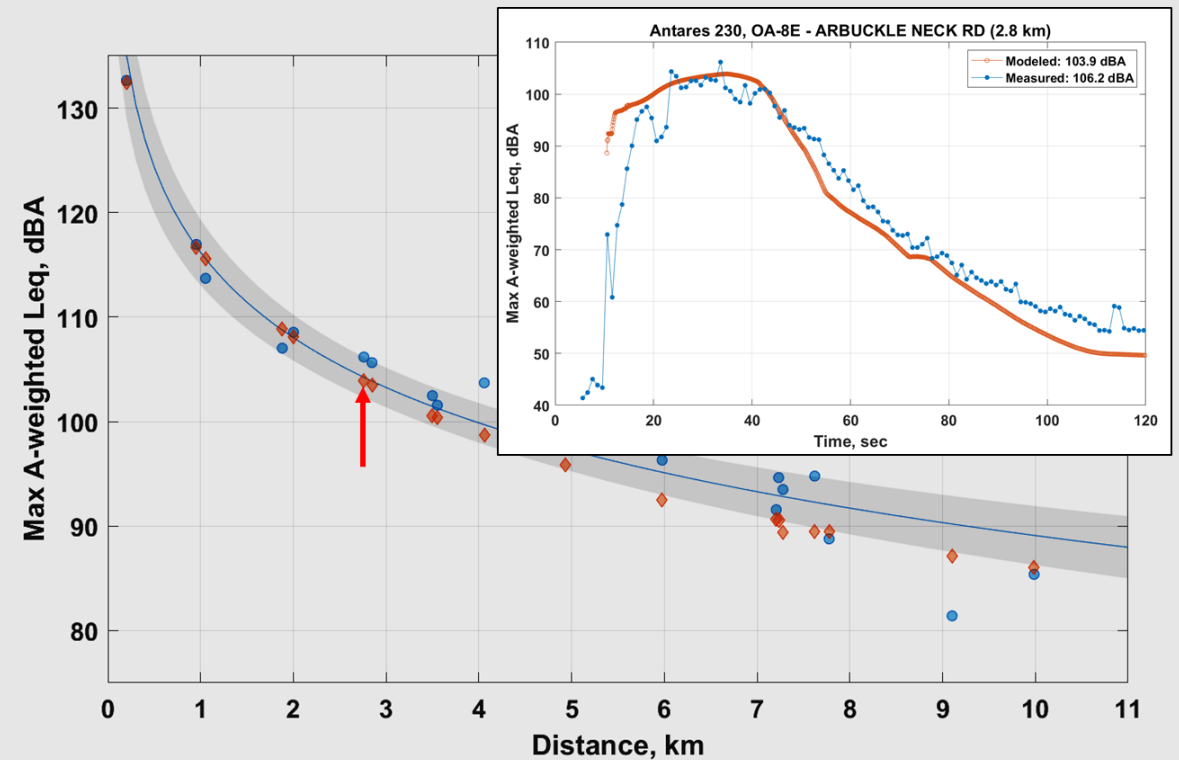


Noise Model
Validation



Emissions
Modeling

- Appears to predict time of peak directivity well, but the measured maximum A-weighted Leq is determined by brief periods of higher levels versus the smooth model levels
- Time history comparison shows that model does not accurately predict
 - Initial ramp up



Current/Future Commercial Space Efforts



Noise
Measurements



Noise Model
Validation



Emissions
Modeling

Commercial Space Vehicle Emissions Modeling

- The objective of this research is to develop a method to estimate emissions from commercial space vehicle operations.
- The method should:
 - ⬆ Allow users to estimate emissions for existing and emerging commercial space vehicles, engines, and propellants;
 - ⬆ Allow users to estimate emissions both below and above the mixing height;
 - ⬆ Be incorporated into RUMBLE and a simple (e.g., spreadsheet) emissions estimator tool to allow for easy estimations; and
 - ⬆ Be designed with the intent to be integrated with AEDT.

Current/Future Commercial Space Efforts



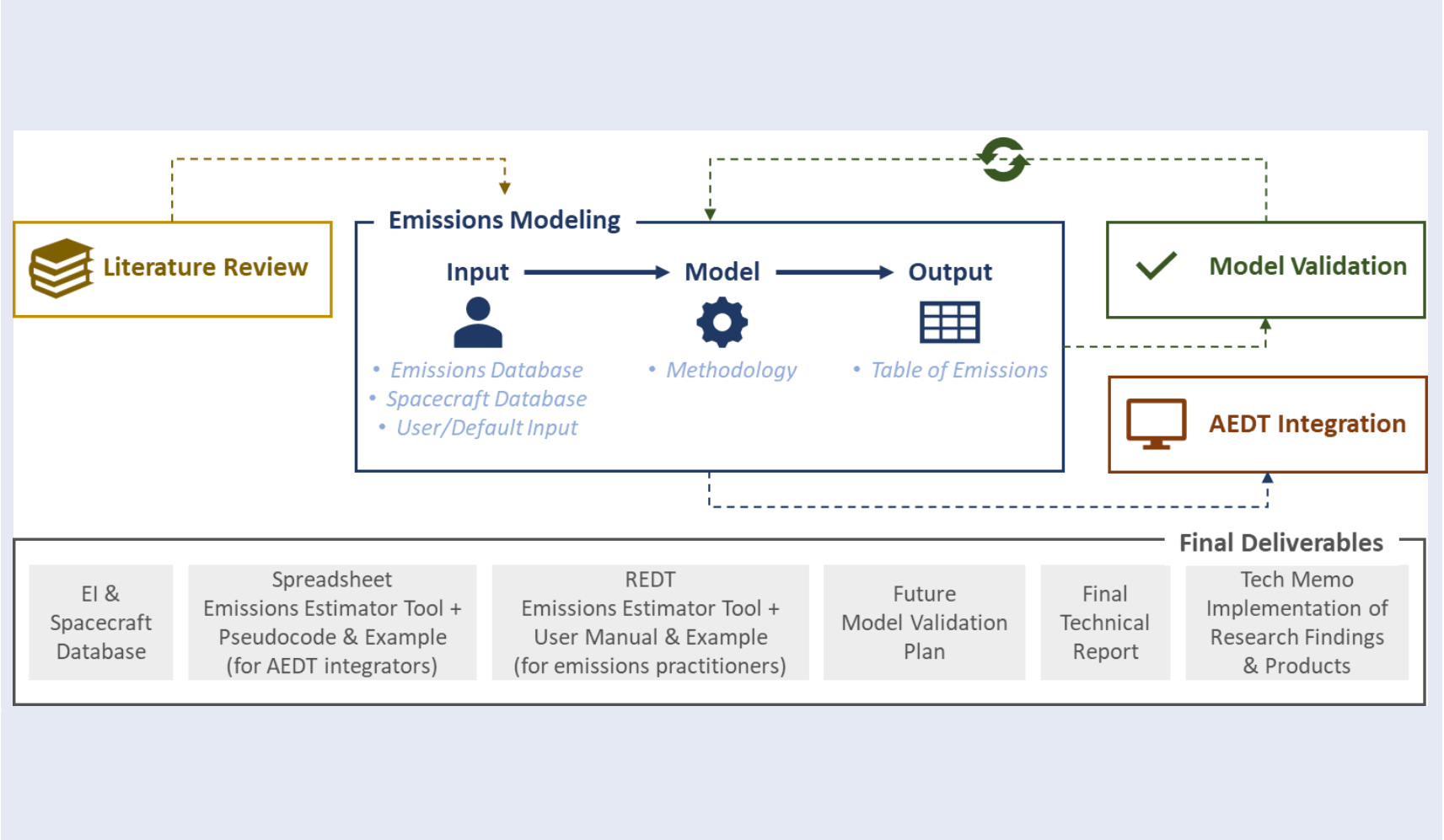
Noise Measurements



Noise Model Validation



Emissions Modeling



Questions?



Credit: Michael James