Initial Investigation into the Psychoacoustic Properties of Small Unmanned Aerial System Noise

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NASA Langley Research Center 1917-2017

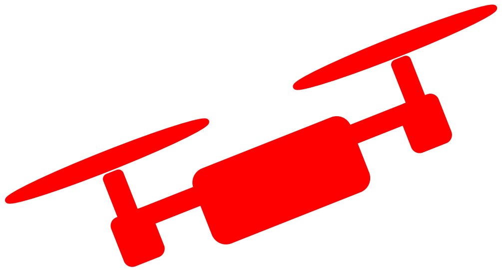
Taking on the Package Delivery Industrial Complex

- As there is no previous work directly on evaluating the subjective response to noise from small, unmanned aerial systems (sUAS), the direction of this research was relatively wide-open.
  - Start with package delivery, one of the most cited future applications of sUAS.

- The party line on noise is, basically "As long as the noise is no worse than a [delivery truck], we'll be ok."

- This has several obvious problems (trucks don't fly over your house, etc.), though the premise can be easily tested:
  - Collect fly-over/fly-by sounds from various sUASs, as well as drive-by sounds from several vehicles.
  - Use the Exterior Effects Room @LaRC (EER) to solicit people's subjective impression of the recordings.

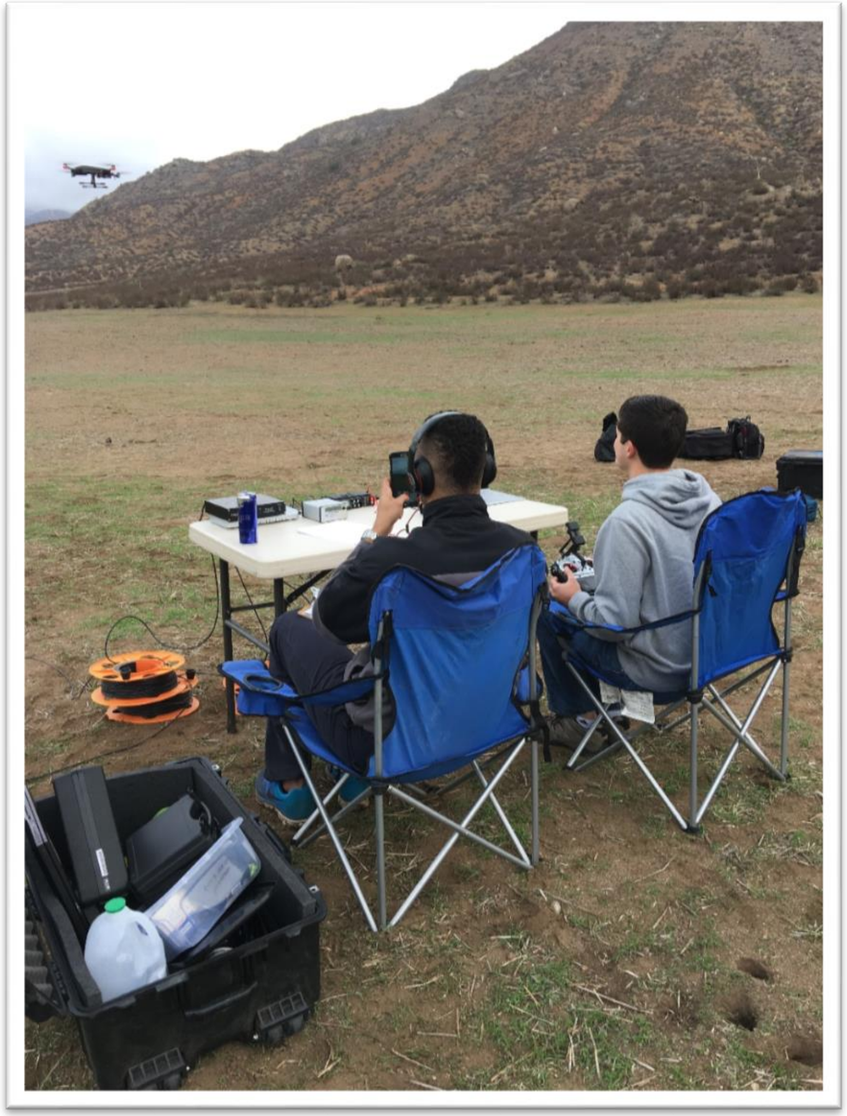
"I don't like going on fishing trips."
-Kevin Shepherd



Sound Collection: SUI

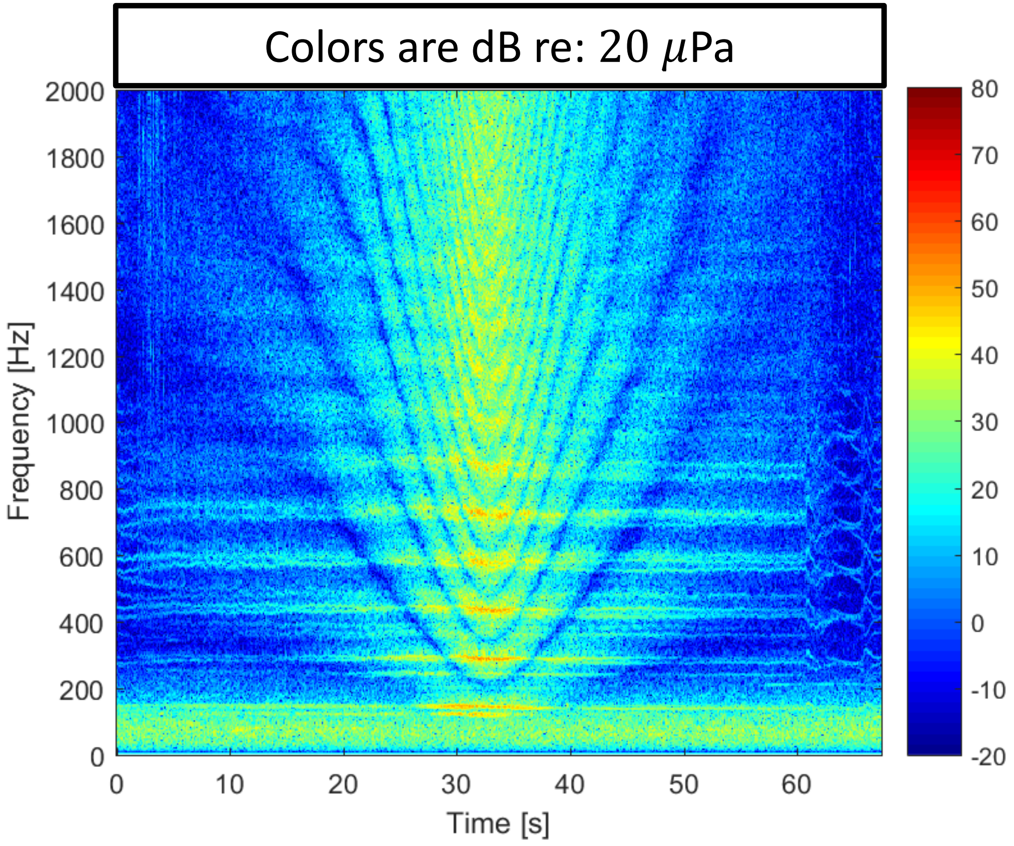
- The first set of sounds was provided with assistance from Straight-Up Imaging (SUI), a company in San Diego, CA that builds, owns, and operates sUAS for photographic purposes.

- Their flagship 'Endurance' model was flown



Sound Collection: SUI

- Given that SUI built the vehicle, the operators were able to have a high degree of control over it.
  - Multiple runs at tightly controlled altitudes and speeds.
- These recordings were used as the ‘core’ of the test.
- This sound:
  - 20 m over a 4 ft mic, 5 m/s



Sound Collection: Oliver Farms

- The second set of sounds comes from several days of sUAS (multi-copter) recording.
  - Fall 2016
  - A sorghum field in Smithfield, VA

- Vehicles recorded and included in the test:
  - DJI Phantom 2
    - Flown with 3 different blade sets
  - DaX 8
  - VPV/Stingray
    - Variable pitch blades, one motor

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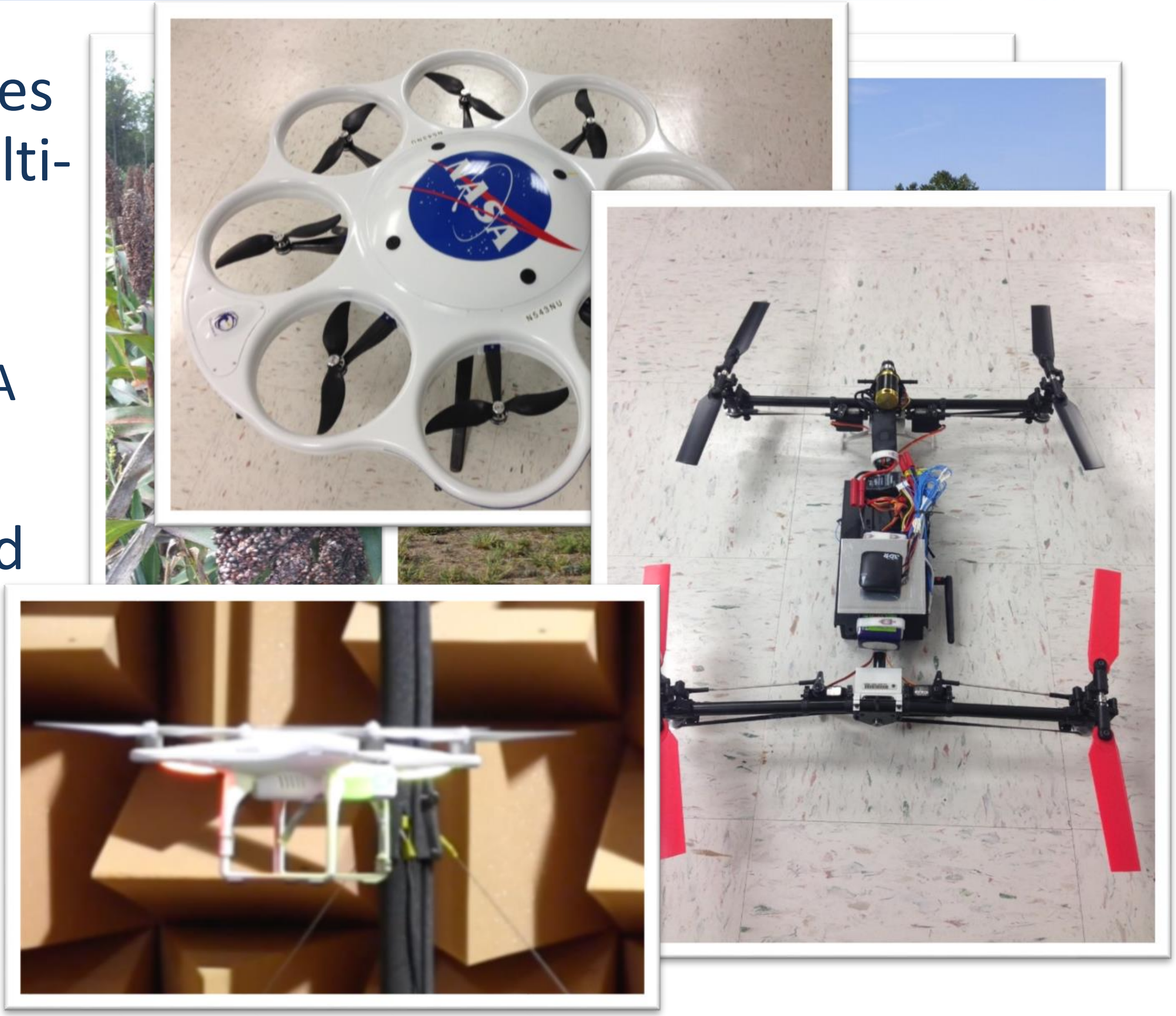
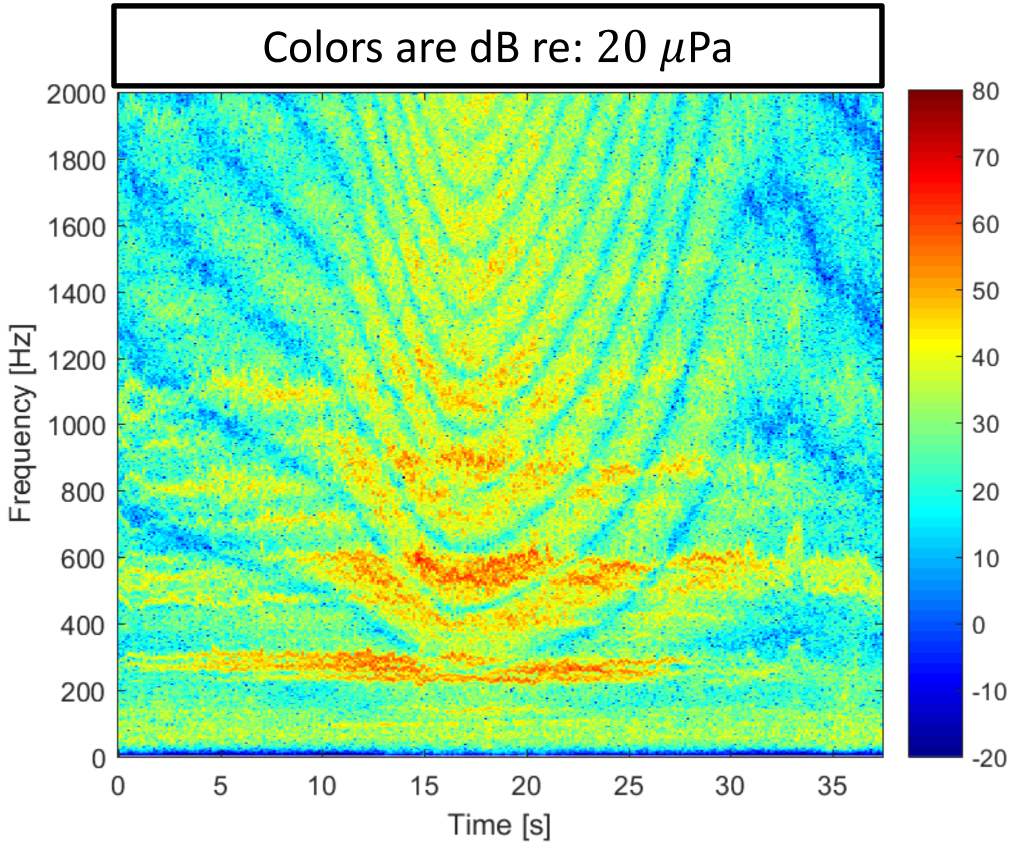


Sound Collection: Oliver Farms

- The vehicles were not well-guided (i.e., poor control on altitude, velocity, etc.).
- These sounds were used to span the magnitude range desired for the test (in dB) and to provide sounds that varied qualitatively.
- Dax 8 flyover:
  - 20m above a 4 ft mic, 5 m/s



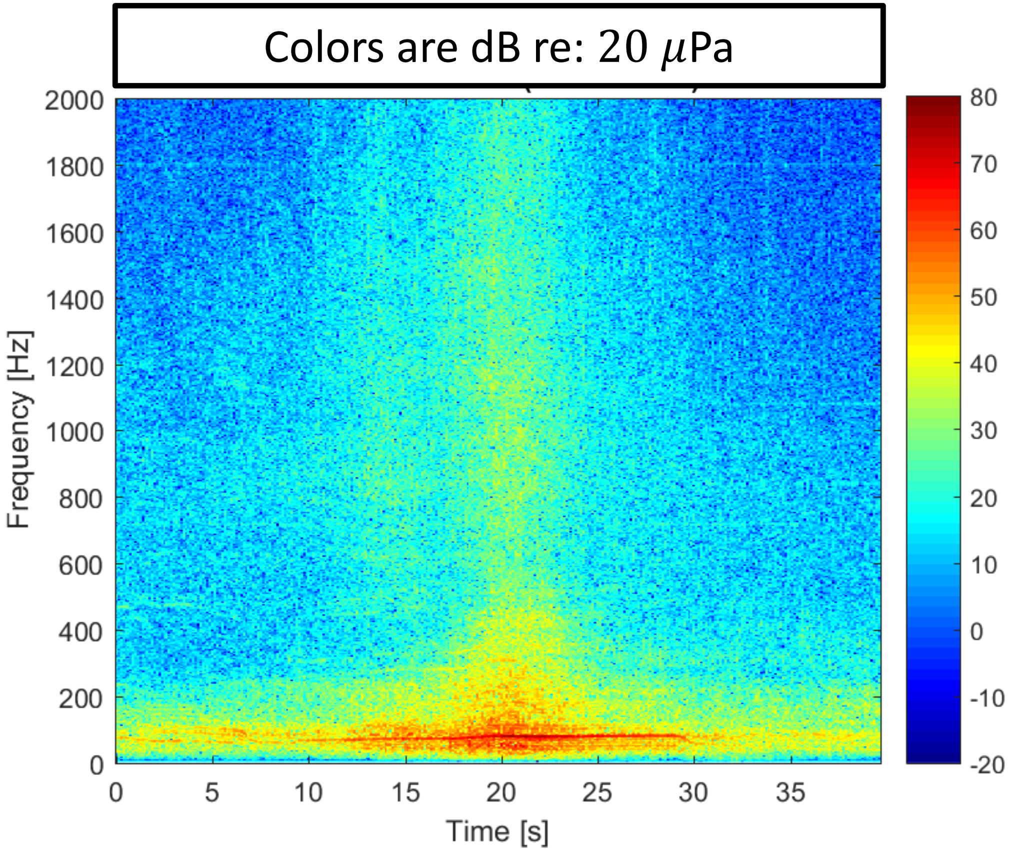
Sound Collection: Cars

- The last set of recordings was taken at LaRC on a quiet Sunday in early 2017. Several vehicles that might be used to deliver packages around a residential neighborhood were recorded.

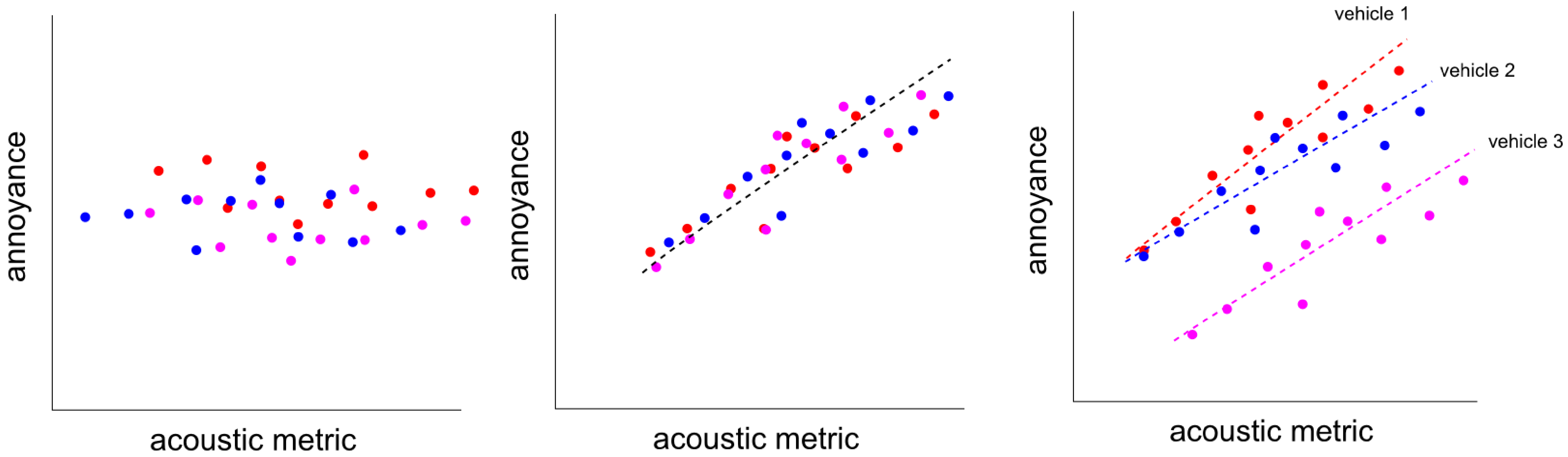
- Included:
  - Andy’s 2010 Subaru Impreza
    - Over 100,000 miles on it.
  - A ‘step van’
    - Typical of certain commercial package delivery outfits.
  - A 20’ diesel box truck.
  - A van-like vehicle.

Sound Collection: Cars

- All drive-bys recorded at 25 mph (about 10 m/s).
- Recordings were adjusted (gain) to span the range of dB required for the test.
- Step van
  - 4 ft mic @ 25 ft from the edge of the road



A Well-Planned Fishing Trip



- 103 Sounds:
  - 62 sUAS recordings
  - 20 road vehicle recordings
  - Auralizations of a quadcopter and a SCEPTRE-like vehicle

- With this sort of data, there are many possible modes of analysis. (One will be discussed here.)

Subject Experience

- 38 subjects participated during a 1-week period
- 4 subjects at a time took about 1 hour to listen to all 103 sounds.
- The ordering of the sounds had both Latin-square and random layers.

Spatialization

- The EER is a real-time 3D sound environment. Using 27 full-range speakers and 4 subwoofers, it can reproduce the sensation of the sound source moving.

- GPS data captured with the recordings was used to drive this spatialization capability:
  - Fly-overs went overhead front to back.
  - Fly-bys went overhead L to R
  - Drive-bys were on the horizon L to R.

Signal Preparation

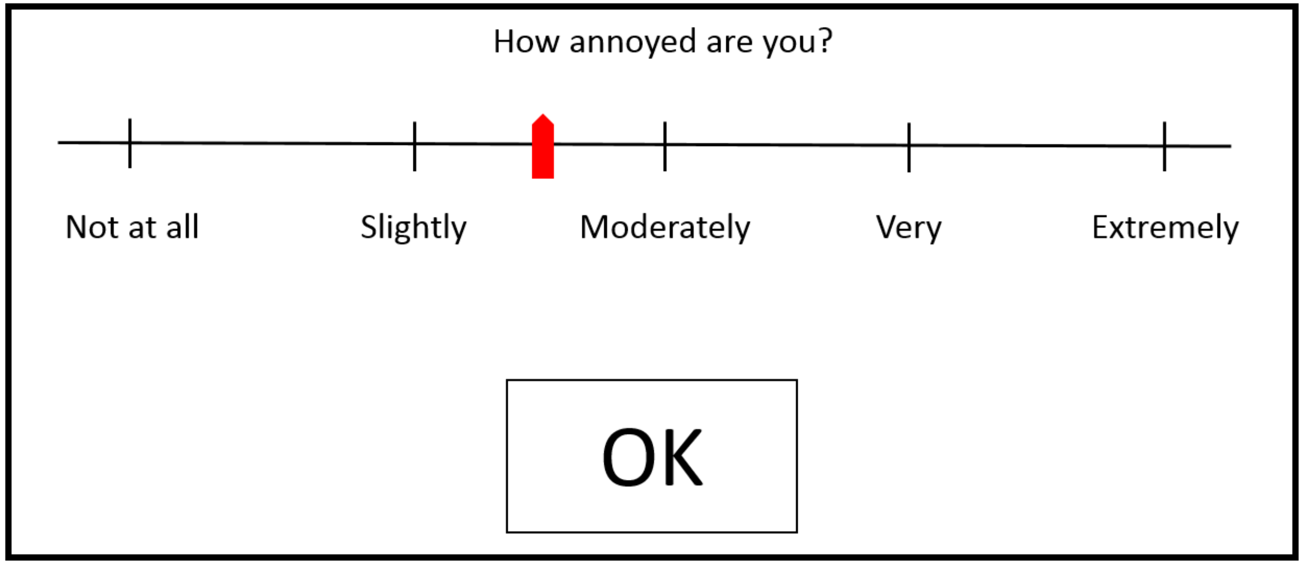
- The sounds had various lengths:
  - Tried to get 10 – 20 dB down
  - Limited by environmental noise (e.g., birds)
  - Limited when sUAS were at great altitude

- 2 second fade-ins and -outs were added to window the sounds.

- Oliver Farms sUAS and Cars were adjusted in gain to span a 20 dB range.

The Question

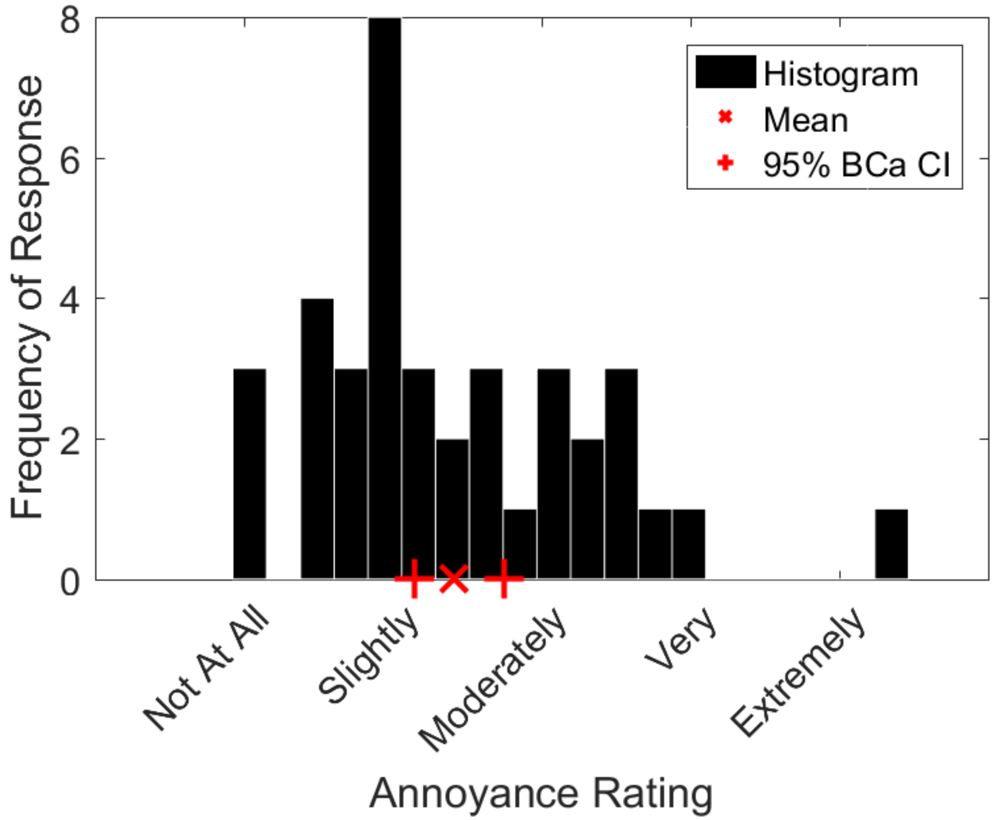
- Subjects were asked to simply rate how annoying a sound was to them.
- They were presented with this scale on a tablet computer, and could answer only after the entire sound had played.
- Asking the question this way supposedly makes the response data linear…



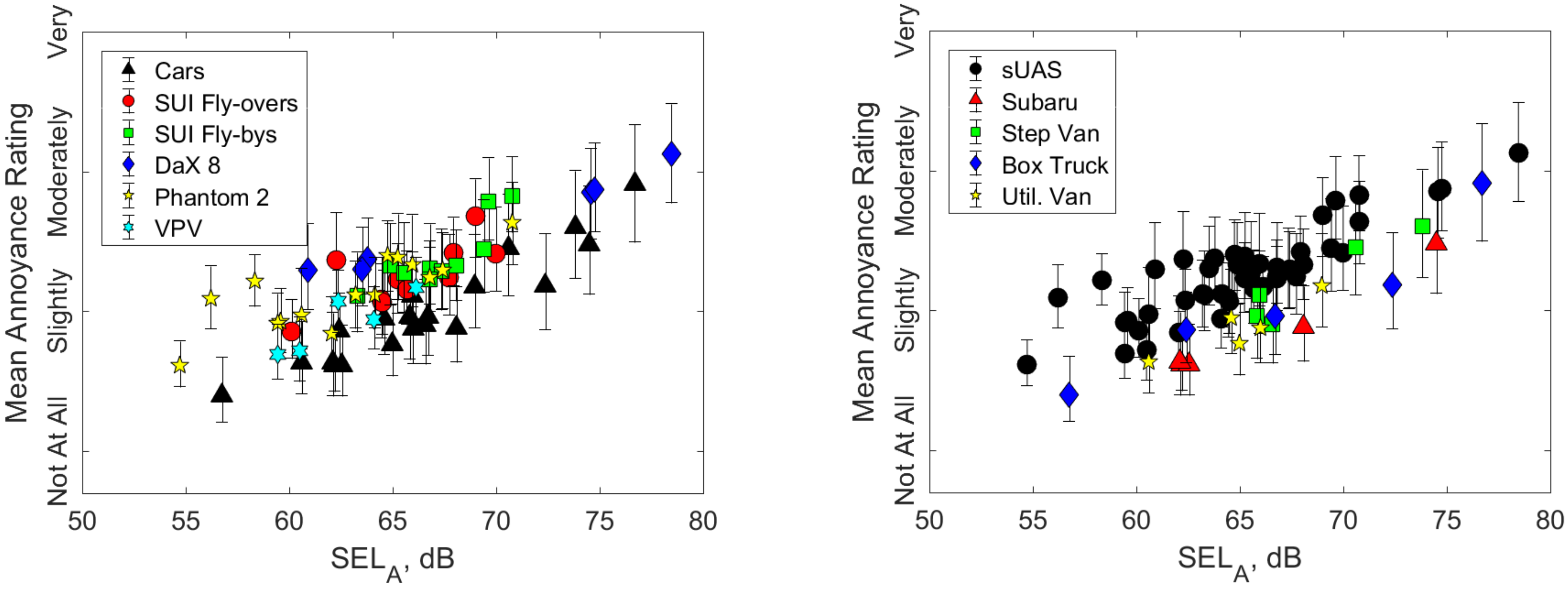
Inter-subject Variation

- People have very different opinions!
  - They are not normally distributed.

- Use a nonparametric bootstrapping method to compute confidence intervals (CIs) on individual samples.
  - Bias-corrected Accelerated (BCa)
  - Variable width/skewness
  - All results here 95% certainty.



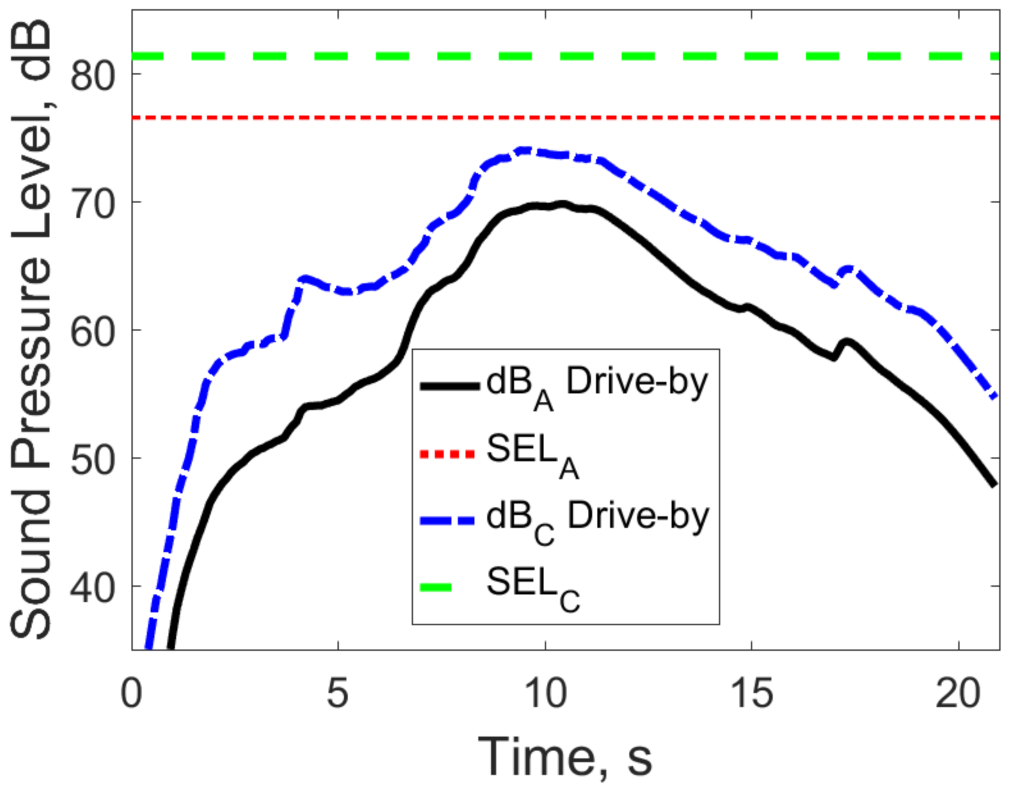
Inter-vehicle Variation



- Annoyance ratings on the y-axis.
- The x-axis is a noise metric value: a number computed from the sample sound.

Metrics

- Several common noise metrics were used:
  - SEL_A
    - Based on the dB_A psophometric curve.
  - SEL_C
    - Based on dB_C weighting, incorporates more low-frequency.



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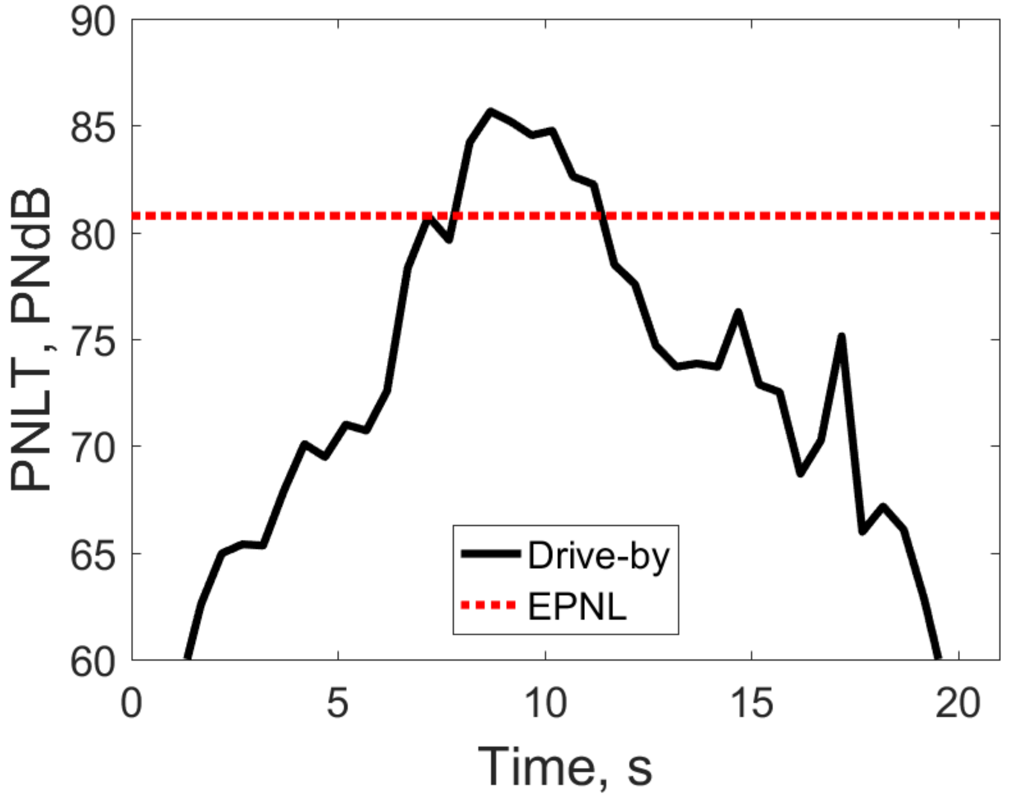
  - EPNL
    - Based on PNLT. Uses 1/3rd-octave spectra. Tries to account for ‘tonality’ of the sound.
    - Decibel-like units.



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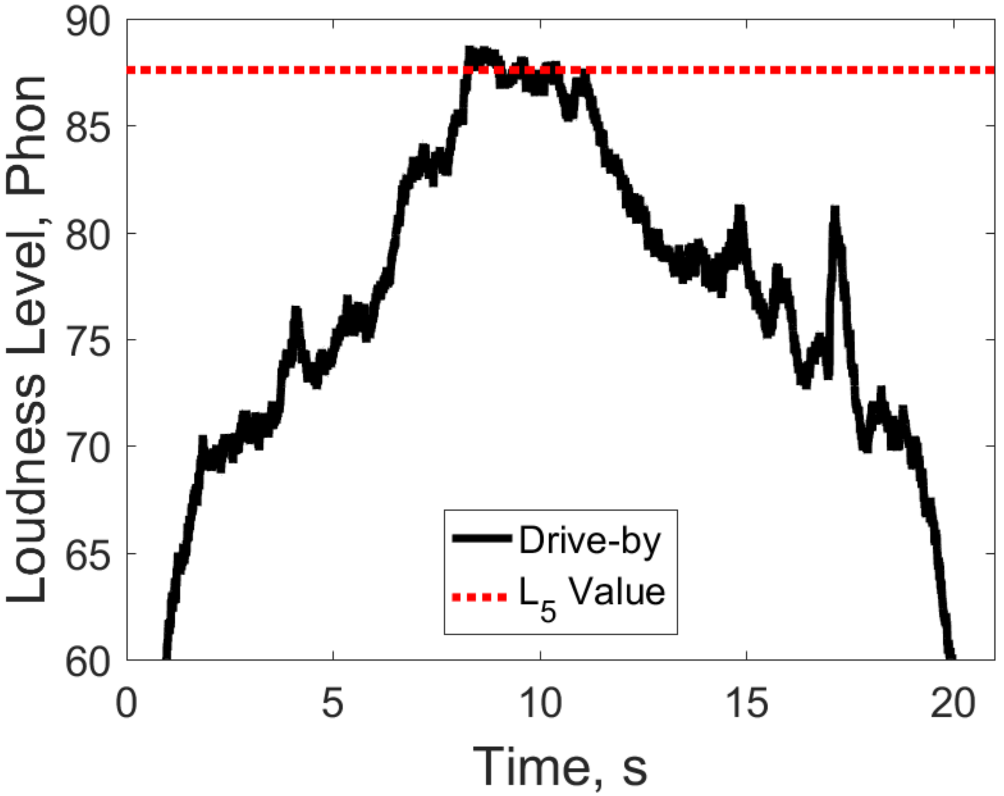
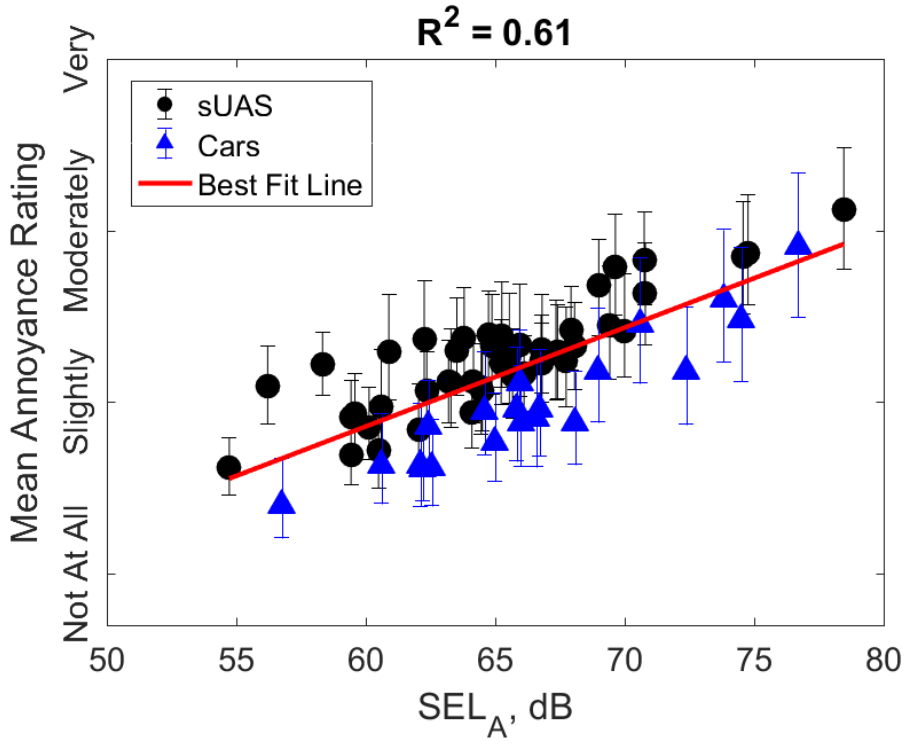
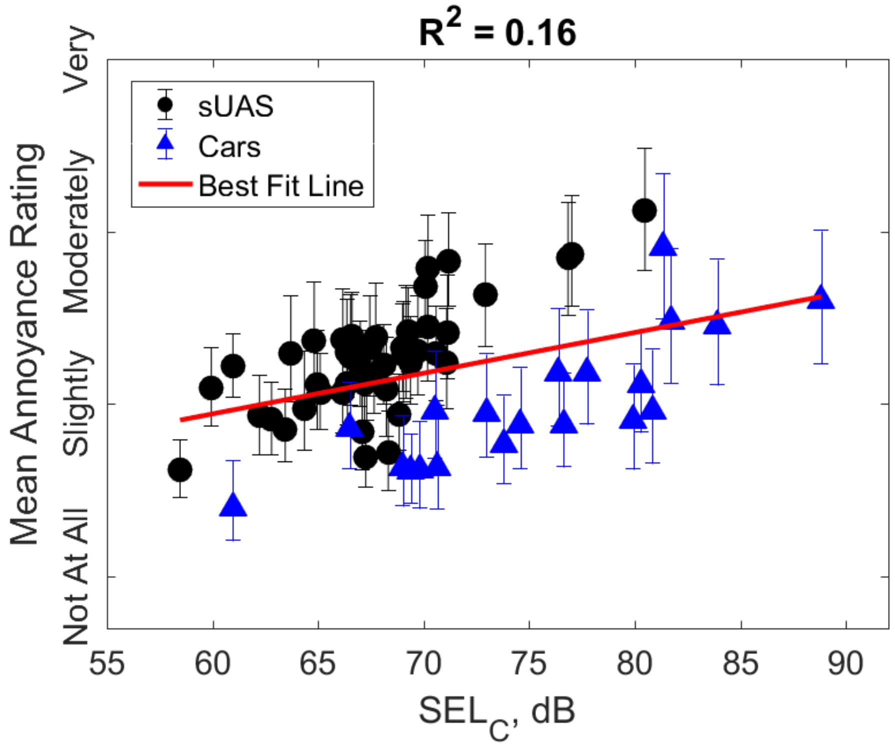
  - EPNL
    - Based on PNLT. Uses $1/3^{rd}$-octave spectra. Tries to account for 'tonality' of the sound.
    - Decibel-like units.
  - 'Zwicker' N-5 Loudness
    - Based on a model of the human auditory system.
    - Loudness exceeded 5% of the time.
    - Decibel-like units.



"R^2"





- The square of the correlation coefficient (R^2) describes the percentage of the variance that is observed in the y-value, that is accounted for by the model that maps x to y.

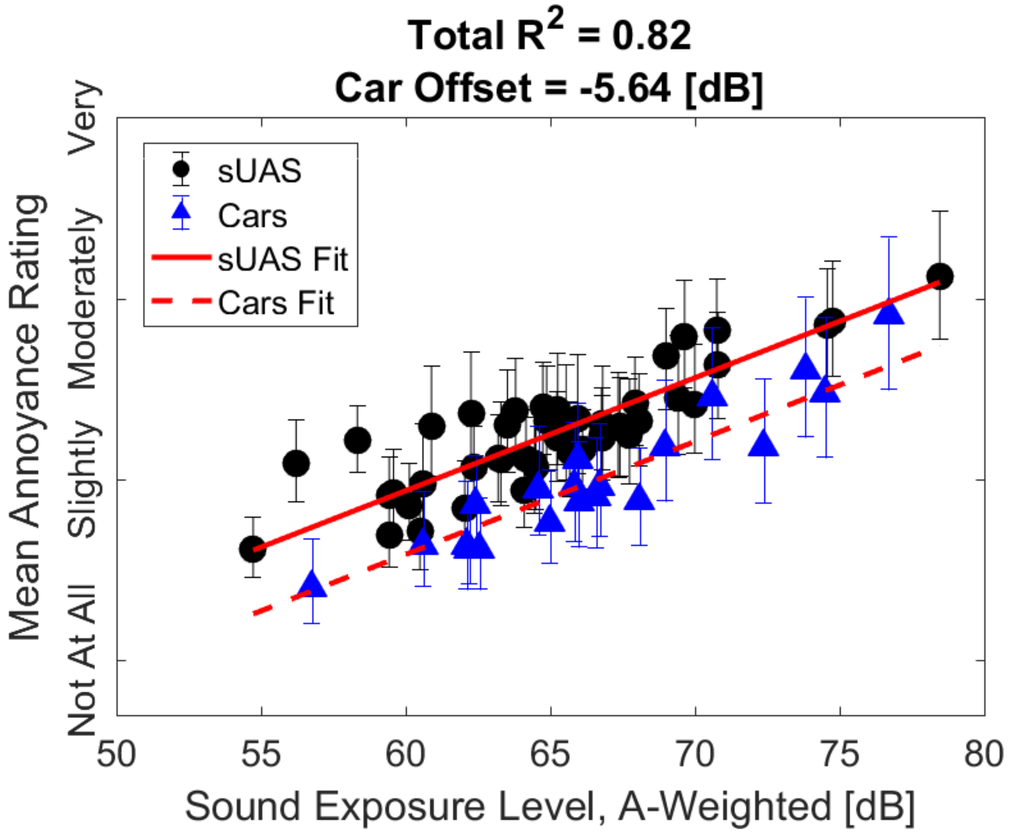
"Multiple Regression" Model

- For all of the metrics looked at, there seems to be a trend of the cars being less annoying.
  - 66 of the 103 sounds (all recordings, no repeats)

- Augment the typical linear regression model:

$$y = a + b \times x\big(p(t)\big) + \frac{c}{b} \times z(i)$$

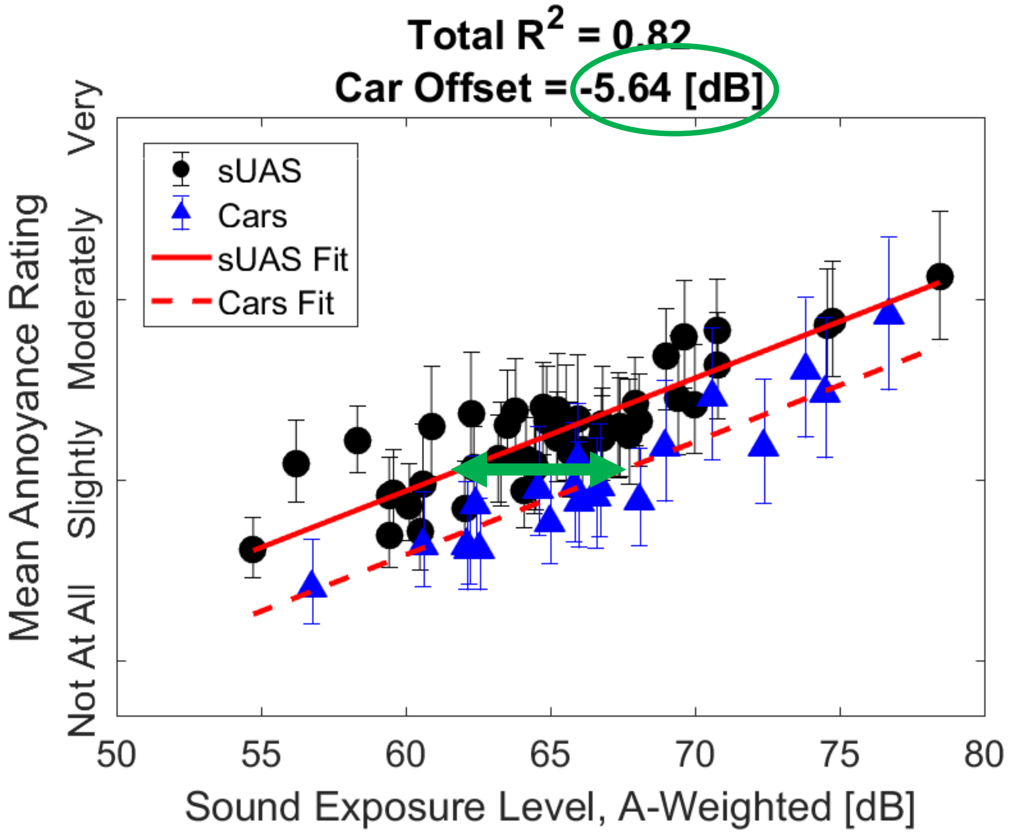
Where: $z = \begin{cases} 0 \;\; if \;\; i \in sUAS \\ 1 \;\; if \;\; i \in Cars \end{cases}$



"Multiple Regression" Model

- This model allows two lines to be fit: one to the collection of sUAS, and one to the 'car' data.
  - These lines are constrained to have the same slope

- The resulting offset measures the difference between the two lines in terms of the metric value.
  - How much more noise can a car make before it's as annoying as a sUAS?



Multiple Regression

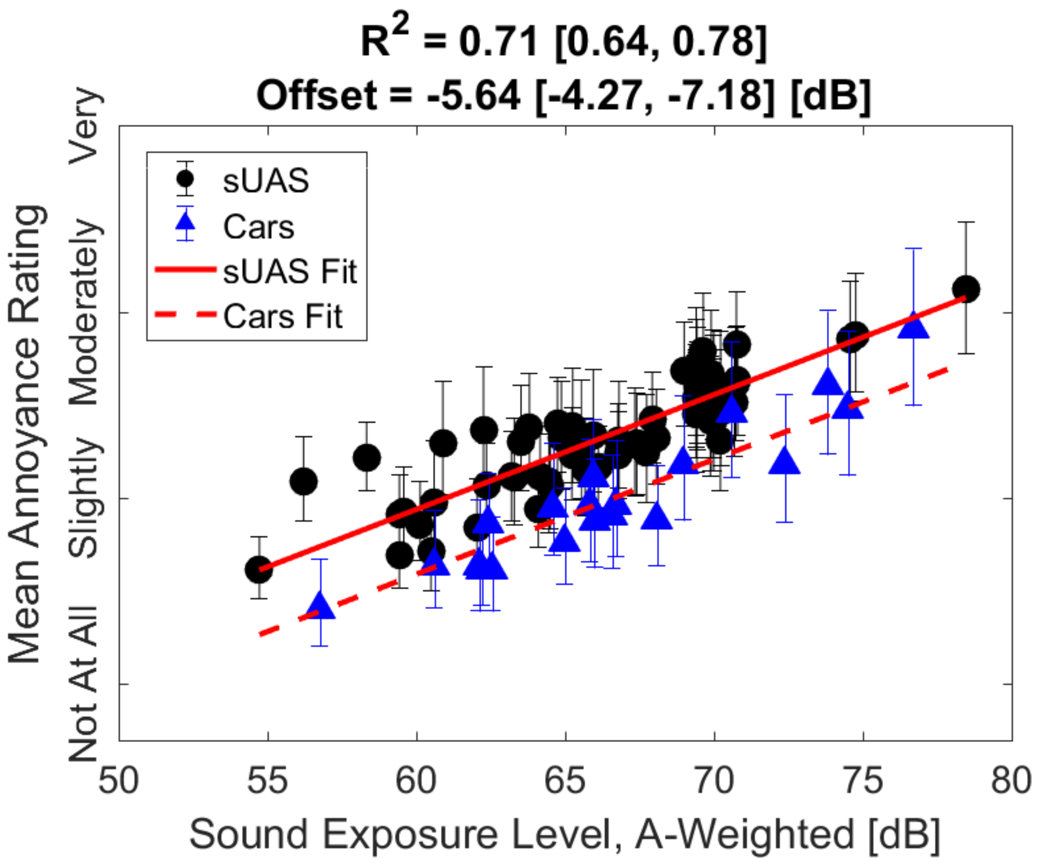
- Dramatic increase in explanatory power over models that do not discriminate between vehicle types.
- The offset is not a small number…
  - In general, better fitting models yield smaller numbers.
  - We want to know how significant the offset is given the data.

Metric	R^2	Offset
SEL_A	.82	5.6 dB
SEL_C	.68	12.8 dB
EPNL	.80	7.6 PNdB
Loudness	.75	7.5 Phon

Bootstrapped Regression

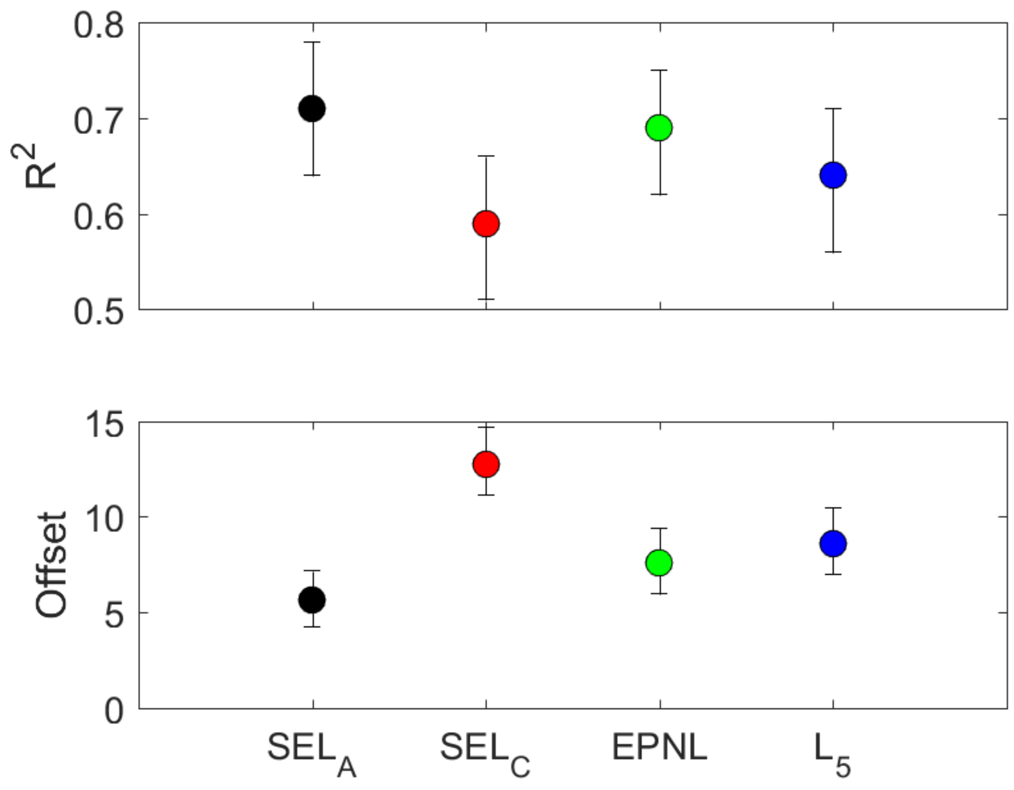
- We can use a method similar to BCa to bootstrap confidence intervals for the regression results.
  - 100,000 regressions using data resampled from the original responses.
  - ~30 minutes/metric on my laptop…

- R^2 takes a hit by adding the variation into the analysis.



Bootstrapped Regression

- Main observations:
  - Given the differences between people, we can not confidently discriminate between the various metrics, though all of the trends still hold.
  - For all metrics, the offset is very significant (CI does not come anywhere close to 0).

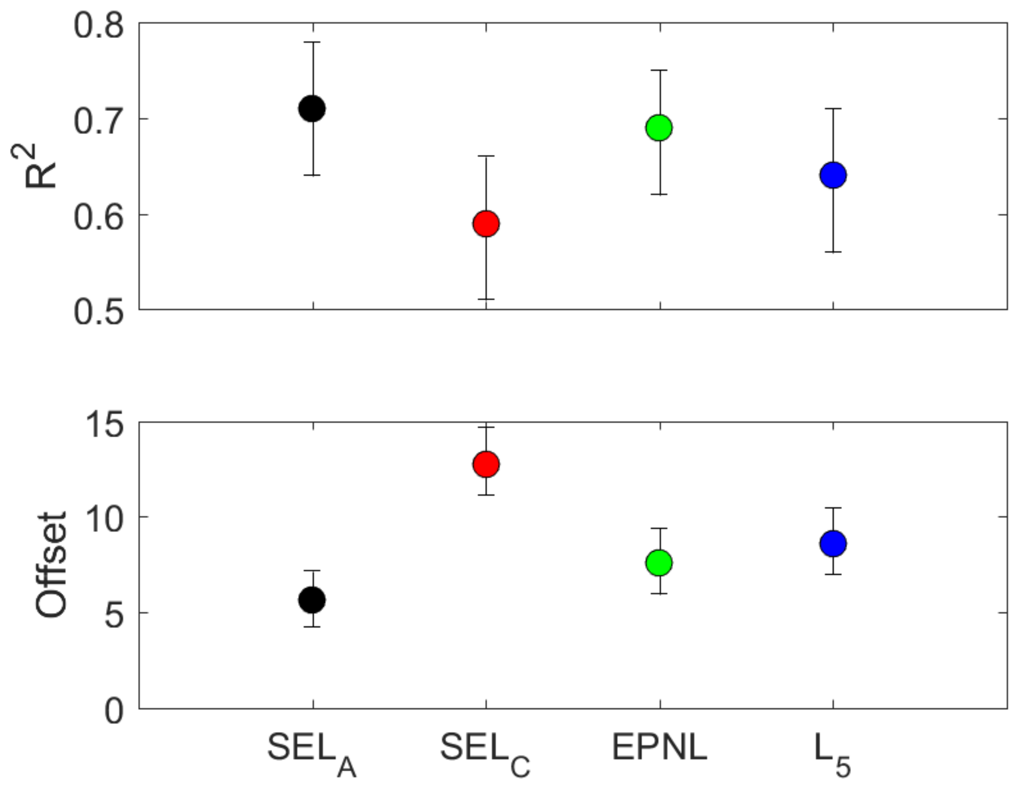


(As measured in each metric's unit.)

The Implication

- If you use a contemporary noise/certification metric, prepare to pay a price for operating an sUAS.

- If you want a metric that treats sUAS noise fairly, prepare for it to take into account qualitative aspects of the noise.



(As measured in each metric's unit.)

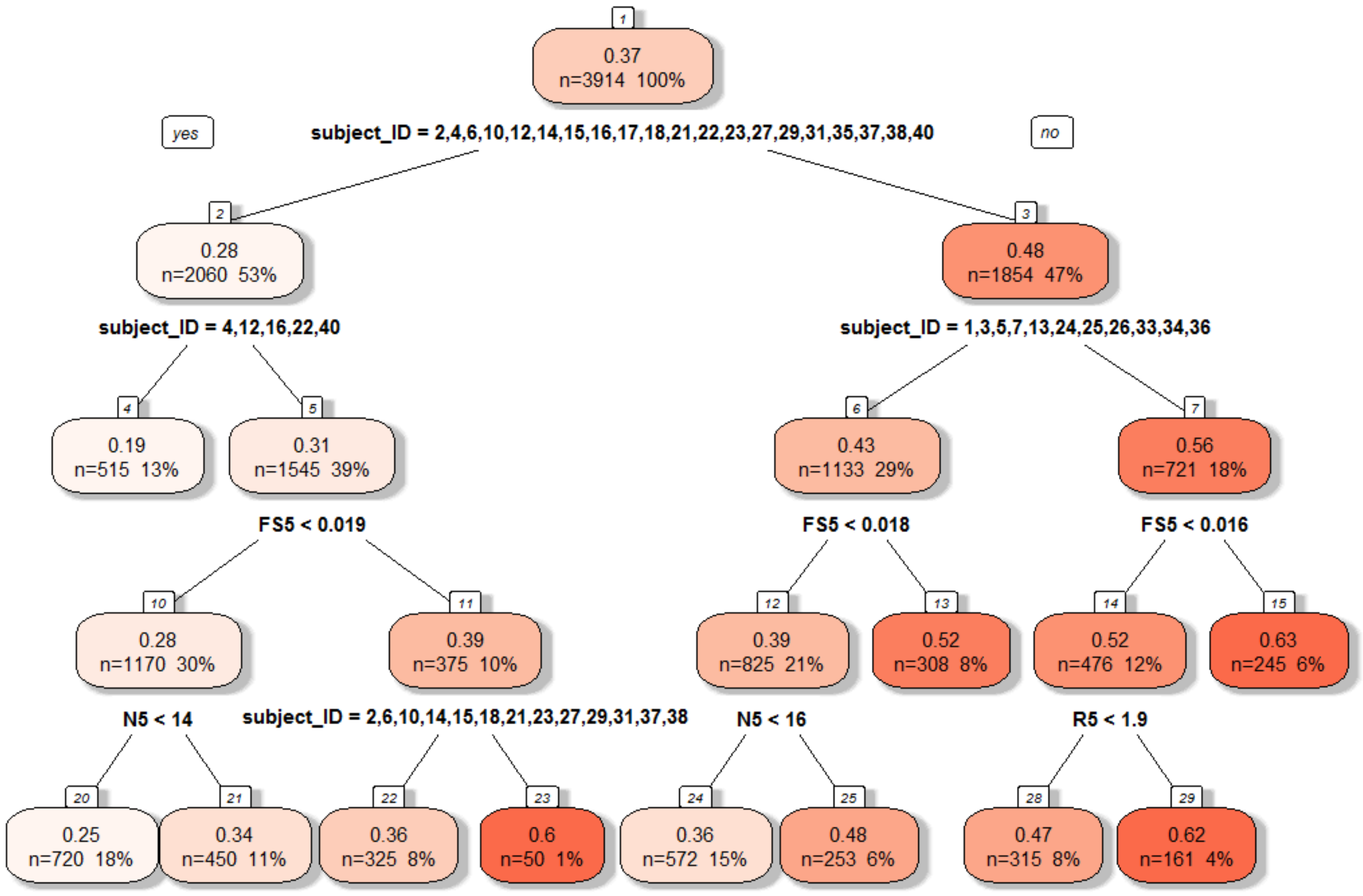
Other Relevant Points

- Road, rail, and aircraft sources of noise are already known to be significantly different in terms of annoyance.
  - This has been shown in both lab studies and *in situ*.
  - The disparity found here is on par with that in the literature (~6 dB).
  - Aircraft is always the most annoying class, though road/rail swap between studies (and countries).
  - Most subjects in this study could not identify the sUAS noises.

- Many caveats…
  - This is only one study!
  - This is the first study of its kind (so there’s not much to compare to).
  - The vehicles were not flying real mission profiles.
  - Etc.

Other Analysis Approaches

- Rafaelof and Schroeder have used this data set to train several machine learning algorithms to predict annoyance.
  - Support-vector Machines
  - Random forests
- The inputs to these techniques are values of “sound quality metrics” calculated for the samples
  - Tonality, Roughness, etc.



Questions?

SUI Endurance

Delivery Truck

The DELIVER Project

- DELIVER is a small CAS project (now in its last of 3 years), the theme of which is to figure out whether tools we already possess can be extended easily to aid the design process of small unmanned aerial systems (sUAS).

- Work toward the goal of understanding human annoyance that results from the sound of sUAS has fallen into 3 categories:
  - Synthesis (2015):

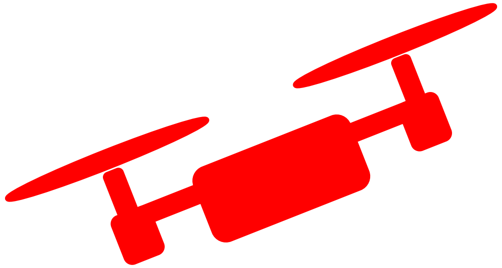
    Generating the capability to produce an auralized sUAS flyover.

  - Simulation (2016):

    Producing vehicle dynamics histories (distance, attitude, etc.) that can be used for auralization.

  - Psychoacoustic Testing (2017):

    Presenting sounds to human subjects in order to get a sense of what the effects these sounds may be on a general population.



Bootsrapped Fits