SAND2024-10087C

Transformational Tools and Technologies (T^3) Project

Perception Testing in Fog for Autonomous Flight

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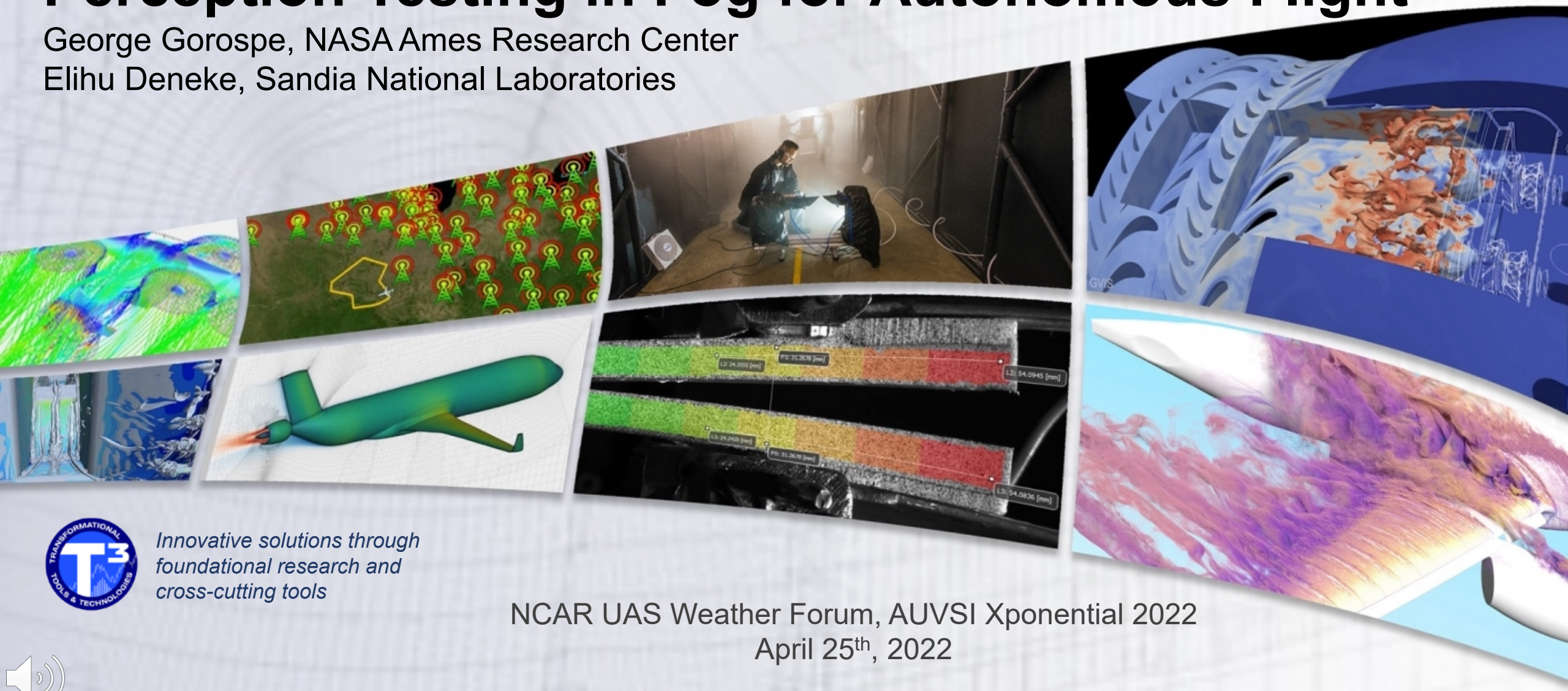
Elihu Deneke, Sandia National Laboratories

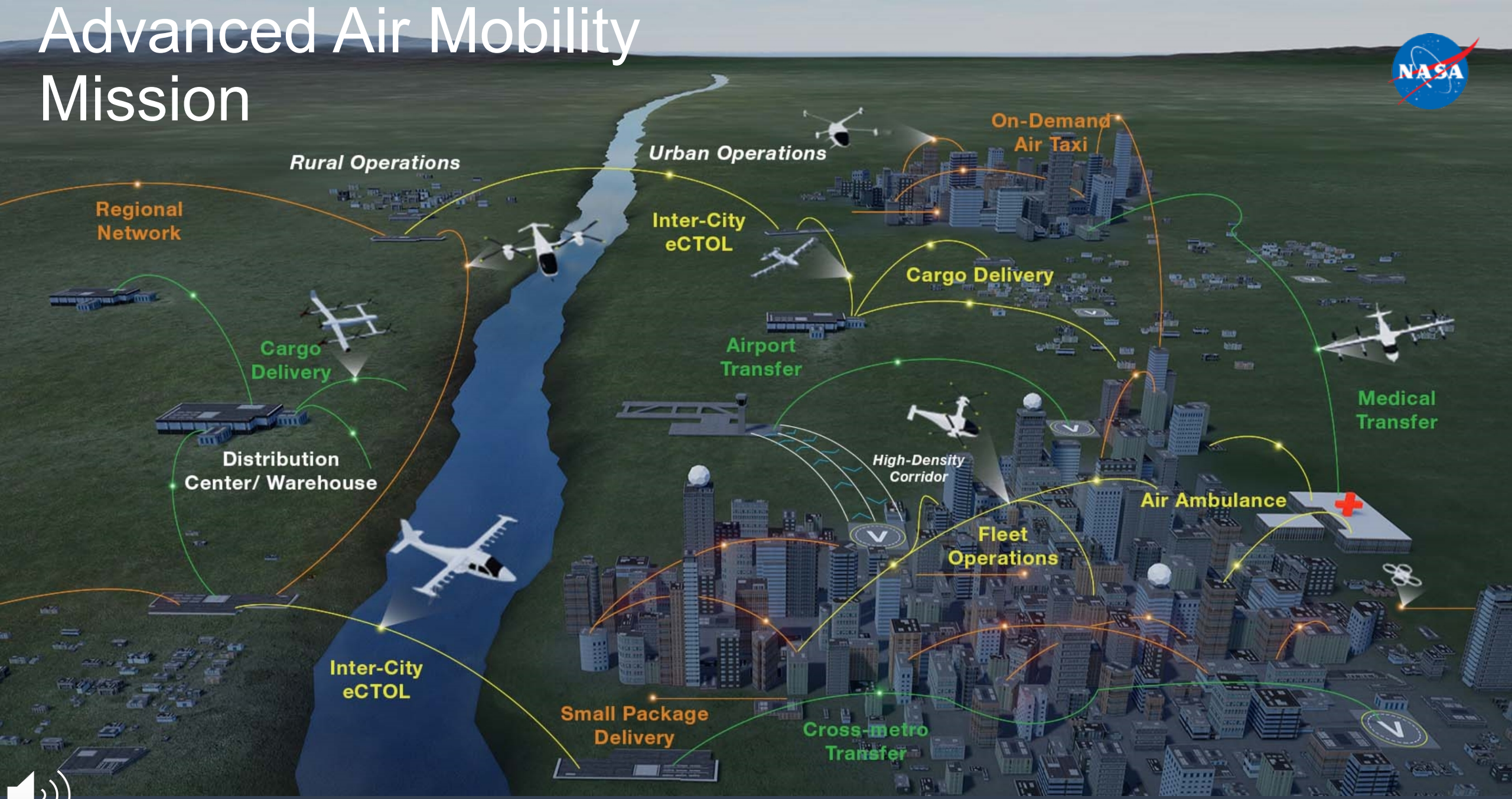


Innovative solutions through foundational research and cross-cutting tools

NCAR UAS Weather Forum, AUVSI Xponential 2022
April 25th, 2022

The Future of Flight: Advanced Air Mobility

Advanced Air Mobility Mission



Safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions

Perception

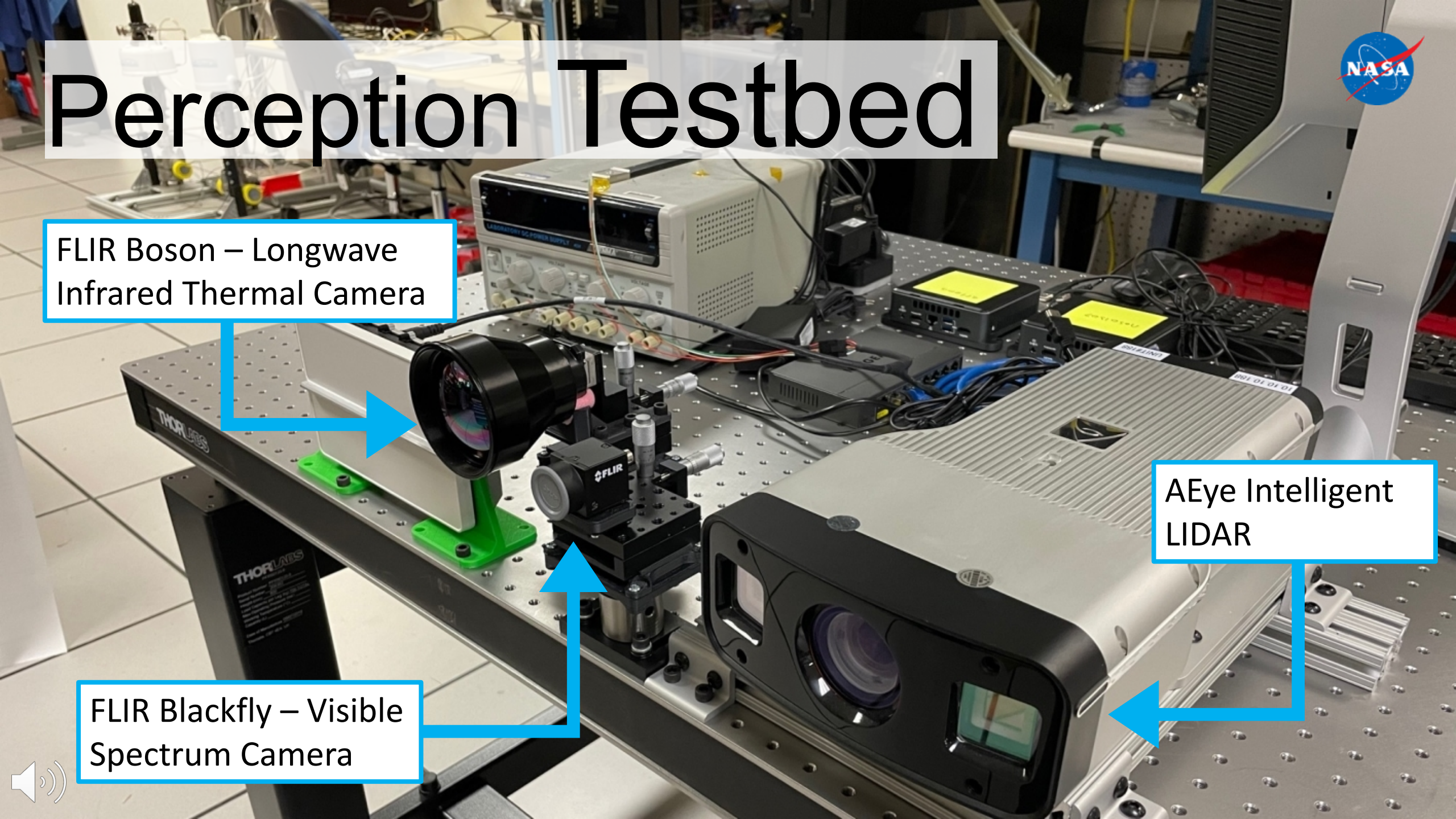
Building an accurate and detailed understanding of the state of the vehicle and its surrounding environment

Obscured By Fog

Aviation accidents in which fog plays a major role, often prove fatal. [flightsafety.org]

Each year, around 440 people are killed due to weather-related aviation accidents including the conditions of low visibilities and ceilings. [weather.gov]

Perception Testbed



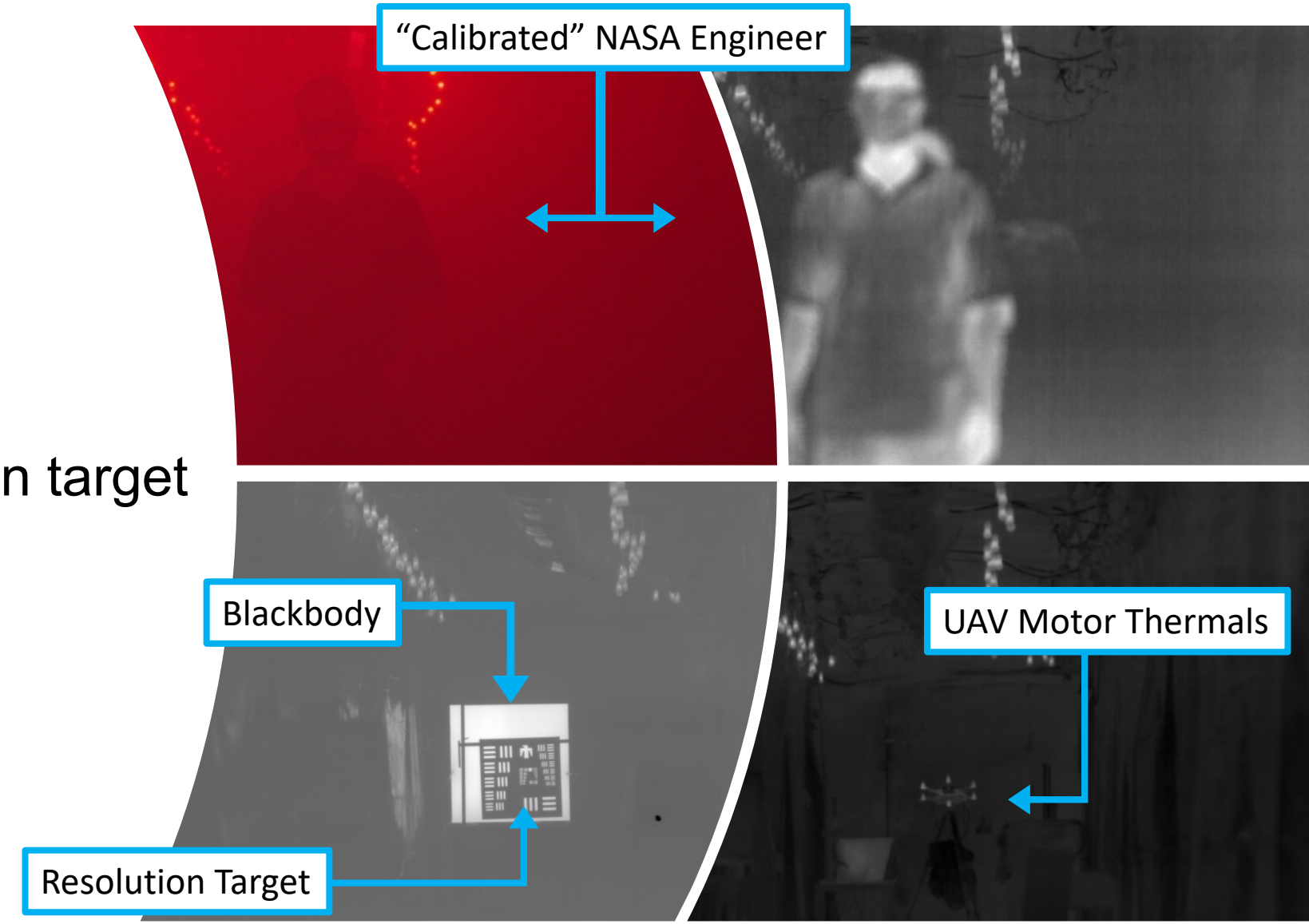
SNL's Fog Chamber

A 180' long, 10' tall, 11' wide controlled-fog environment for sensor testing. Mimics the composition and particle size of costal fog.

Test Variables

Controlled Variables:
- Distance from testbed
- Target temperature
- Chamber lighting
- Targets:
  human, UAV, resolution target

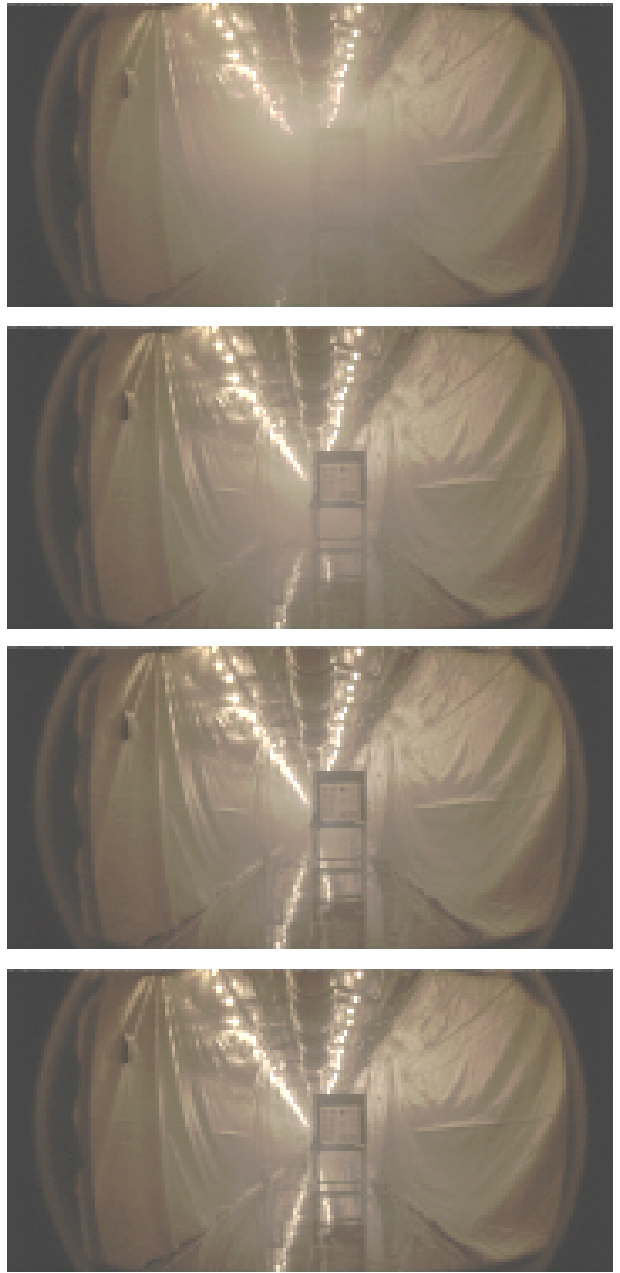
Uncontrolled Variables:
- Air humidity
- Air temperature



Data Elements

Testbed Data (24 total tests)

- Longwave IR images (.tff) files
- Vis, Camera images (.jpg) files
- LIDAR Data:
  - Thumbnail images (180x90 pixels)
  - LIDAR data (.csv) files



Fog Characterization Data

- Fog particle sizing
- Transmissometer Data

Visible Spectrum

1951 USAF Resolution Test Chart	Human in the Fog	UAV on Test Stand (red and green navigation lights)

FLIR Blackfly: Model: BFS-U3-50S5C-C

- 5.0 MP, resolution 2448x2048,
- 35 FPS, Sony IMX264, CMOS Color
- FoV: 32° horizontal, 24° vertical @15mm focal length (60’ Hx44’ V @ 100’)
- Blackfly lens: Fujinon 15mm 50mm 1/3 inch CS mount lens

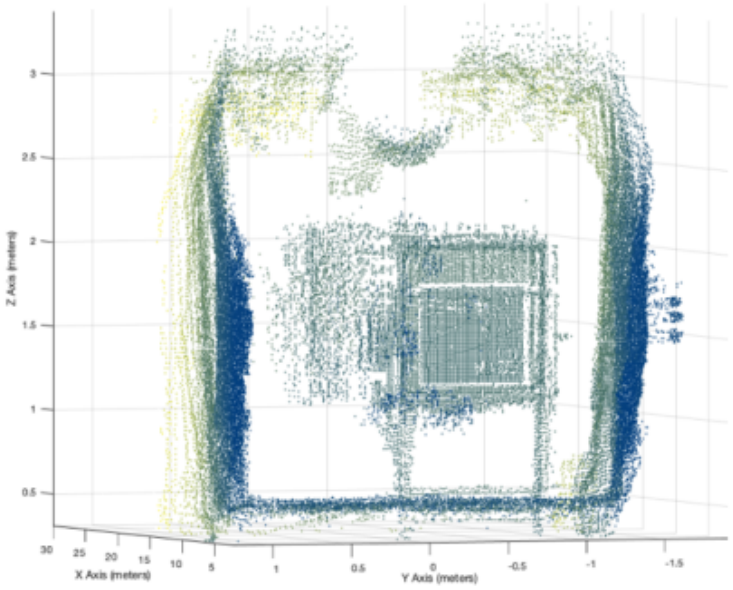
Longwave Infrared

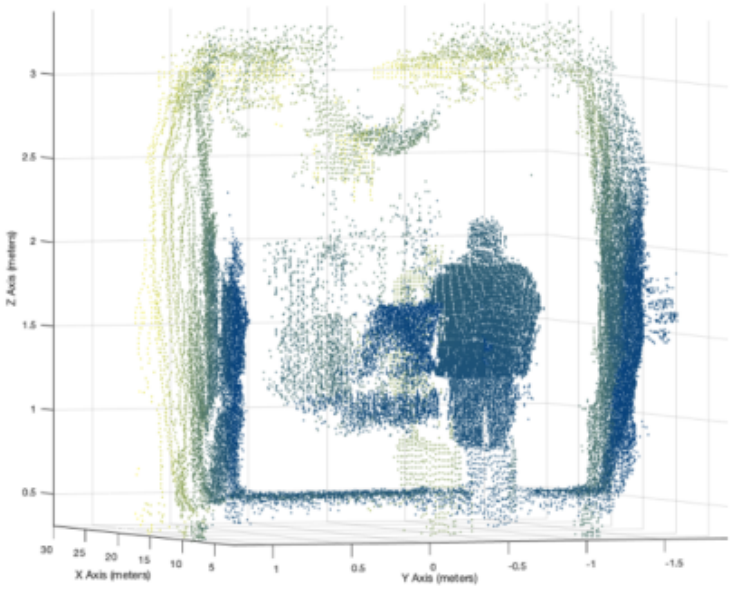
1951 USAF Resolution Test Chart	Human in the Fog	UAV on Test Stand (motors are hot)

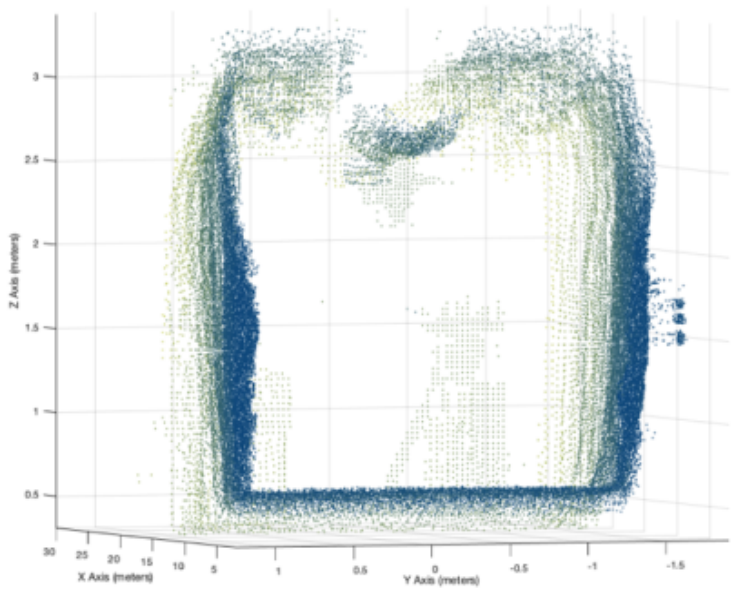
FLIR Boson: Boson 640

- 640x512 pixels,
- Longwave infrared; 8 µm – 14 µm
- 60 Hz baseline FPS
- Scene Temperature Range 140 °C (high gain) to 500 °C (low gain)
- Boson lens: 73 mm lens, 6° FoV

LIDAR







1951 USAF Resolution Test Chart	Human in the Fog	UAV on Test Stand

Aeye LIDAR - 4Sight M

- Field of View: 60° x 30° baseline
- Angular Res.: 0.1° horiz. & vert
- Frame Rate: upto 200hz
- Range: up to 1000 m

Autonomous Systems Perception Testbed Campaign at the Sandia National Laboratories' Fog Chamber: Test Data and Documentation

In 2020 and 2021 a new perception testbed was developed at NASA Ames Research center to collect data from an array of sensing systems representative of those that could be found on a future UAM vehicle. Under the Perception task of the Autonomous Systems project, funded by the Aeronautics Research Mission Directorate (ARMD) through the Transformative Tools and Technologies project, this testbed was both built and deployed for testing in the Fog Chamber located at Sandia National Laboratories in Albuquerque, New Mexico. This site contains an outline of the tests, test data, and associated documentation.

In May of 2021, the perception testbed was deployed to the Fog Chamber at Sandia National Laboratories. The testbed featured a FLIR Blackfly visual spectrum camera, a FLIR Boson longwave infrared camera, and a AEye 4Sight M intelligent LIDAR. Within the chamber various fog species, including coastal fog, may be produced consistently. Over the course of five days, more than 40 experiments, calibration runs, baseline tests, and additional tests were performed in the fog chamber with 3 different targets. A human target, a small (less than 10 kg) unmanned aerial vehicle (UAV), and a USAF 1951 resolution target were used in testing. Controlled test variables include, the ambient lighting in the chamber, target distance from the perception testbed, and target type and temperature of the target.

Testbed Sensor Specifications:

- FILR Blackfly USB Camera: model: BFS-U3-50S5C-C, 5 MP, 35 FPS, SONY IMX264
  - Blackfly Lens: Fujinon 15mm 50mm 1/3 inch CS mount lens
- FILR Boson 640
  - Boson Lens: 72 mm lens with 6 degrees FoV
- AEye 4Sight M LIDAR System

More than 2 terabytes of data was collected during the deployment to the Fog Chamber. This data consists of images from both the visual spectrum camera and the longwave infrared camera, range and intensity da
fog characterization data from the chamber's own sensing systems. To promote consumption of the data by the public, the data and documentation are here arranged by experiment. Three types of test exist, 1) bas
not feature fog, were used to collect a baseline of a new experimental configuration, 2) fog tests - experiments featuring fog and lasting until significant dissipation of the fog, 3) public affairs office tests - tests featuri
document the tests and provide relatable data for consumption by the broader public.

Characterization of the developed fog within the chamber is done with Sandia's instrumentation which measure both fog particle size distribution and meteorological optical range (MOR). A Spraytec instrument from
which uses a laser diffraction as a method for measuring droplet size distribution is used to characterize the fog in real-time. Additionally, a transmissometer consisting of a light emitting diode (LED) and a standard p
distance across the length of the fog chamber is used to calculate the relative MOR measurement for baseline tests with no fog and fog tests. The data from these instruments is collected into sets representing each
(4 days). On a given day, the timestamps of the imagery of LIDAR data may be fit to the timestamps from the environmental data. Environment data for all four days of testing is available in the fog_chamber_enviro

Data Structure:

The experiment data is enclosed in .zip files with the name of the given experiment. Within each zip file there are two folders, "Database" - which holds the images from the visible spectrum camera and longwave in
metadata.csv file with information about collection sequence and file names. The older folder "Lidar" contains both point-cloud .csv files with associated frame number in the file name and image files taken with the L

The following table is a list of the Perception Testbed Fog Chamber Experiments with links to their data and associated documentation.

Fog Test Compiled Documentation featuring experimental setup, experiment sequence and all experiment documents: Sandia_Test_Documentation_v1.pdf, 5 MB

Experiment Table

Experiment Name	Link to Dataset .zip File	Link to Documentation File	Ambient Lighting (on/off)	Target	Target Distance (meters)	Target Temperature (C)	Notes
baseline01	baseline01.zip	baseline01.pdf	On	USAF-1951	6.5 m	37 C	Boson was out of focus.
baseline02	baseline02.zip	baseline02.pdf	On	USAF-1951	6.5 m	37 C	Boson was out of focus.
baseline03	baseline03.zip	baseline03.pdf	Off	USAF-1951	6.5 m	37 C	Boson was out of focus.
baseline04	baseline04.zip	baseline04.pdf	Off	USAF-1951	6.5 m	37 C	Boson was out of focus.
fog00	Not Available	Not Available	On	USAF-1951	6.5 m	37 C	Boson was out of focus.
fog01	fog01.zip	fog01.pdf	On	USAF-1951	6.5 m	37 C	Boson was out of focus.
fog02	fog02.zip	fog02.pdf	Off	USAF-1951	6.5 m	37 C	Boson was out of focus.
fog03	fog03.zip	fog03.pdf	Off	USAF-1951	6.5 m	60 C	Boson was out of focus.
fog04	fog04.zip	fog04.pdf	On	USAF-1951	6.5 m	60 C	Boson was out of focus.
fog05	Not Available	Not Available	On	USAF-1951	41 m	60 C	Boson was out of focus.
fog06	fog06.zip	fog06.pdf	Off	USAF-1951	41 m	60 C	Boson was out of focus. End of testing day 1.
baseline05	Not Available	Not Available	On	USAF-1951	41 m	N/A	Boson was out of focus.
fog07	Not Available	Not Available	On	USAF-1951	41 m	37 C	Lidar data only.
fog08	fog08.zip	fog08.pdf	On	USAF-1951	41 m	37 C	Boson was out of focus.
fog09	fog09.zip	fog09.pdf	Off	USAF-1951	41 m	37 C	Boson was out of focus.
fog10	fog10.zip	fog10.pdf	On	USAF-1951	17.6 m	37 C	Boson was out of focus.
fog11	fog11.zip	fog11.pdf	Off	USAF-1951	17.6 m	37 C	Boson was out of focus.

Perception Testing at the Sandia National Laboratories' Fog Chamber: Data Publication and Data Documentation

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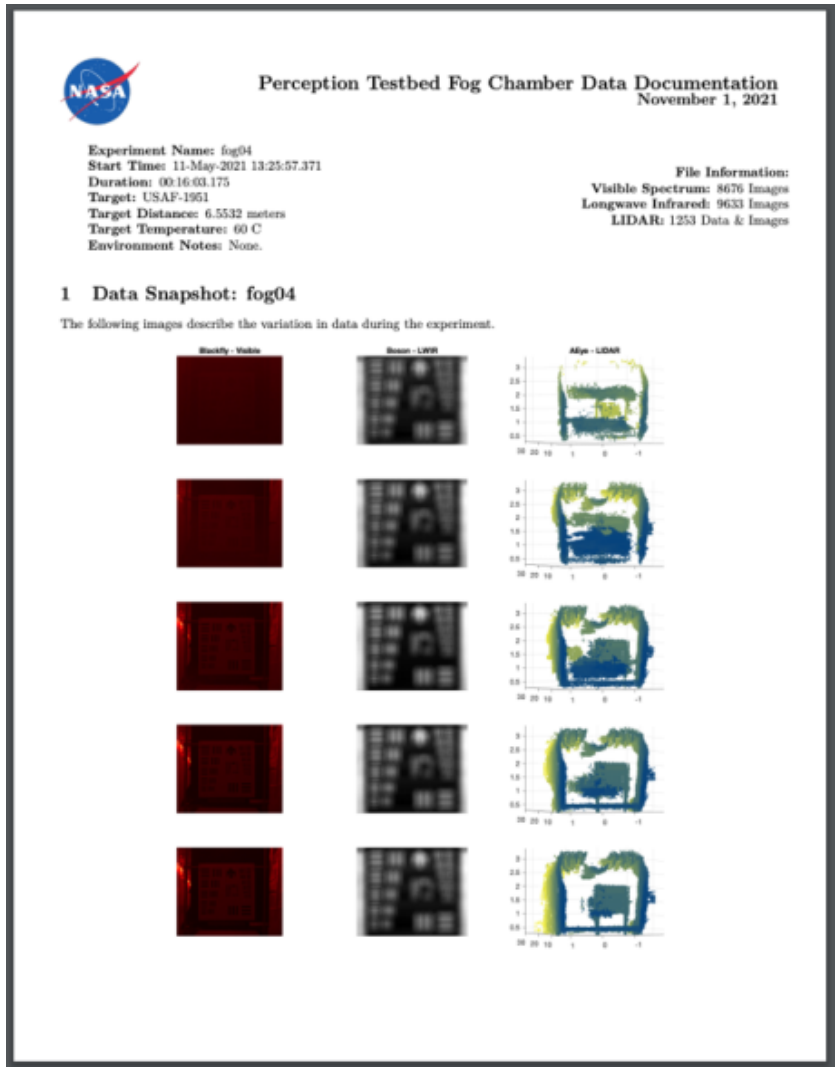
[2]NASA Langley Research Center, Hampton, Virginia, USA
[3]KBR LLC, NASA Ames Research Center, Moffett Field, California, USA

Website w/ Data & Documentation:
https://workshops.larc.nasa.gov/RAM_Fog_Test/

Documentation

Exp_Name	Description	Lights	Target	Distance (m)	Target Temp
cal01	Calibration for BlackFly	T	USAF-1951	N/A	37 C
cal02	Calibration for Lidar	T	USAF-1951	N/A	37 C
baseline01	Full sensor suite	T	USAF-1951	6.5532	37 C
baseline02	Full sensor suite	T	USAF-1951	6.5532	37 C
baseline03	Full sensor suite	F	USAF-1951	6.5532	37 C
baseline04	Full sensor suite	F	USAF-1951	6.5532	37 C
fog00	Preview - Full sensor suite	T	USAF-1951	6.5532	37 C
fog01	Full sensor suite	T	USAF-1951	6.5532	37 C
fog02	Full sensor suite	F	USAF-1951	6.5532	37 C
fog03	Full sensor suite	F	USAF-1951	6.5532	60 C
fog04	Full sensor suite	T	USAF-1951	6.5532	60 C
cal03	Calibration (FOV adjustment)	T	USAF-1951	41.148	60 C
fog05	Preview - Full sensor suite	T	USAF-1951	41.148	60 C
fog06	Full sensor suite	F	USAF-1951	41.148	60 C
End of Testing Day 1, Tuesday May 11th, 2021					
baseline05	Full sensor suite	T	USAF-1951	41.148	N/A
fog07	LIDAR Only	T	USAF-1951	41.148	37 C
fog08	Full sensor suite	T	USAF-1951	41.148	37 C
fog09	Full sensor suite	F	USAF-1951	41.148	37 C
cal04	Full sensor suite	T	USAF-1951	17.6276	N/A
fog10	Full sensor suite	T	USAF-1951	17.6276	37 C
fog11	Full sensor suite	F	USAF-1951	17.6276	37 C
fog12	Full sensor suite	T	USAF-1951	17.6276	60 C
fog13	No LIDAR Data	T	USAF-1951	17.6276	60 C
fog14	Blackbody temp. is likely 60 C.	T	USAF-1951	17.6276	N/A
pao01	One human in chamber	T	Human	N/A	N/A
Configuration Change: Boson camera focus set to infinity					
fog15	Full sensor suite	T	USAF-1951	45.6692	37 C
End of Testing Day 2, Wednesday May 12th, 2021					
baseline07	Full sensor suite	T	USAF-1951	45.6692	20 C
baseline08	Full sensor suite	T	USAF-1951	45.6692	60 C
fog16	Full sensor suite	T	USAF-1951	45.6692	60 C
Configuration Change: Switch to UAV target on a tripod w/ motors running					
baseline09	UAV Target	T	UAV-Oncoming	18.2372	N/A
fog17	UAV Target	T	UAV-Oncoming	18.2372	N/A
pao02	Target	T	USAF-1951	N/A	N/A
fog18	UAV Target	F	UAV-Oncoming	18.2372	N/A
End of Testing Day 3, Thursday May 13th, 2021					
baseline10	Cancel test, problem w/ motors	T	UAV-Oncoming	45.6692	N/A
fog19	UAV Target	T	UAV-Oncoming	45.6692	N/A
fog20	UAV Target	F	UAV-Oncoming	45.6692	N/A
baseline11	UAV Target	T	UAV-Oncoming	45.6692	N/A
baseline12	UAV Target	F	UAV-Oncoming	45.6692	N/A
baseline13	UAV Target	T	UAV-Hover	45.6692	N/A

Experiment Matrix



Perception Testbed Fog Chamber Data Documentation
November 1, 2021

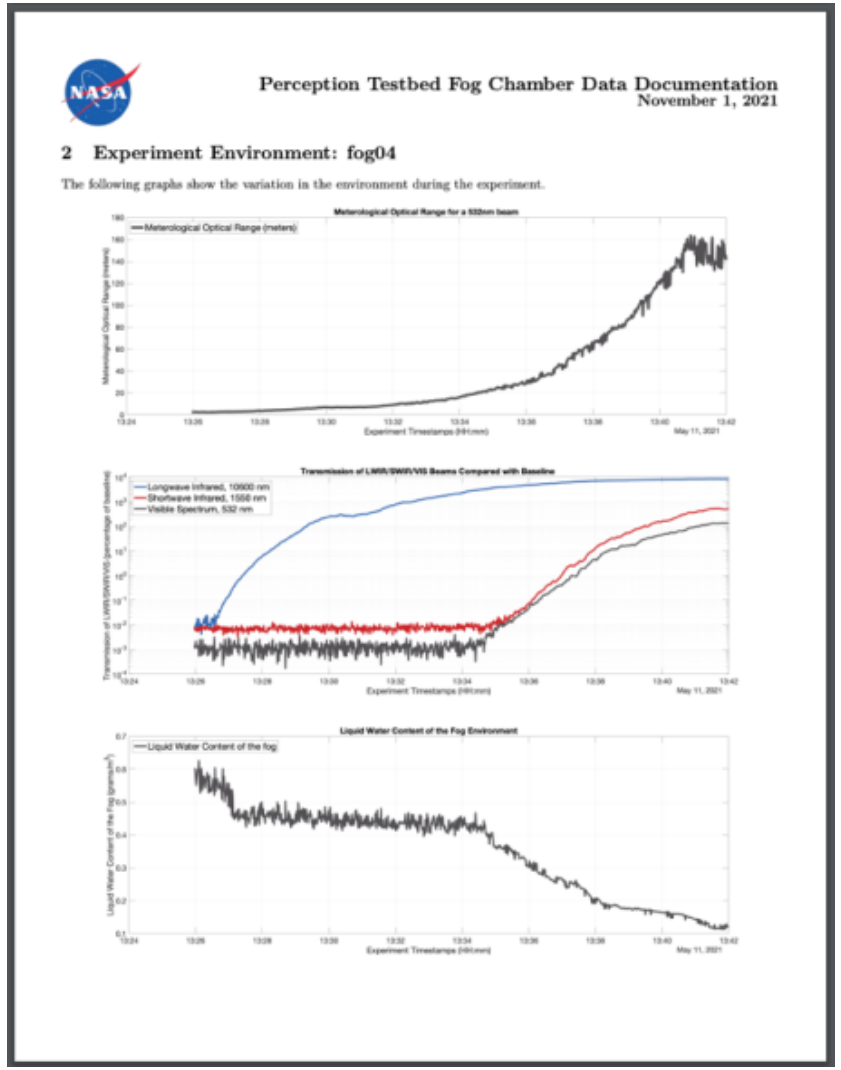
Experiment Name: fog04
Start Time: 11-May-2021 13:25:57.371
Duration: 00:16:03.175
Target: USAF-1951
Target Distance: 6.5532 meters
Target Temperature: 60 C
Environment Notes: None.

File Information:
Visible Spectrum: 8676 Images
Longwave Infrared: 9633 Images
LIDAR: 1253 Data & Images

1 Data Snapshot: fog04

The following images describe the variation in data during the experiment.

Data Snapshot: Visible Spectrum, Longwave Infrared, LIDAR



Perception Testbed Fog Chamber Data Documentation
November 1, 2021

2 Experiment Environment: fog04

The following graphs show the variation in the environment during the experiment.

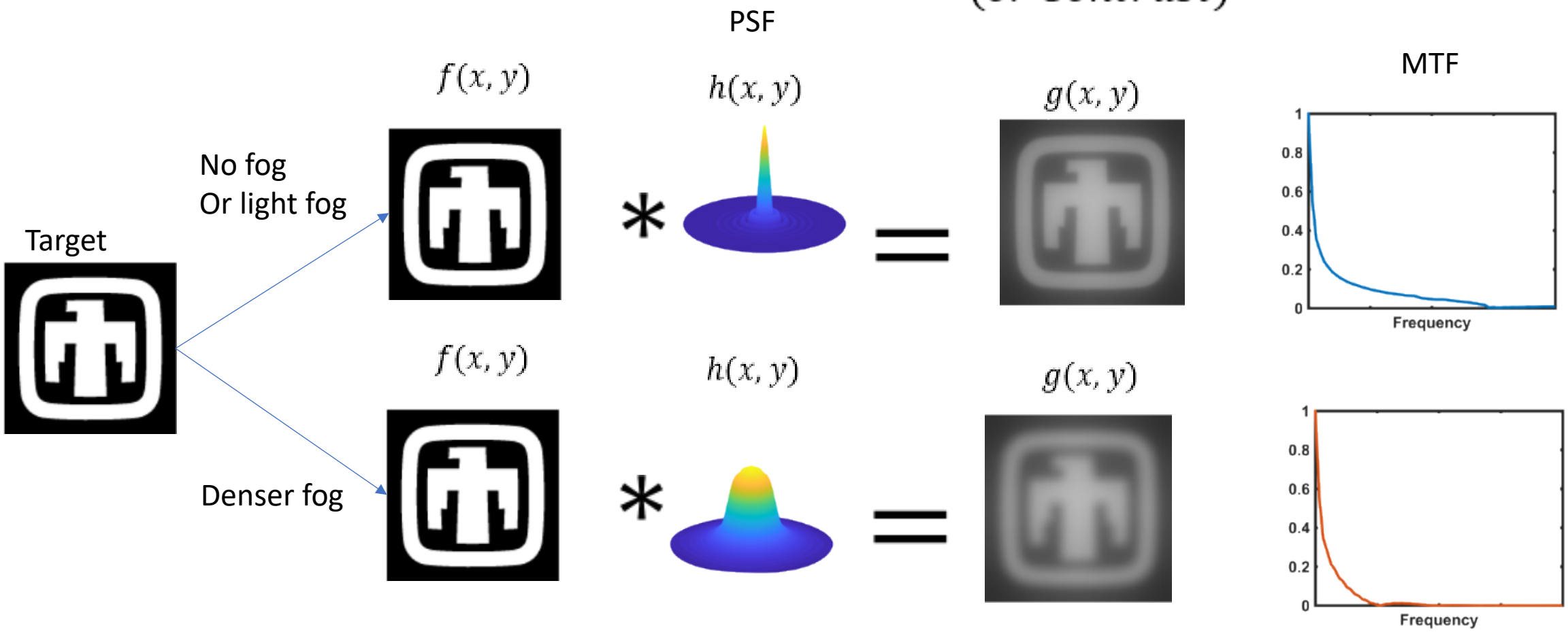
Environment: Meteorological Optical Range, Transmissometer Values at three frequencies, Liquid Water Content of fog.

Spatial Resolution in Fog

$$MTF = \frac{Actual\ Modulation}{Ideal\ Modulation}$$

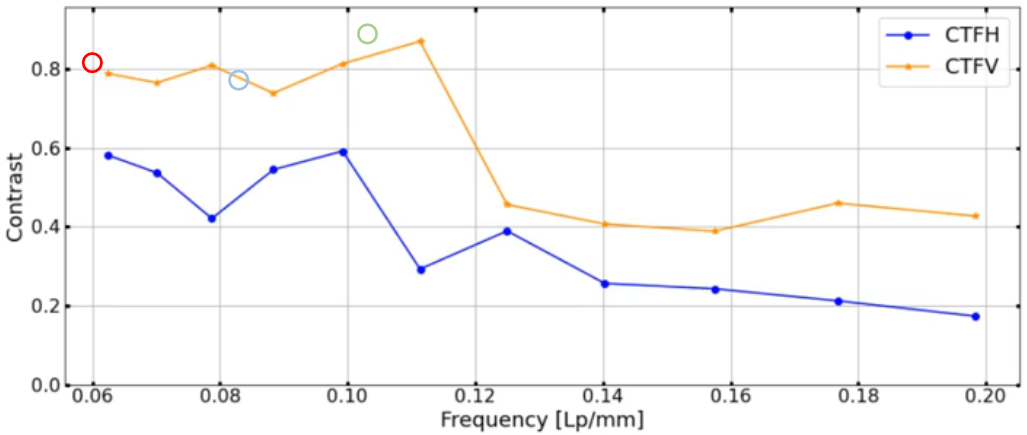
- Modulation Transfer Function (MTF)
- Point Spread Function (PSF)

$$Modulation\ (or\ Contrast) = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$



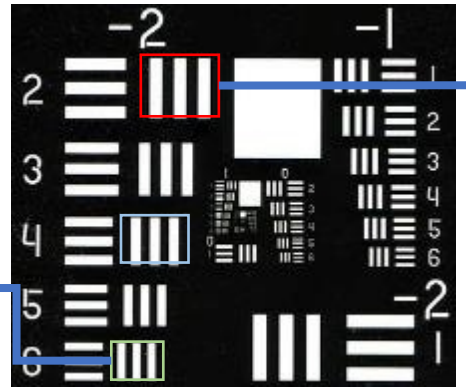
Spatial Resolution Metrics

1. Contrast Transfer Function (CTF)
2. Area Under the Curve (AUC)



CTFH - Horizontal bar set
CTFV – Vertical bar sets

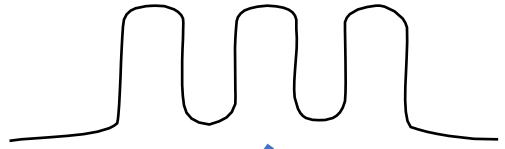
US Air Force 1951 tri-bar target



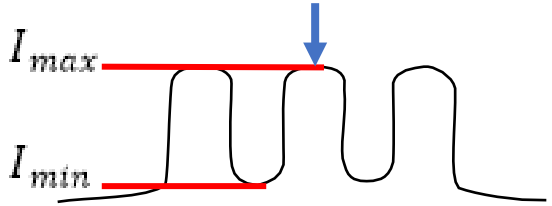
Repeat for each bar set

Select Bars

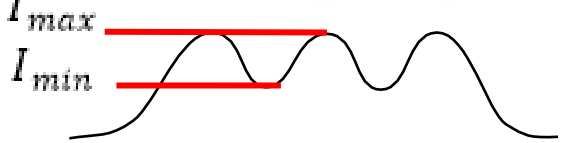
Average to get line profile



Get min and max to calculate contrast



$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

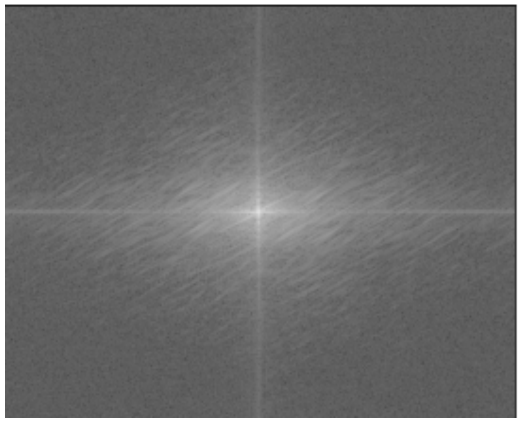


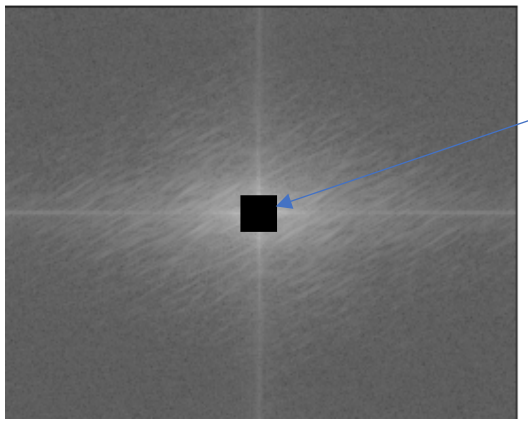
Defined: Spatial Resolution Metrics

1. *Contrast Transfer Function*
   - $CTF = C[f]$
2. Area Under The Curve
   - $AUC = \int C(f)\, df$

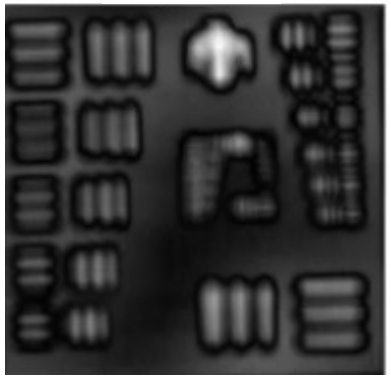
High Pass Filtering

$FT\left(f(x, y)\right)$





$IFT\left(G(u, v)\right)$



Removed ~2.6% of low frequency info

- Removing Low Frequency Information
- Sharpening the Image

Bilateral Filtering

[1]

- Edge Preserving non-linear filtering technique

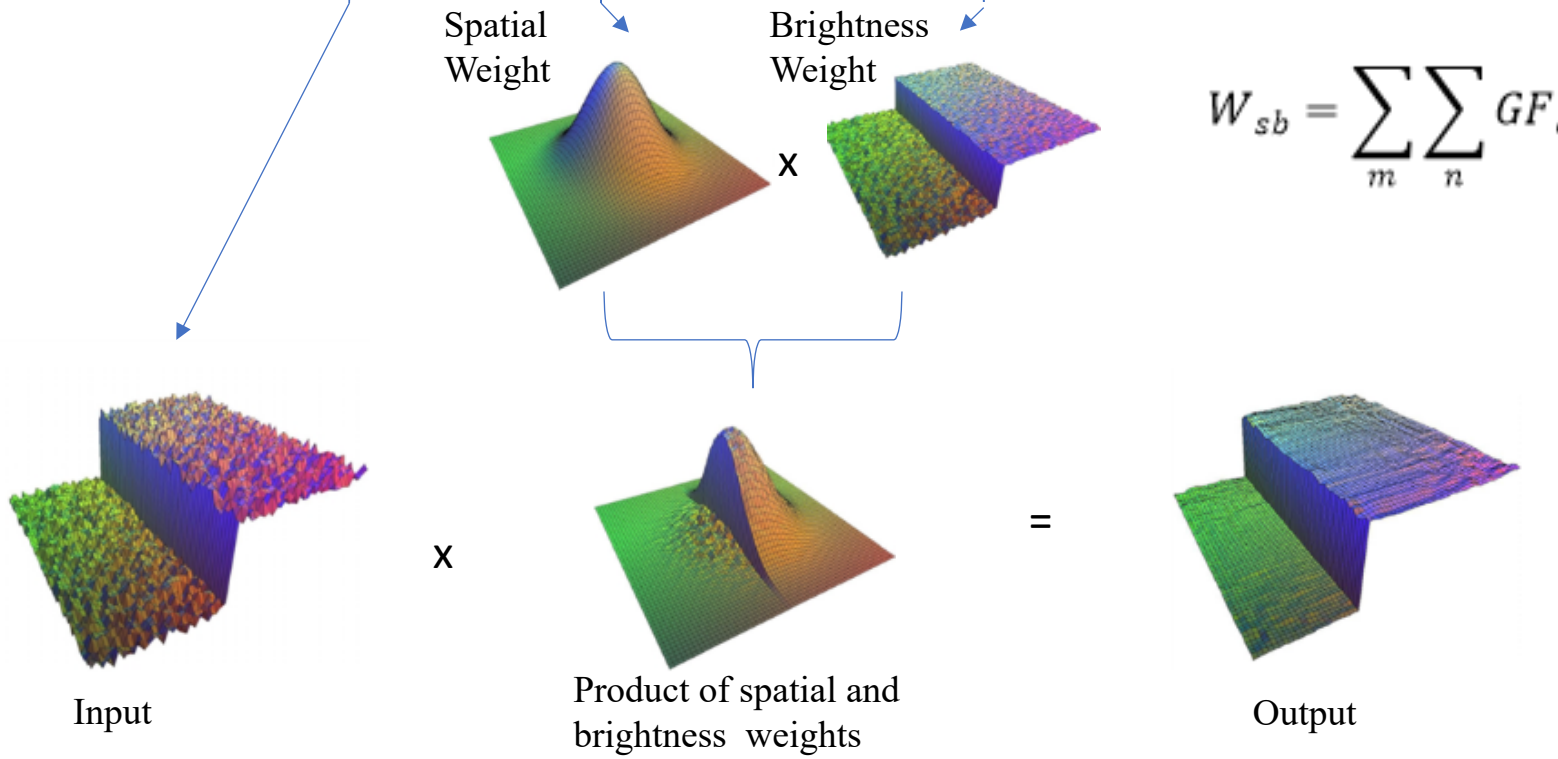
$$g[i,j] = \frac{1}{W_{sb}} \sum_m \sum_n f[m,n] GF_{\sigma_s}[i-m, j-n] GF_{\sigma_b}\left(f[m,n] - f[i,j]\right)$$

Where,

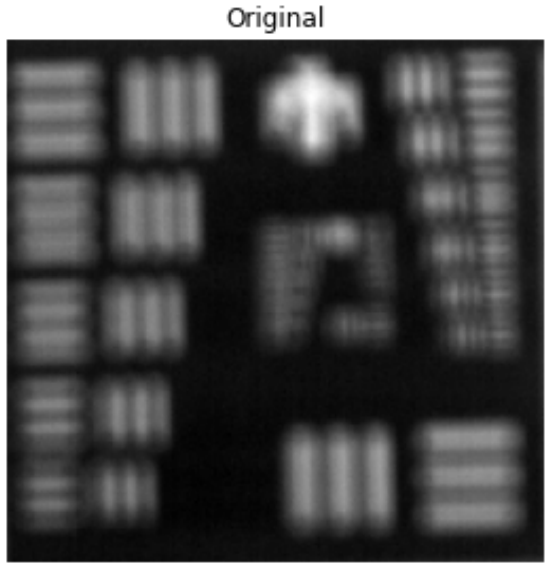
$$GF_{\sigma_s}[m,n] = \frac{1}{2\pi\sigma_s^2} e^{-\frac{\left(m^2+n^2\right)}{2\sigma_s^2}}$$

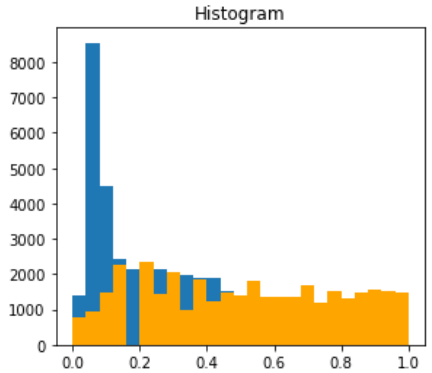
$$GF_{\sigma_b}(\Delta I) = \frac{1}{2\pi\sigma_b^2} e^{-\frac{\left(\Delta I^2\right)}{2\sigma_b^2}}$$

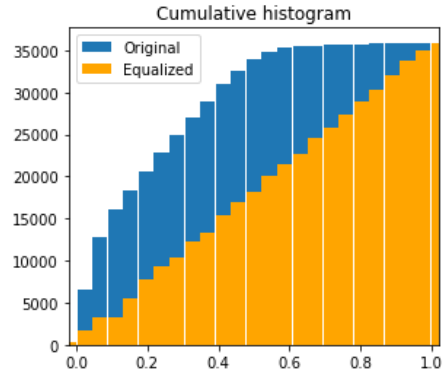
$$W_{sb} = \sum_m \sum_n GF_{\sigma_s}[i-m, j-n]\, GF_{\sigma_b}\left(f[m,n] - f[i,j]\right)$$

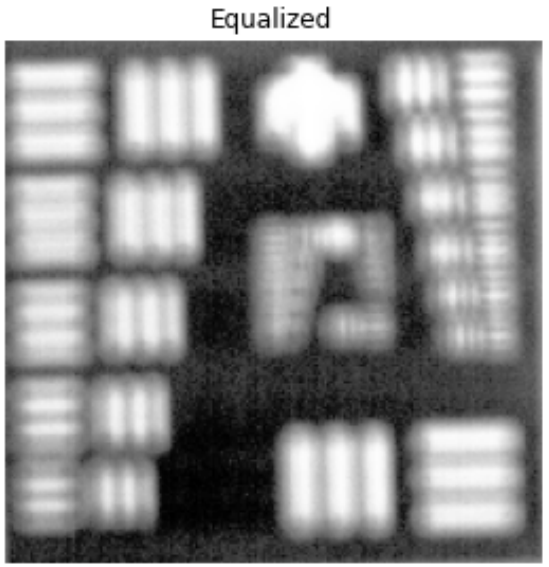


Contrast Enhancing

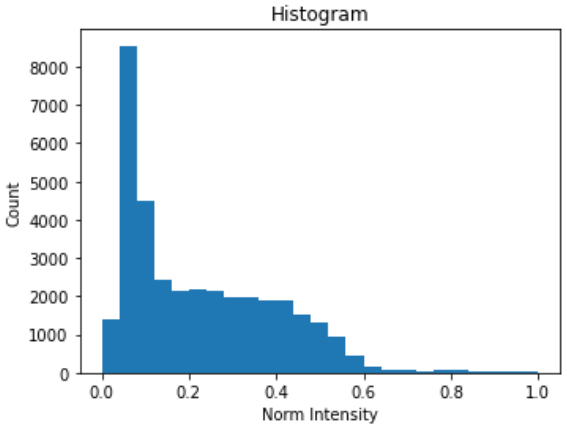


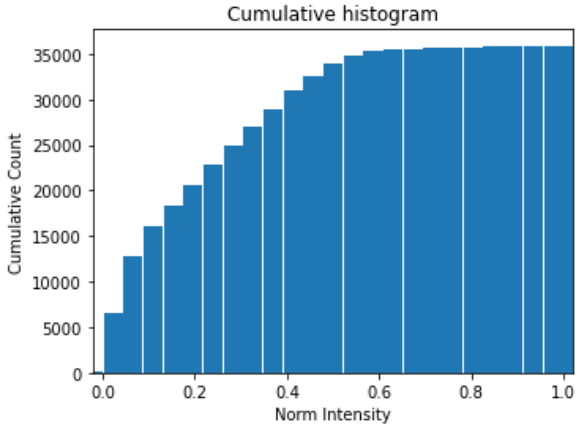


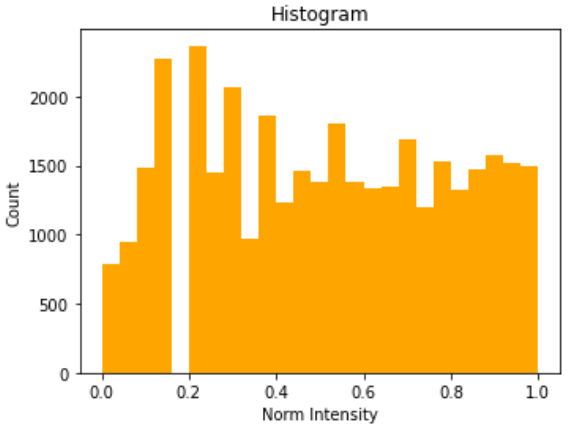


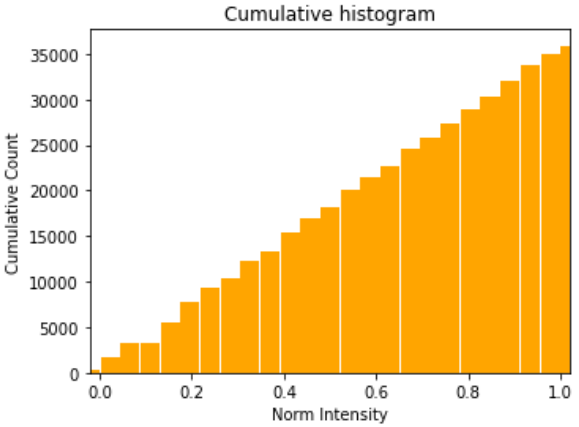


Histogram Equalization







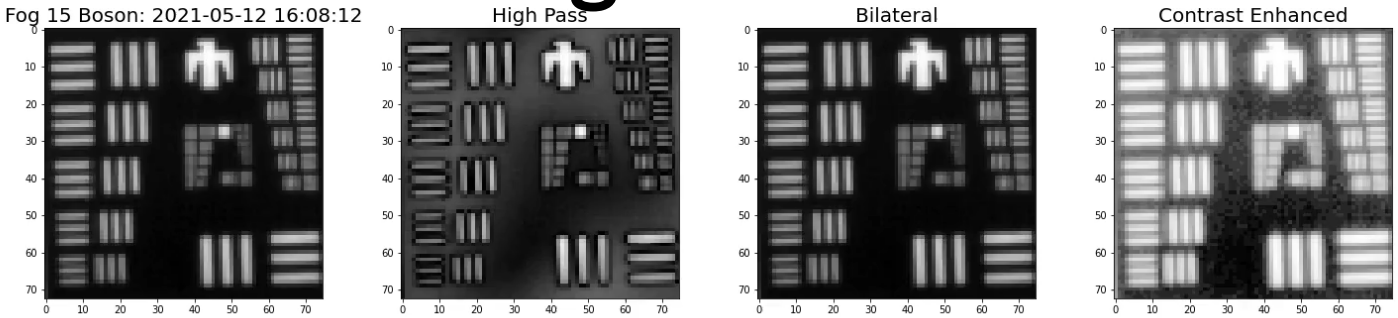


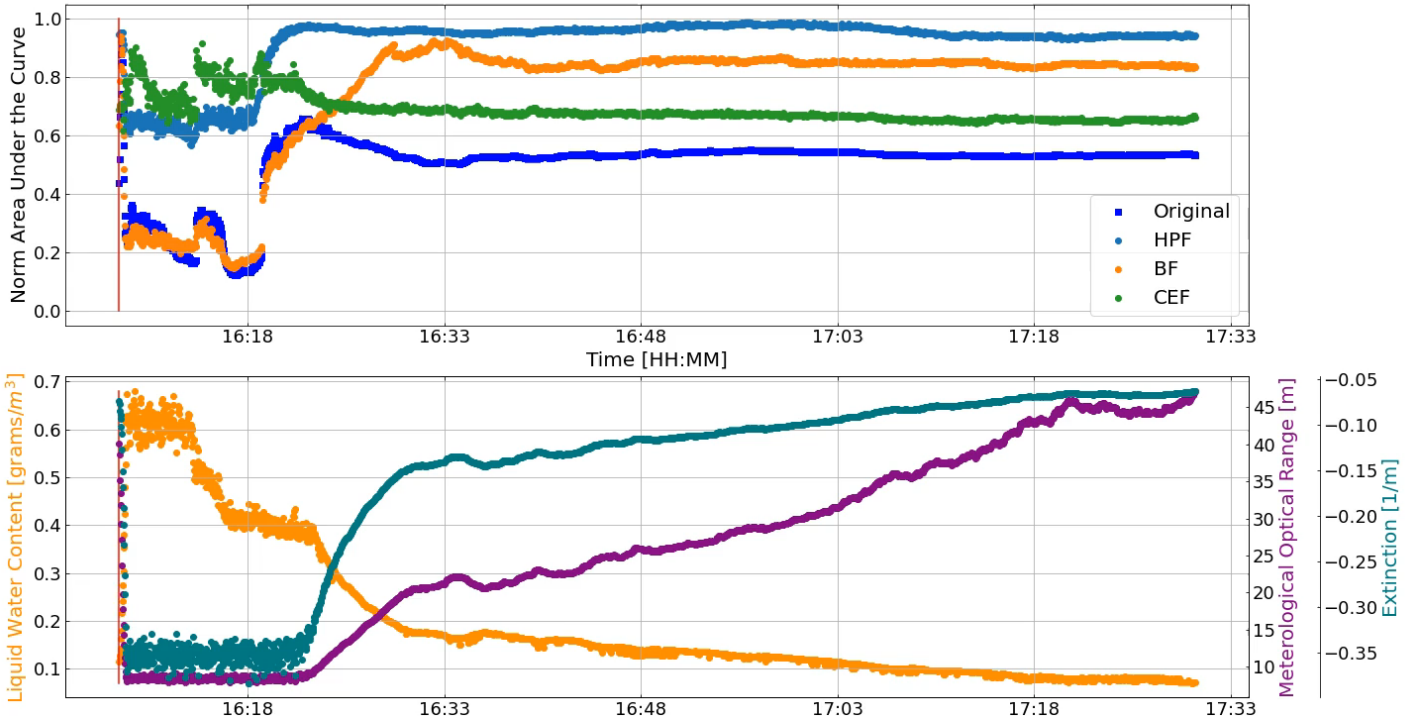
Spatial Resolution of Filtered Images

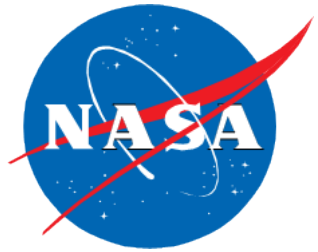
$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$AUC = \int C(f)\, df$$

$$Norm(AUC) = \frac{AUC}{\max(AUC)}$$







Website w/ Data & Documentation:
https://workshops.larc.nasa.gov/RAM_Fog_Test/