



Identification of Acoustic Sources on Antares Launch Pad Using A Microphone Phased Array

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Motivation

- Rocket launches produce severe vibro-acoustics environment
 - Every part of the launch vehicle is affected
 - Sets the acoustic level on Payload/crew vehicle
 - Every part of the pad and ground operations are affected
 - 130dB to 170dB range
 - dominated by low frequencies 10Hz-200Hz
- Even a single dB reduction can lead to savings of millions of \$\$
- Optimization of the sound suppression system is an art
- Single microphones used for scaled model tests and flight verification does NOT show the source of noise
- Microphone Phased Array CAN identify Noise sources
 - Determines evolution of sources through various phases of launch
 - Complements single microphone measurement
 - Complements available tools and analysis to deal with launch acoustics

Space Launch System





Ultimate goal:

Mount a microphone phased array (MPA) on Lightning Tower 2, and to collect acoustic data and camera images during Artemis II launch.

- Identify noise sources and plume impingement zones on pad 39B.
- Validate the source, and location of the acoustic energy responsible for pad damage seen during Artemis launch
- Determine locations on the pad, and time intervals that may require further investigation.
- Determine the effectiveness of the Ignition Sound Suppression system. Identify changes to benefit future launches.

Present goal:

Verification and validation of a newly built Microphone Phased Array (MPA) for the harsh environment of Rocket launch

- Developed by Ames Research Center (ARC), utilizes 70 rugged, high-temp dynamic pressure sensors; IR and visible band cameras
- Determine survivability of the array and the electronics in a launch environment and prolonged exposure to outdoor elements
- Determine quality of sound maps, particularly at the low frequency end
 - Data segmented in small time bins to determine variation of sound sources
- Compare results with a 2013 application when a prototype of the current MPA was used



Microphone Phased Array

Math model/software

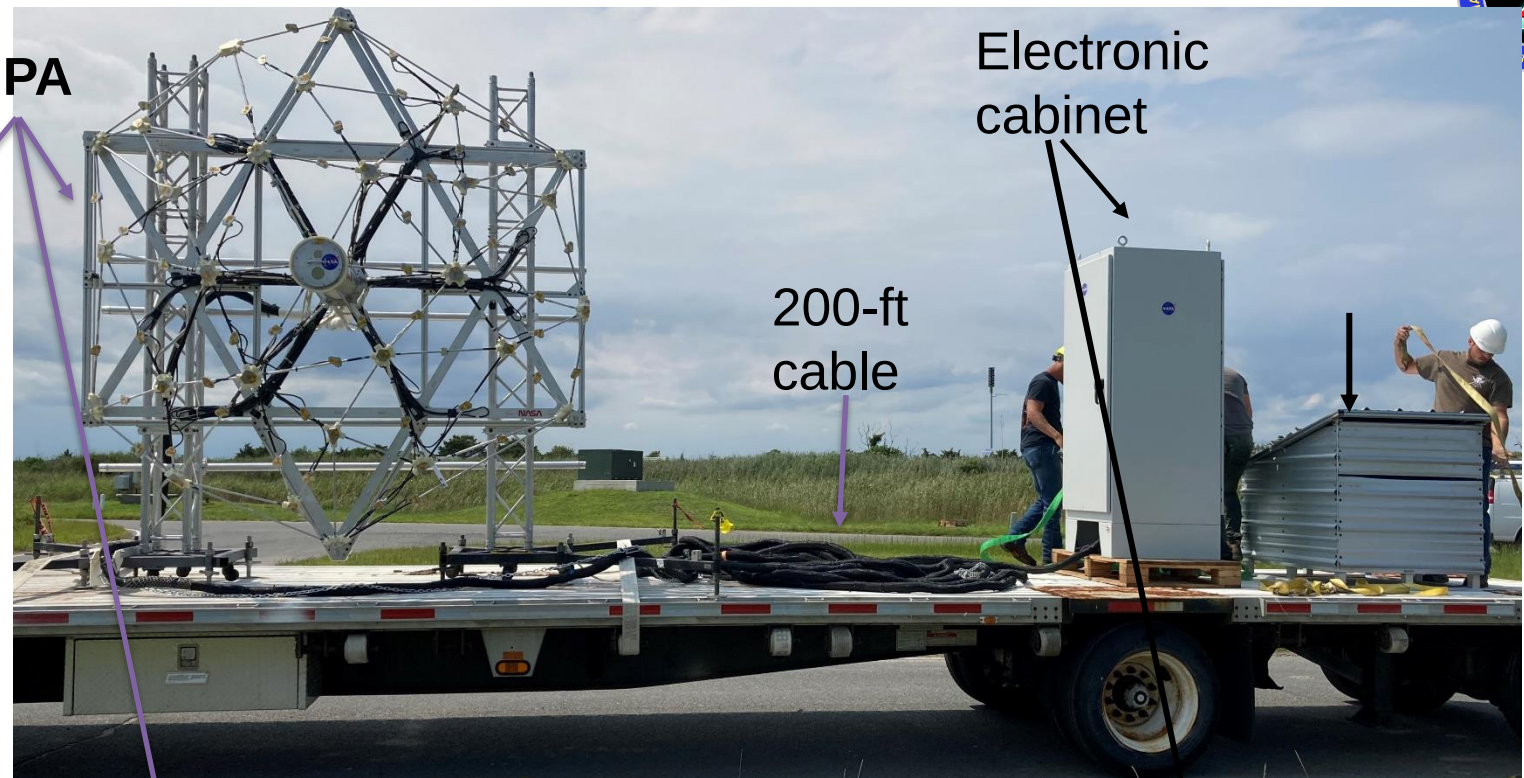
- A veritable field of mathematicians
- Commercial interest led to significant advancements
 - Many advanced models
- **How low a frequency can we go to create useful sound maps?**
 - **In 2013 application we created sound maps at 2 kHz**

Hardware, logistics, safety

- KSC specification of environment
 - 152.6 dB acoustics + 45 mph wind/blast
 - Most extreme of all past uses of MPA
- Continuous improvements from three phases of test
- How to lift, transport, operate at a remote center, safety permits, disassemble



MPA



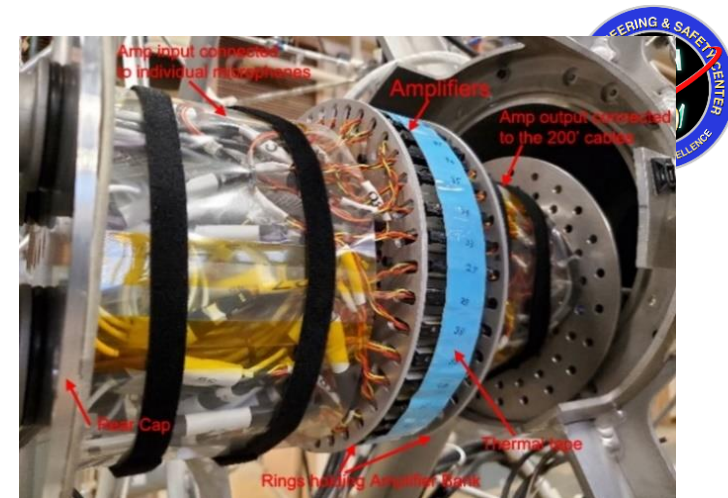


Sensors on the phased array:

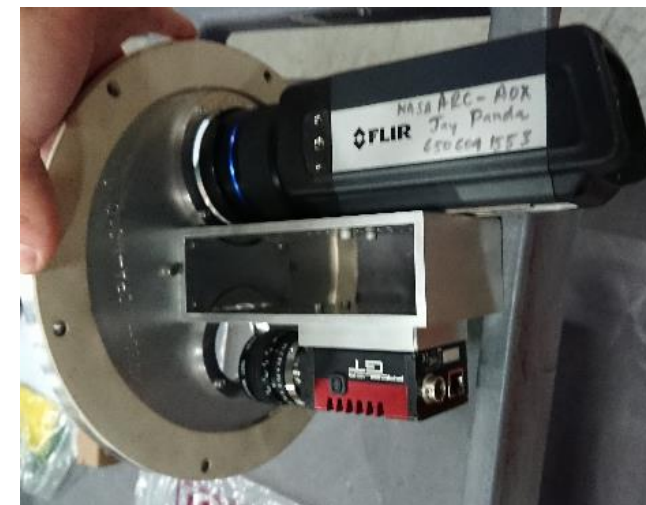
- 70 piezo-resistive (Kulite) microphones and amplifiers
- One visible band video camera
- One long infrared (IR) video camera
- One two-axis accelerometer
- Two resistance temperature detectors (RTDs) (monitor the temperature of amplifier bank and cabinet)

Other:

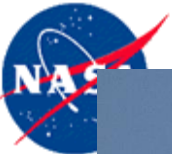
- Primary and backup data systems (80 channels)
- Cooling systems:
 - Dedicated compressor and chiller for the amplifier
 - Air conditioning unit for the cabinet



Bank of amplifiers

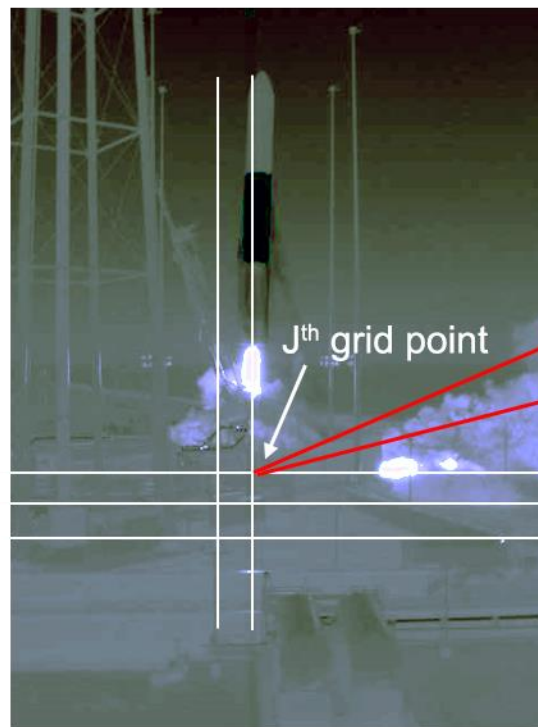
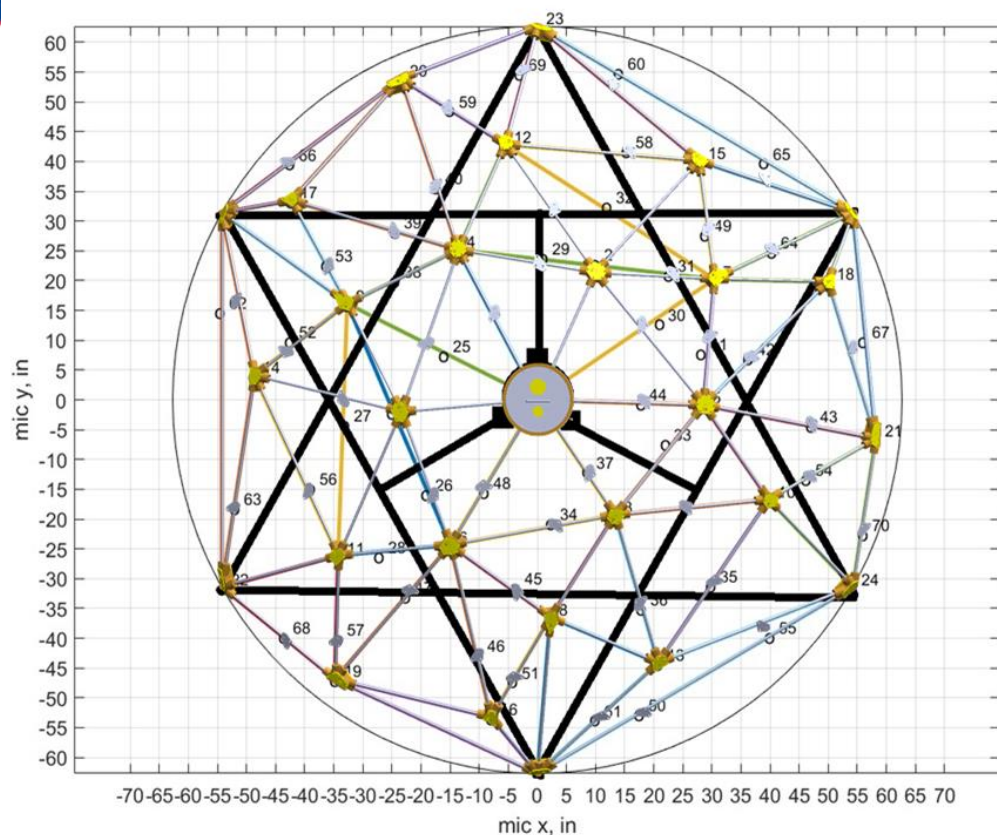


IR and visible cameras

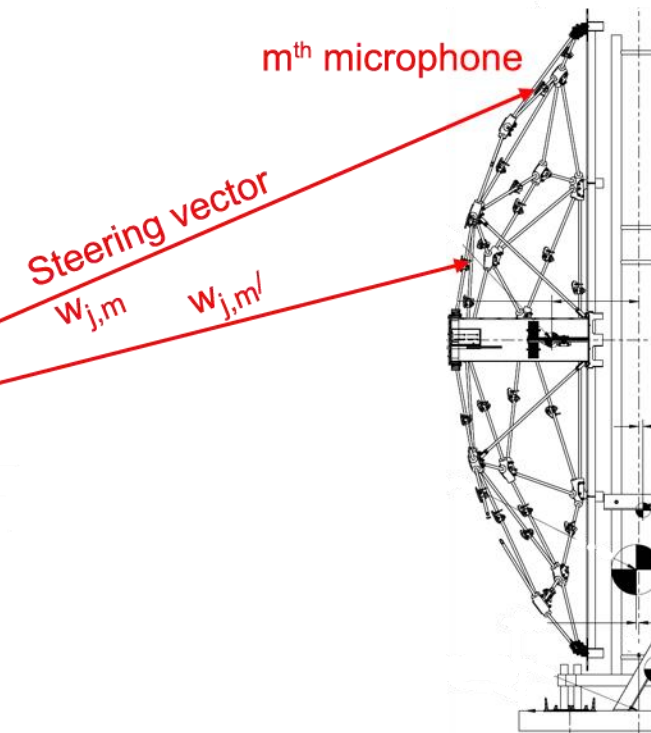


- The array was raised atop a 50-ft tall scaffold structure
 - Cable bundle routed by the side of the scaffold
 - Electronic cabinet placed at the base and supplied with air, AC power and Ethernet connection
- 423ft from the base of the vehicle (comparable to the distance in Artemis-II use)

Mathematical Models of Beamforming



Interrogation grid on photograph of region of interest



- All information is present in the cross-spectra between every pair of microphones: $G_{mm'} = \langle p_m^* p_{m'} \rangle$
- Interrogation grid points were generated on photos of the launch pad.



Math Models of Beamforming



➤ Functional-Orthogonal

- Eigenvalue decomposition of cross-spectra:

$$\mathbf{G} = \mathbf{U}\mathbf{\Sigma}\mathbf{U}^* \quad \mathbf{\Sigma}: \text{diagonal matrix of eigenvalues, } \mathbf{U}: \text{eigenvectors}$$

- removal of weaker eigenvalues

$$\sigma_m < \frac{\sigma_{max}}{40} \rightarrow 0$$

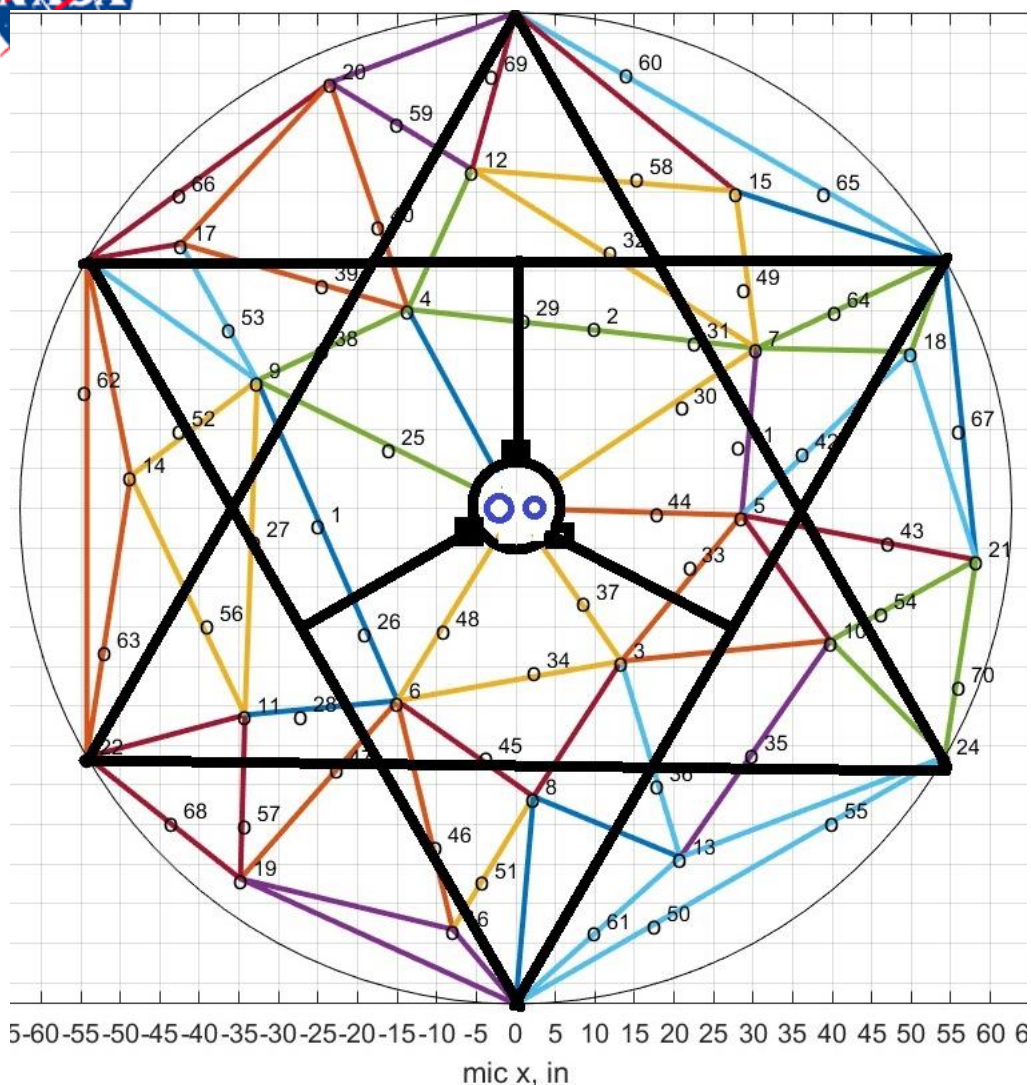
- *Functional beamform:*

$$b_{jj}(f) = \left[\mathbf{w}_{j,m}^* (\mathbf{G})^{\frac{1}{v}} \mathbf{w}_{j,m'} \right]^v \quad v: \text{functional exponent}$$

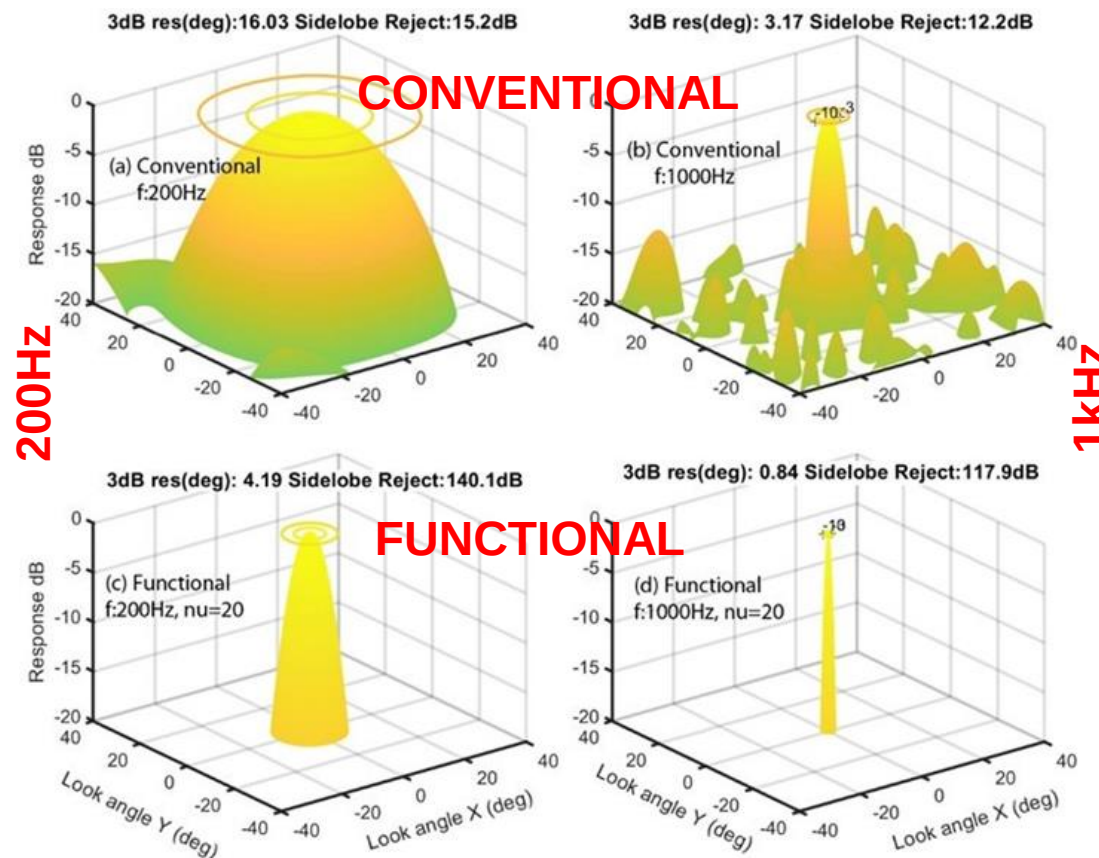
- Theoretically, resolution of noise maps can be improved by factors of 2 to 10 using different exponent v
- **What is the actual possible?**
- $20 \leq v \leq 100$ used for the present work

- Other methods attempted: spectral element method (SEM) to deconvolve point-spread function – Not used (unphysically point representation of sources)

Software and Math models of Beamforming



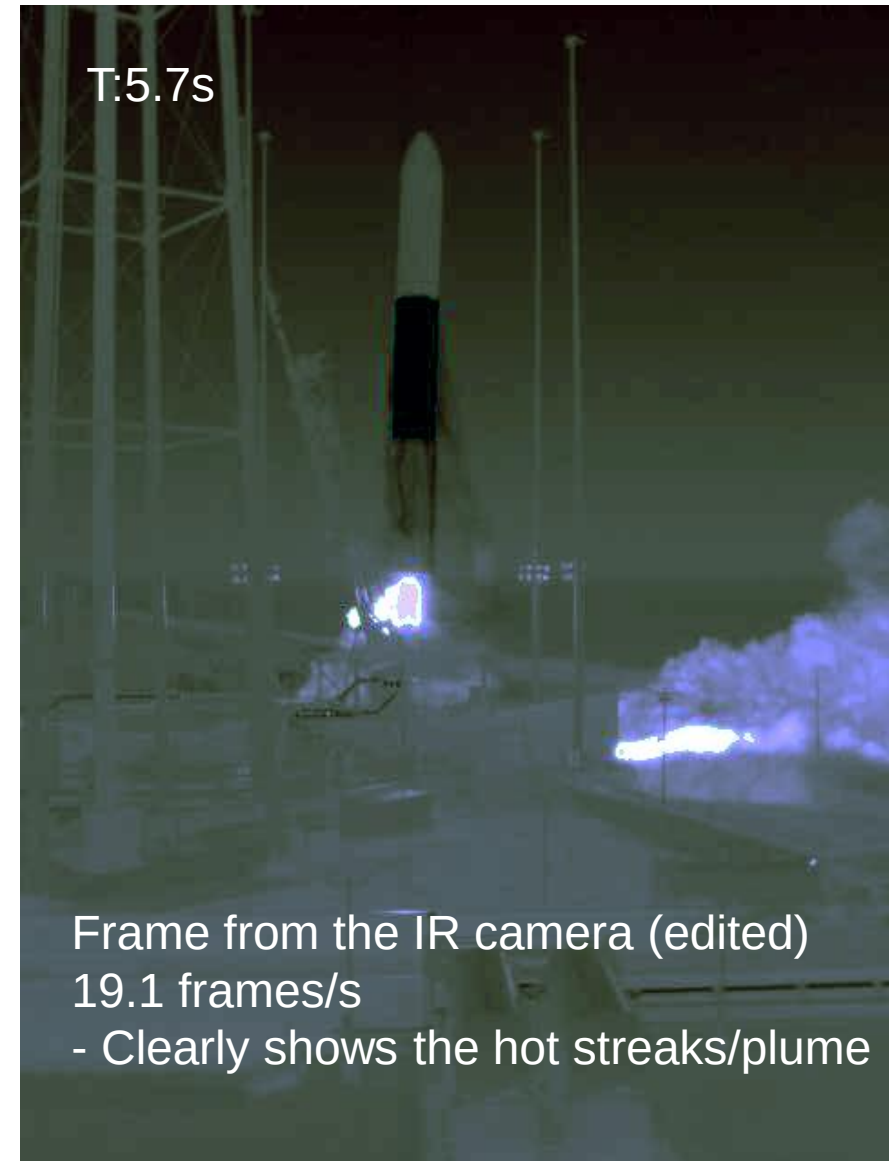
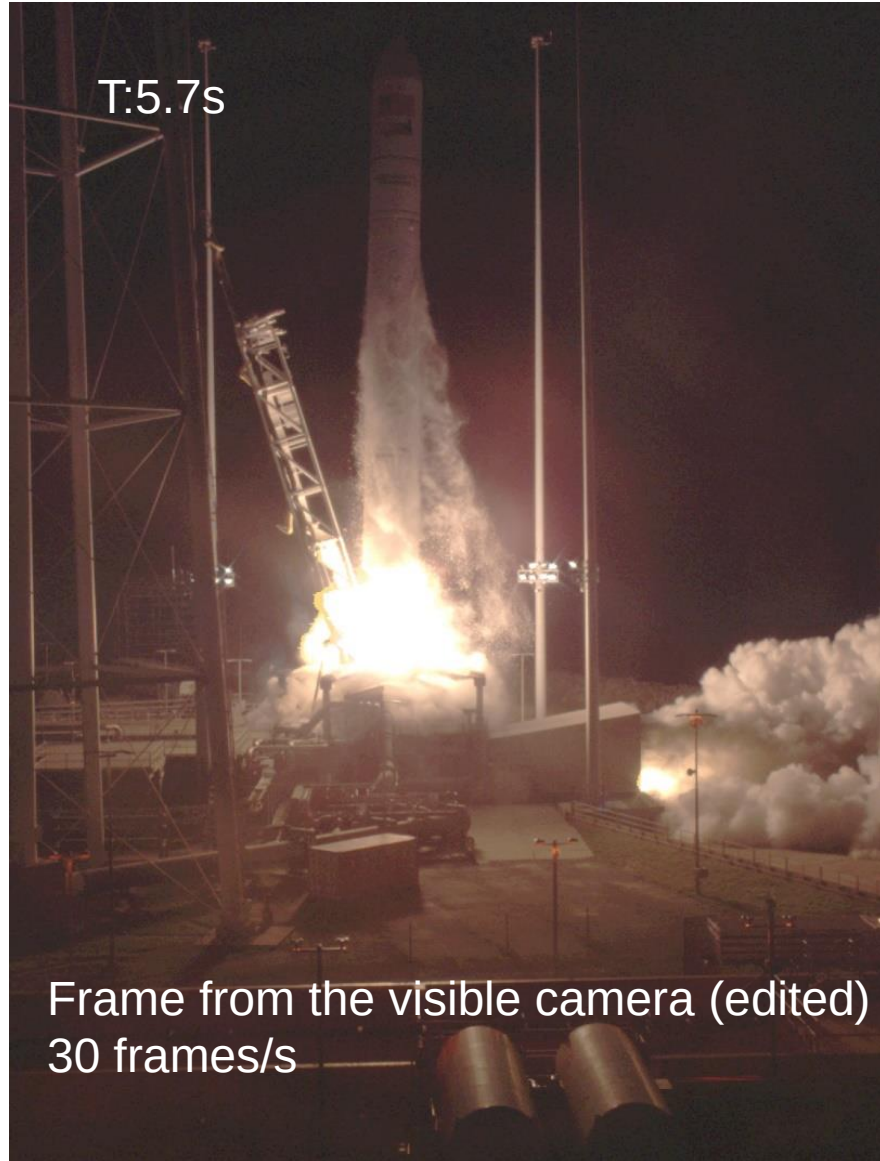
Present Dome Array



- Resolution of the noise sources depends on the frequency.
- Expected to improve resolution by a factor of 2 to 6



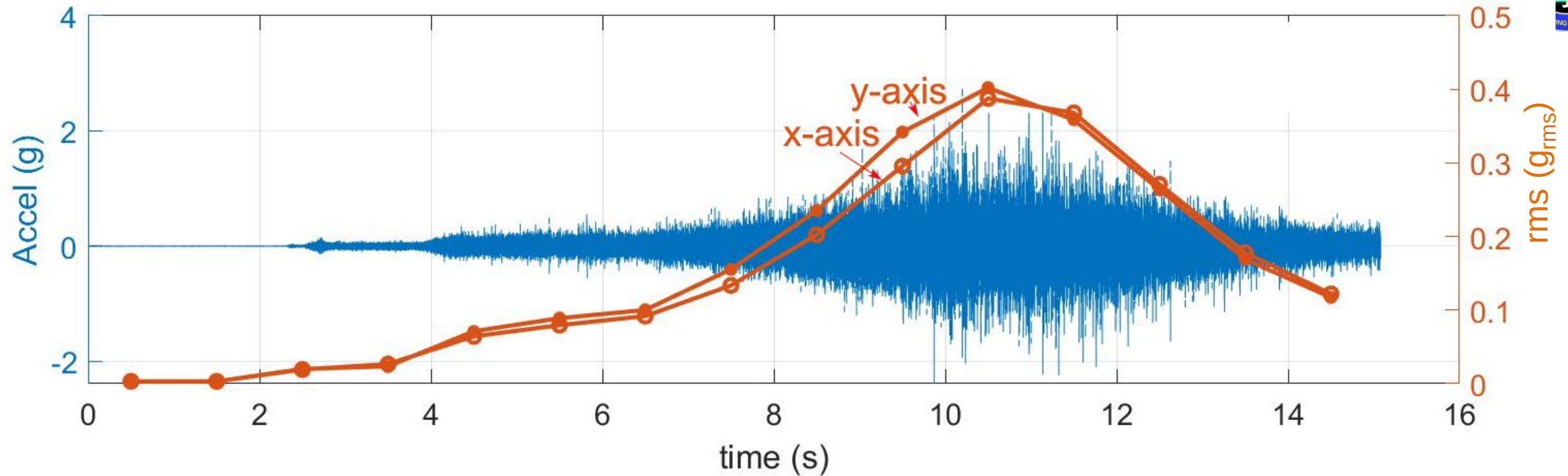
NG19 Launch on Aug 1st, 2023



Timing decided based on identifying video frame showing TEL separation: T:3.3s

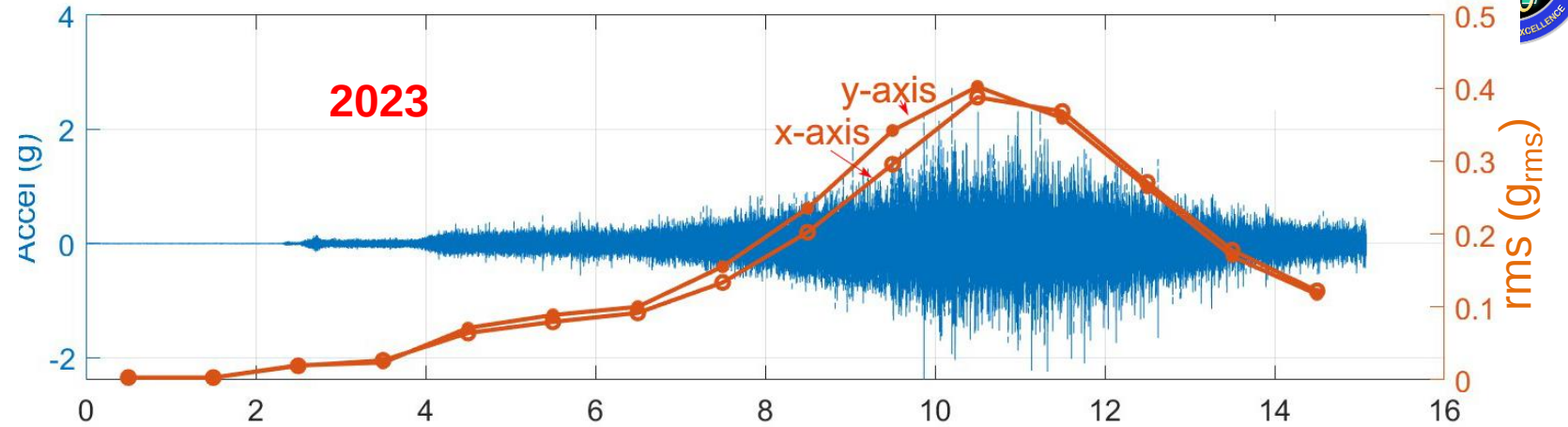
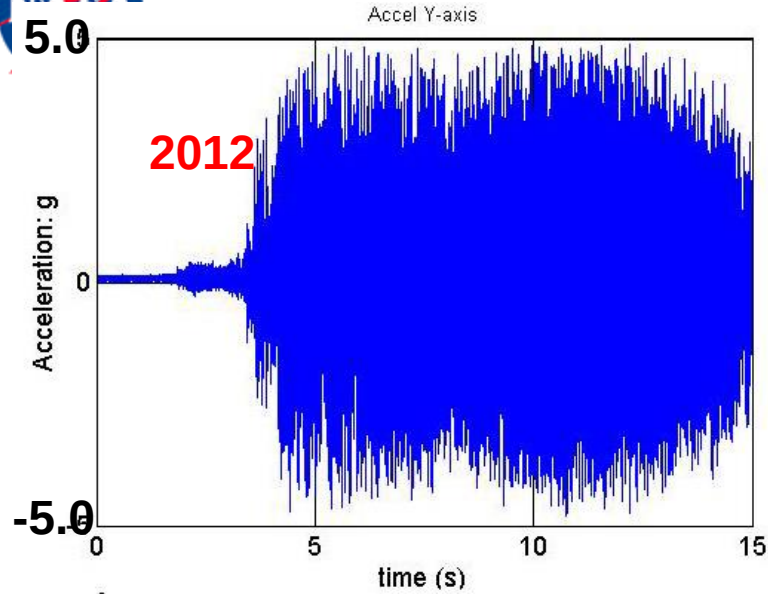


Shaking of the array – accelerometer response



- 2-axis accel inside the canister
 - x: side-to-side direction
 - y: front-back direction
- Relatively small response peak grms ~ 0.4
 - comparable in both x and y
- combination of responses of the scaffold structure and the array itself

Comparison with old array: 2012- Antares A1



Array: Solid frame. Mount: Scissor lift

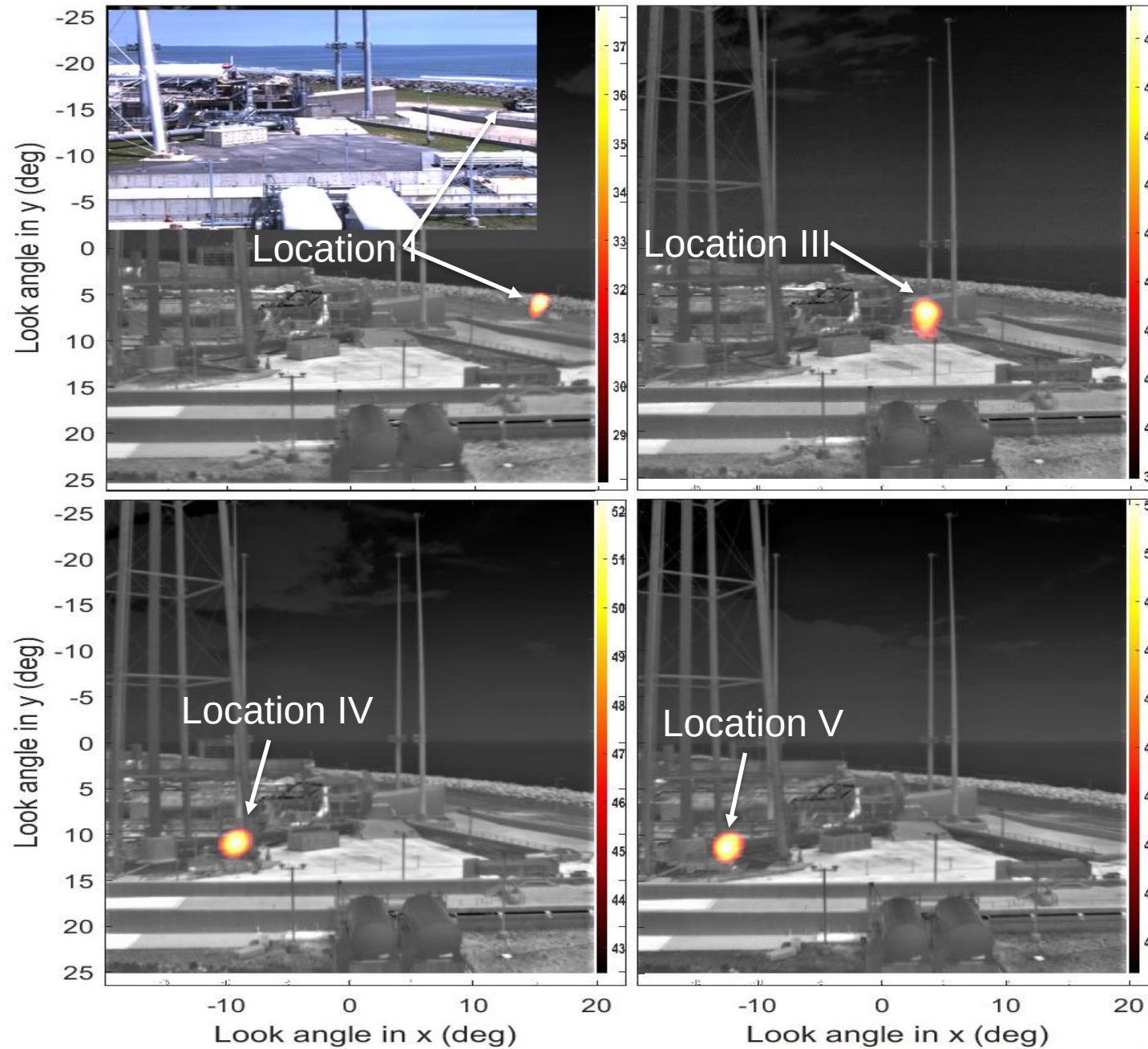


Array: Open lattice
Mount: scaffold structure

- 2012:
 - Saturated the $\pm 5g$ accel
- 2023:
 - At least a factor of 5 decrease in accel response (possibly more)

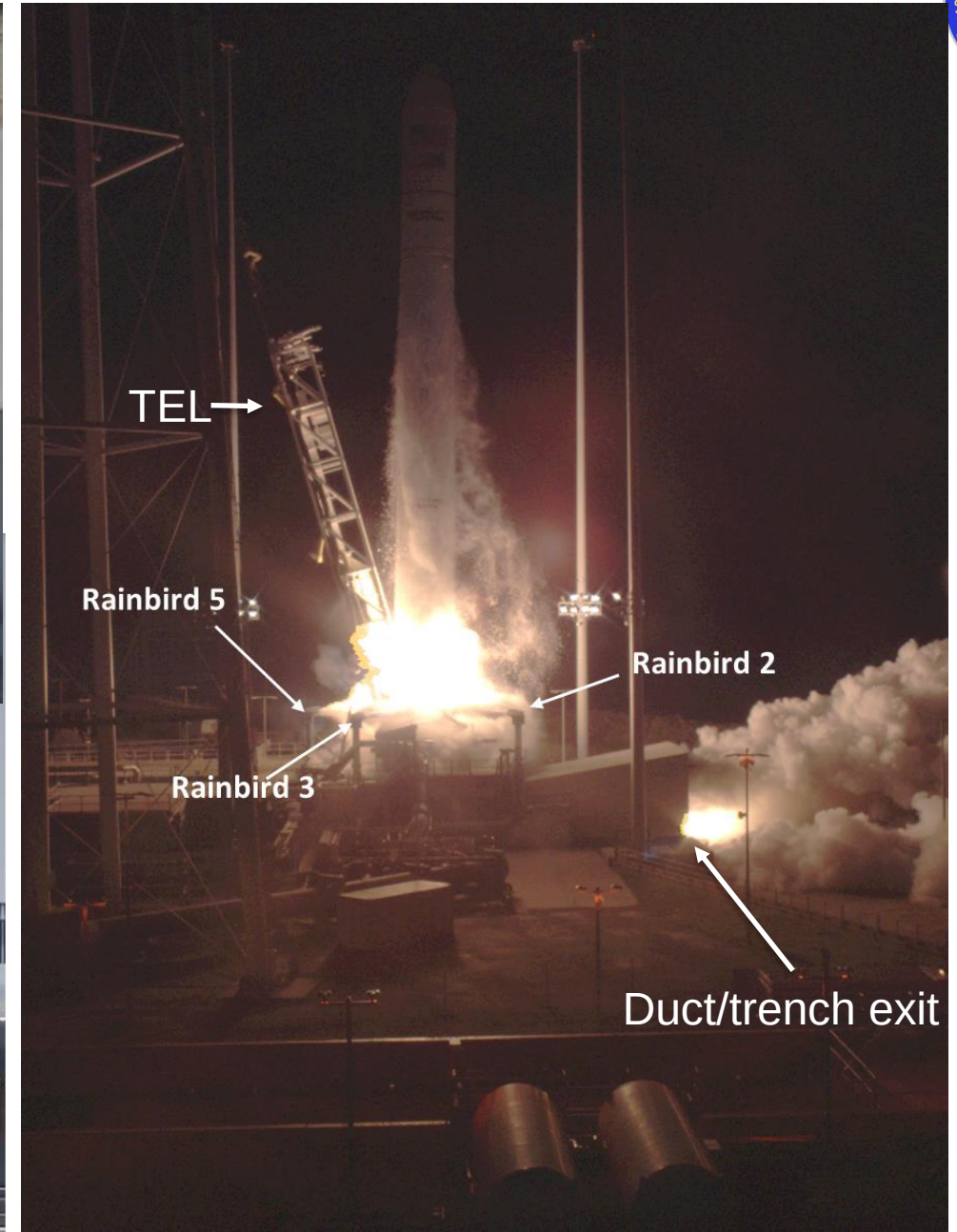


Calibration of the phased array cameras and alignment with the beamformed map



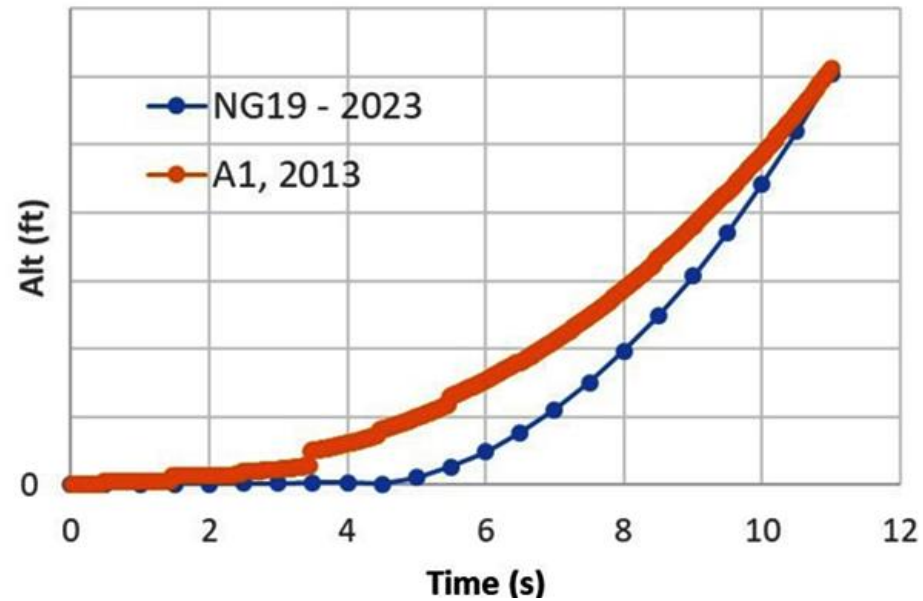
- The LRAD speaker was mounted on a truck and moved at different locations within the camera field of view. Speaker directed towards the array
- Sound generated by the speaker was recorded
- Camera calibration (deg/pixel) was confirmed, and tilt and pitch angles of the cameras were determined from these data

Description of Pad-0A - Rainbirds

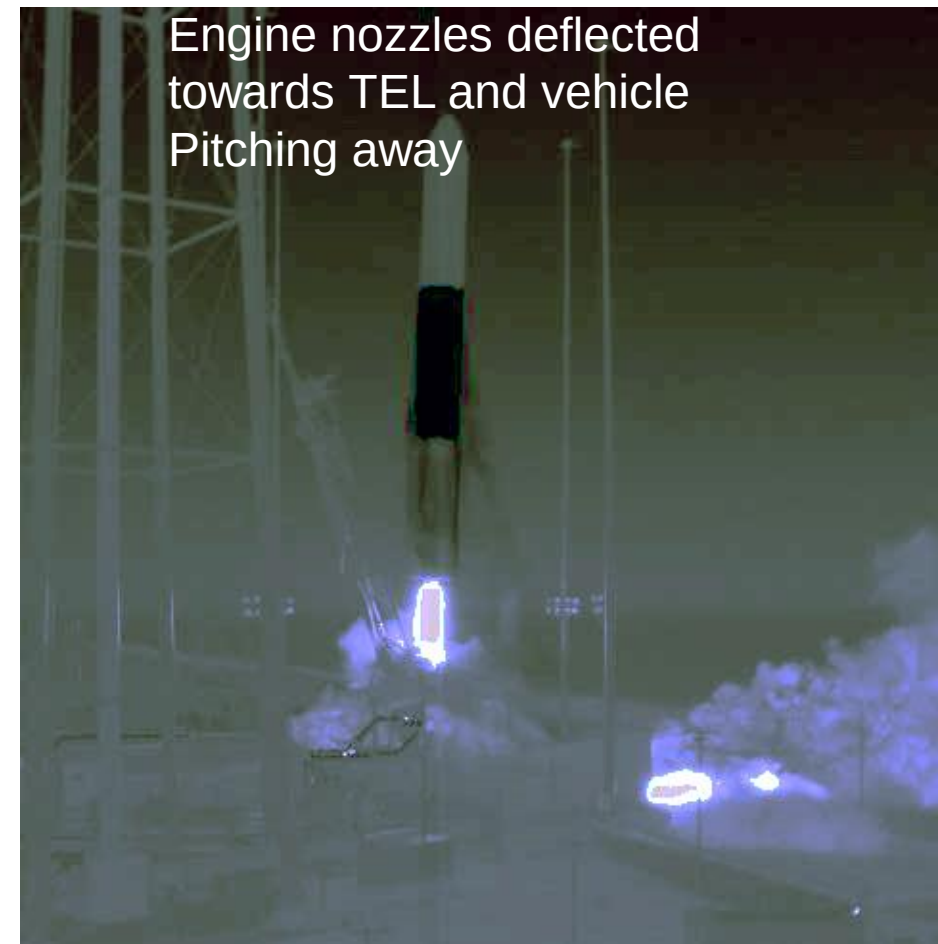




NG19 Trajectory info



Flight Trajectories of the present (2013) NG-19 and that of Antares A1 (2013)





Time Evolution of Beamformed Noise maps

Functional-Orthogonal beamforms with three different exponents:

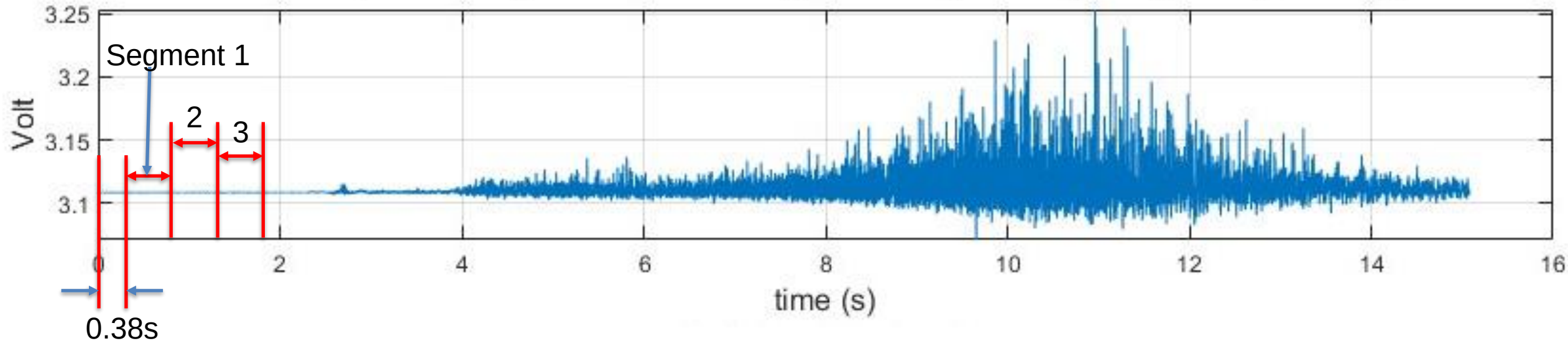
- (a) For $f \leq 100\text{Hz}$, $v=100$, plot range: 5dB
- (b) For $100 < f \leq 512\text{Hz}$, $v=80$, plot range: 10dB
- (c) For $512 < f \leq 2\text{kHz}$, $v=20$, plot range: 10dB



Segmentation of microphone data

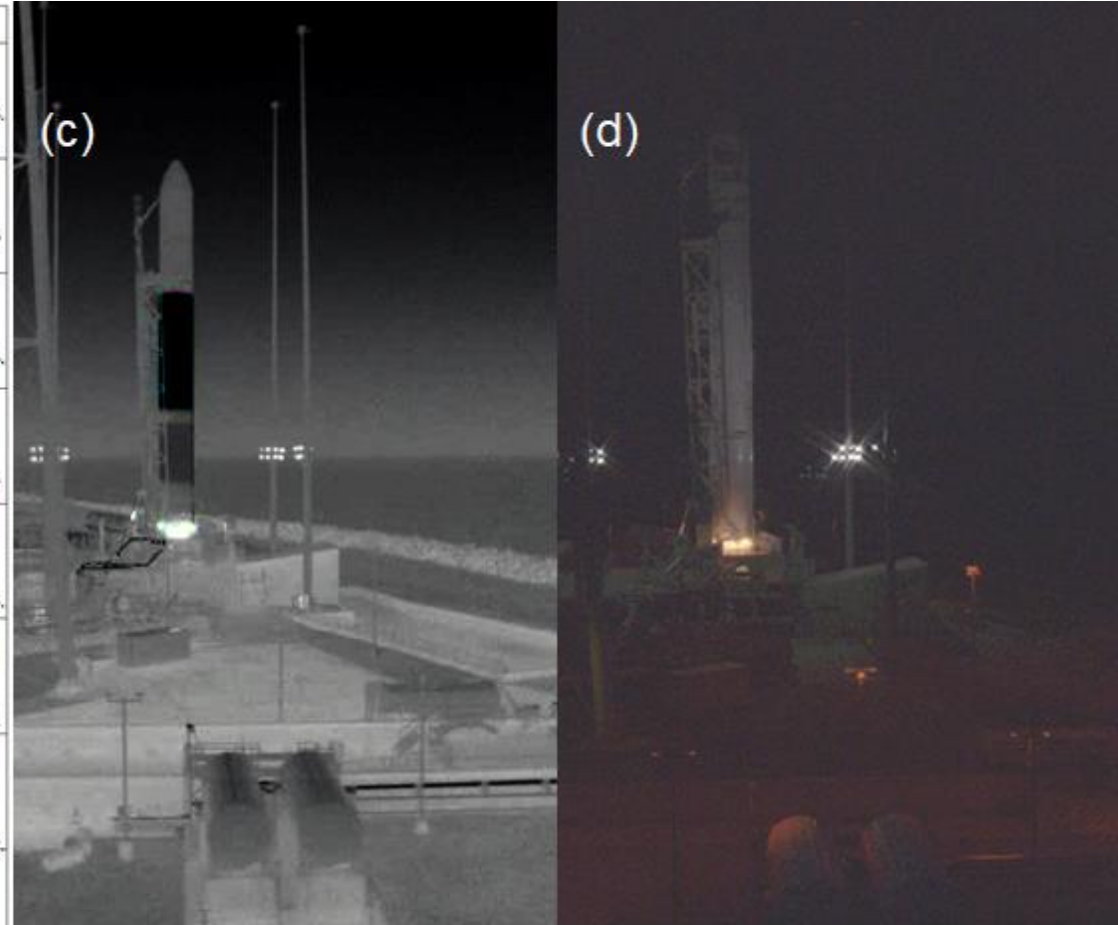
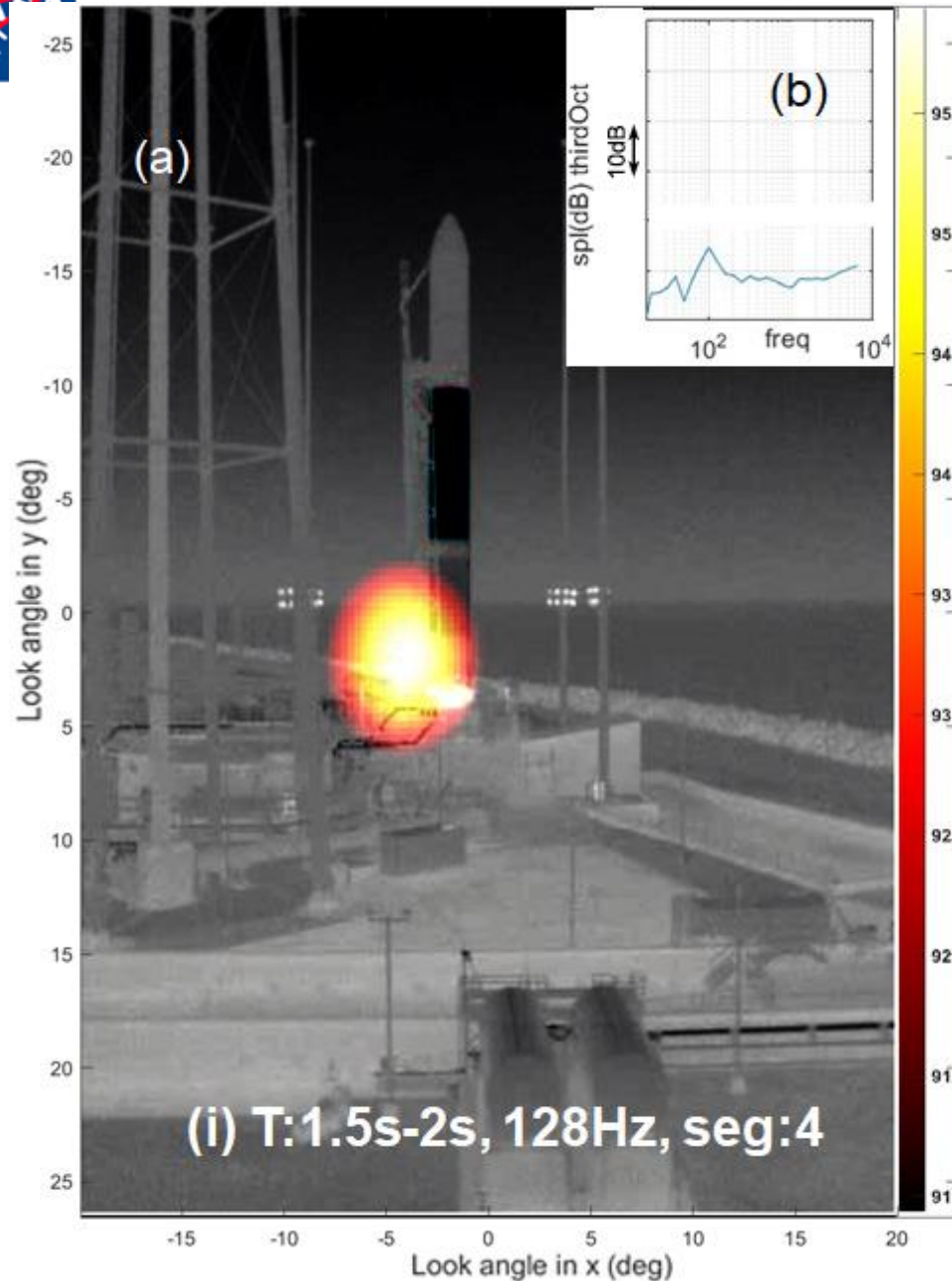


Mic No: 1, Entire signal: Y2023M08D01_h20m30s41₄0960Hz_ac0ch_dc80ch_trunc.single



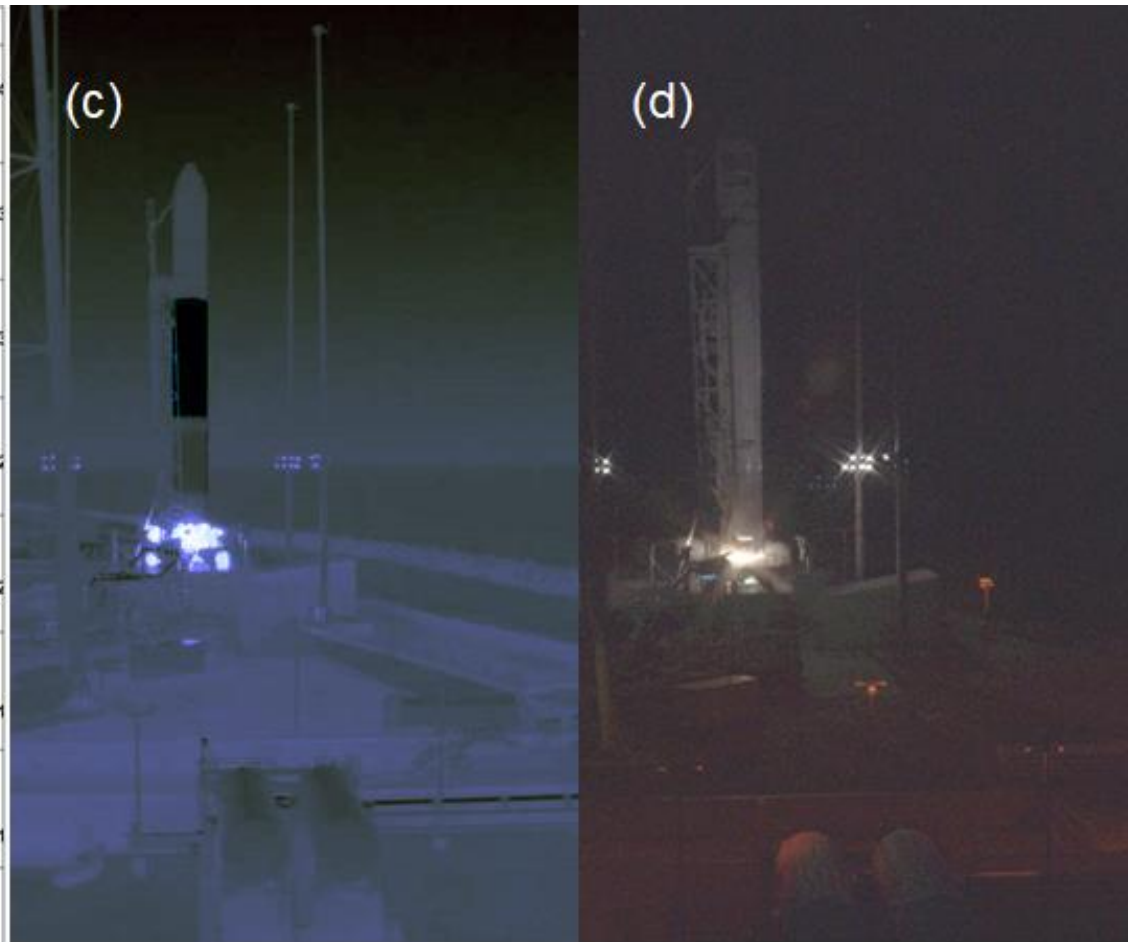
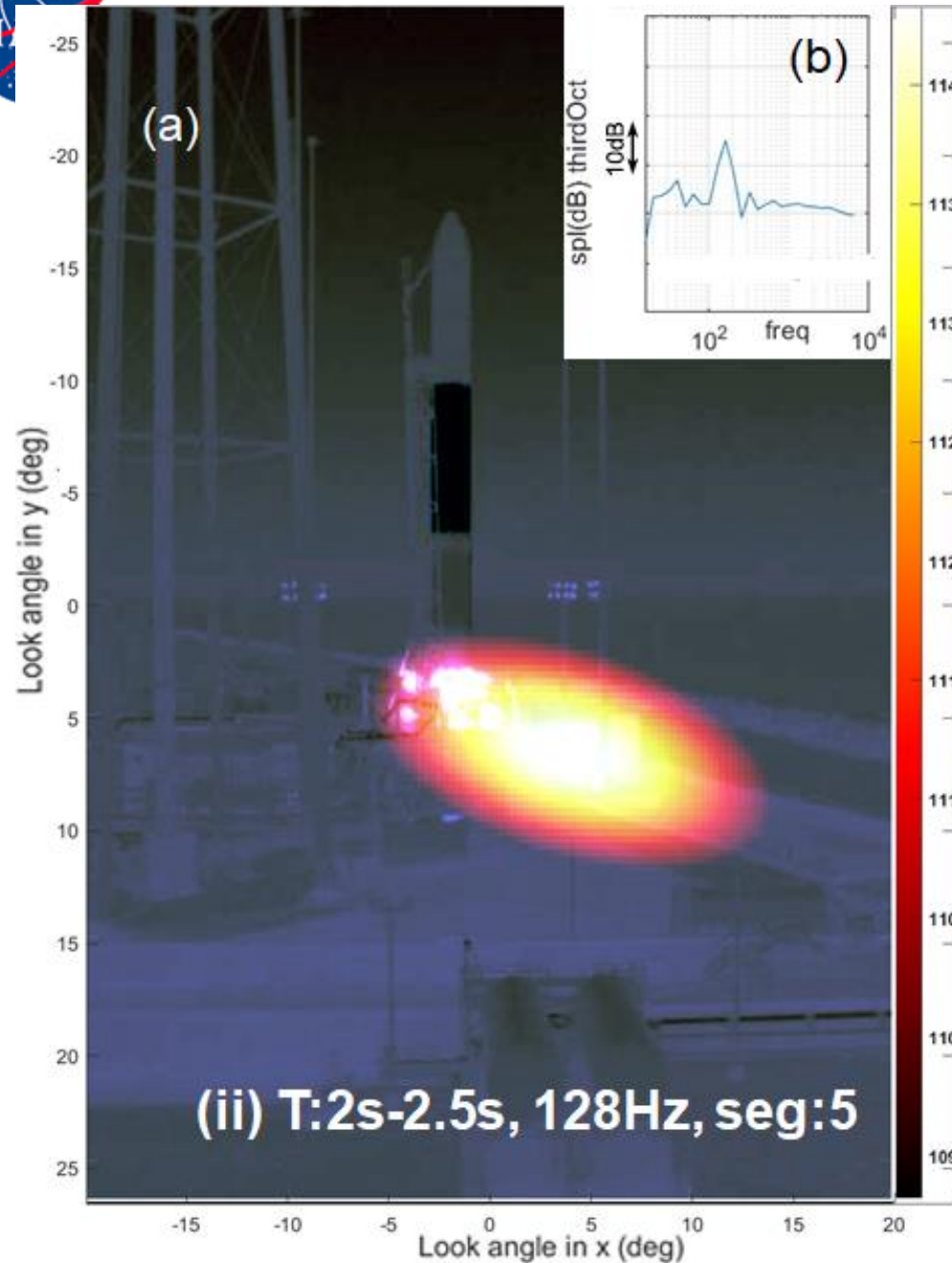
- Time series segmented into 0.5s wide bins – beamforming performed on each segment
- accounted for propagation delay from vehicle to array: 0.38s

T:1.5s-2s, 128Hz, seg:4



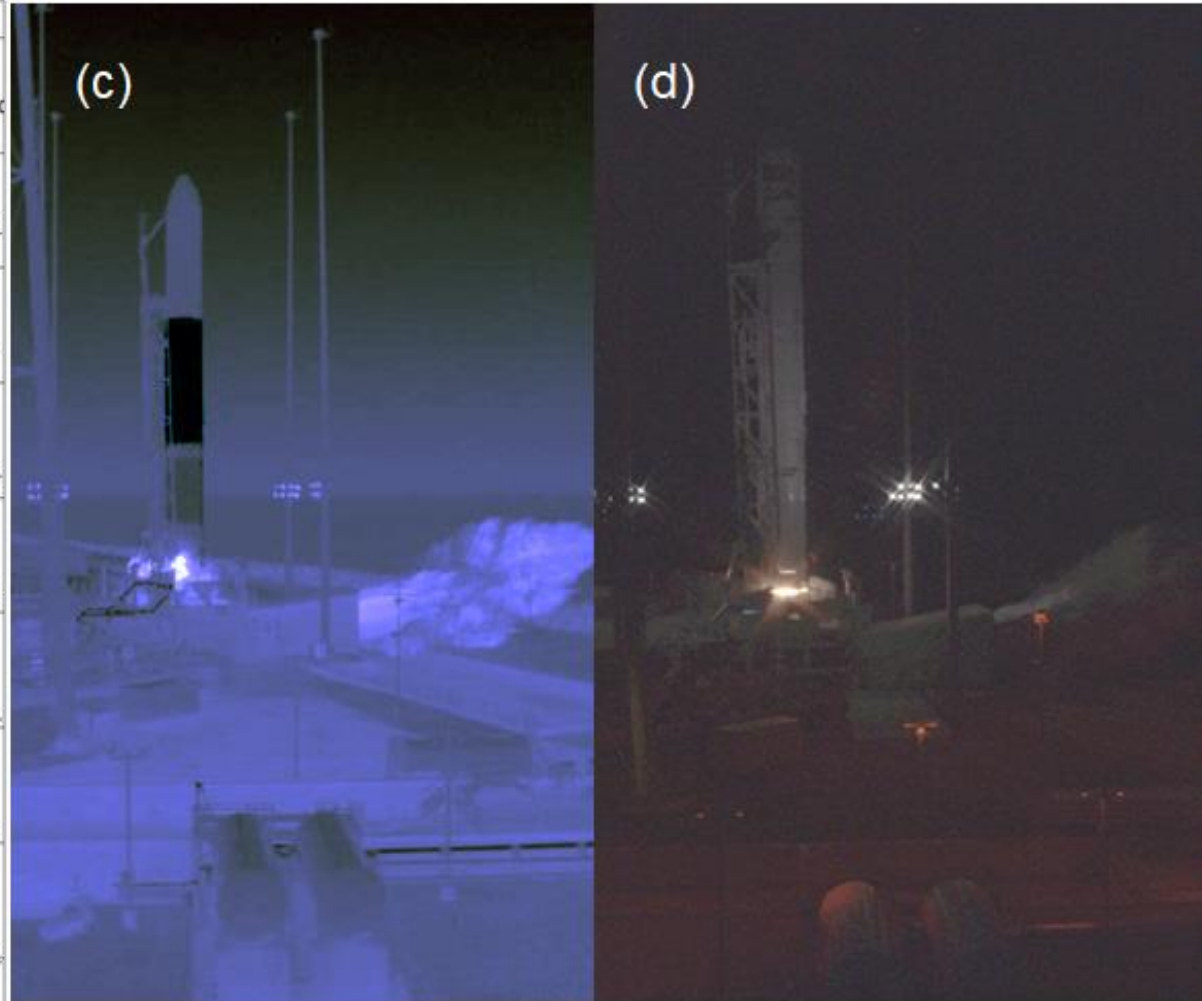
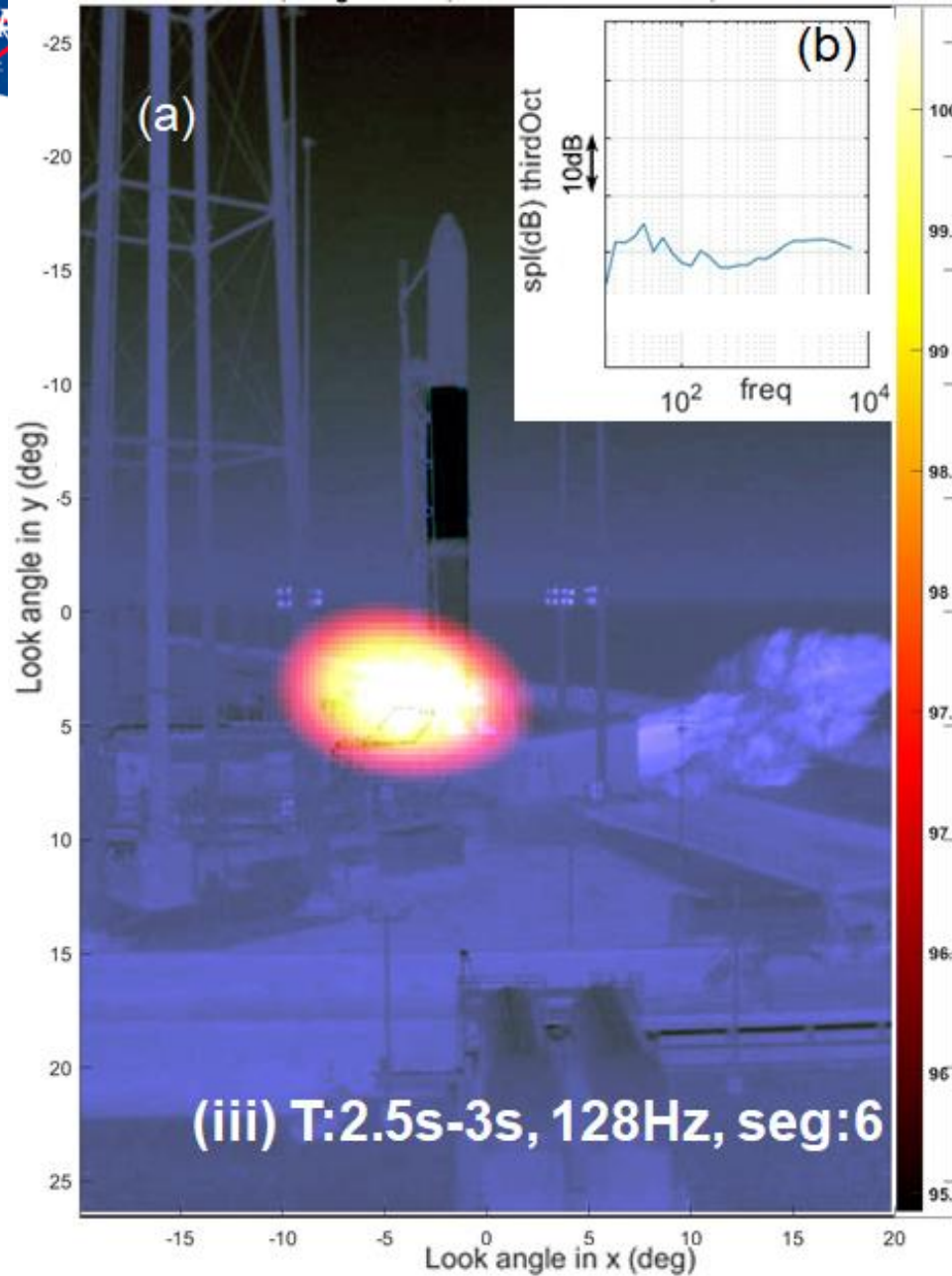
- Engine powering up
- plume visible through gap in the mount
- Nothing coming out of duct outlet
- Low acoustic level
- Sound coming out of the gap between vehicle and the mount hole

T:2s-2.5s, 128Hz, seg:5



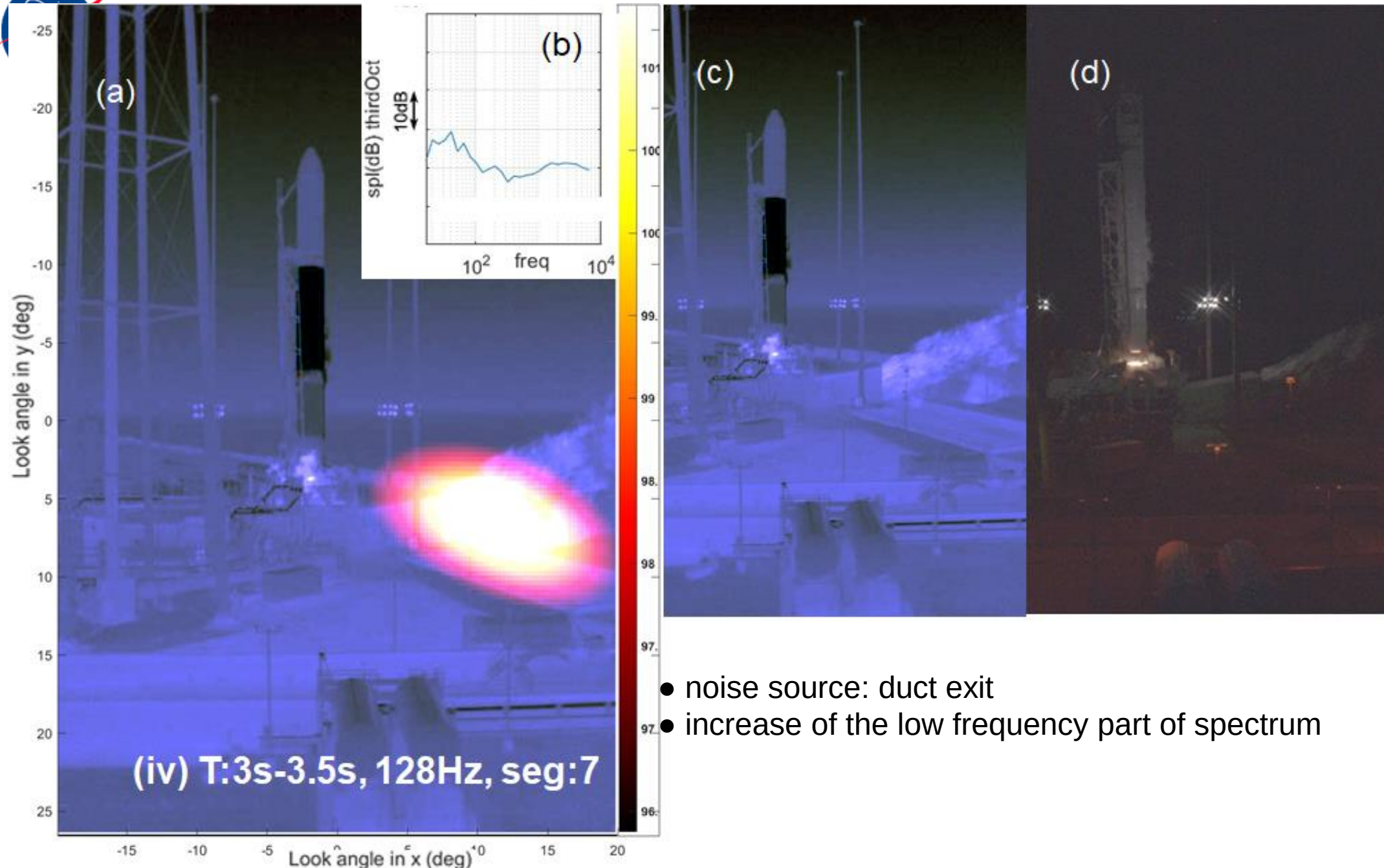
- Low frequency event
- Sound emanating from engine mount & duct exit

T:2.5s-3s, 128Hz, seg:6

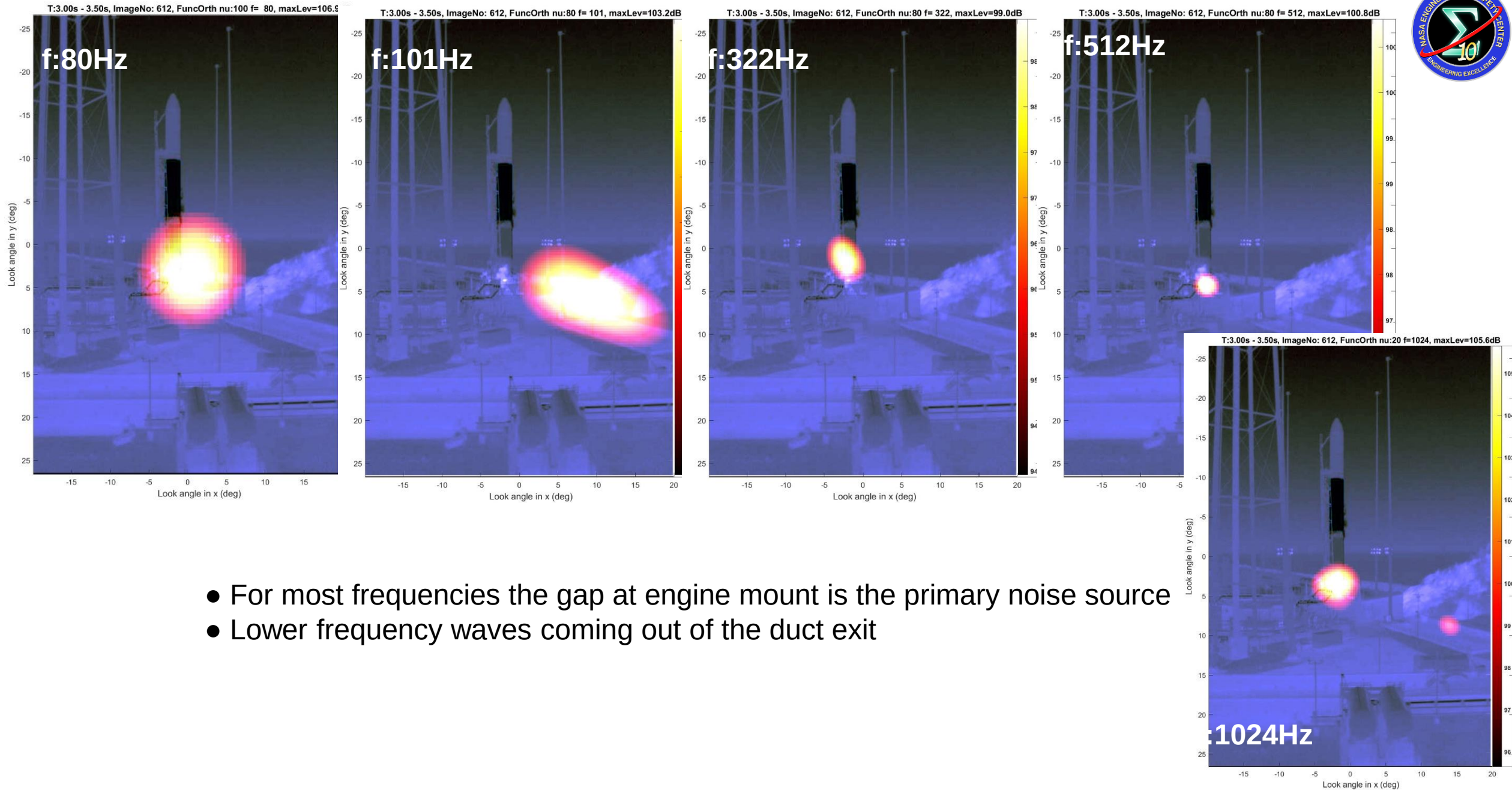


- Engines powering up
- hot gases coming out of duct exit
- Noise generated inside the duct radiating out of the duct exit

T:3s-3.5s, 128Hz, seg:7

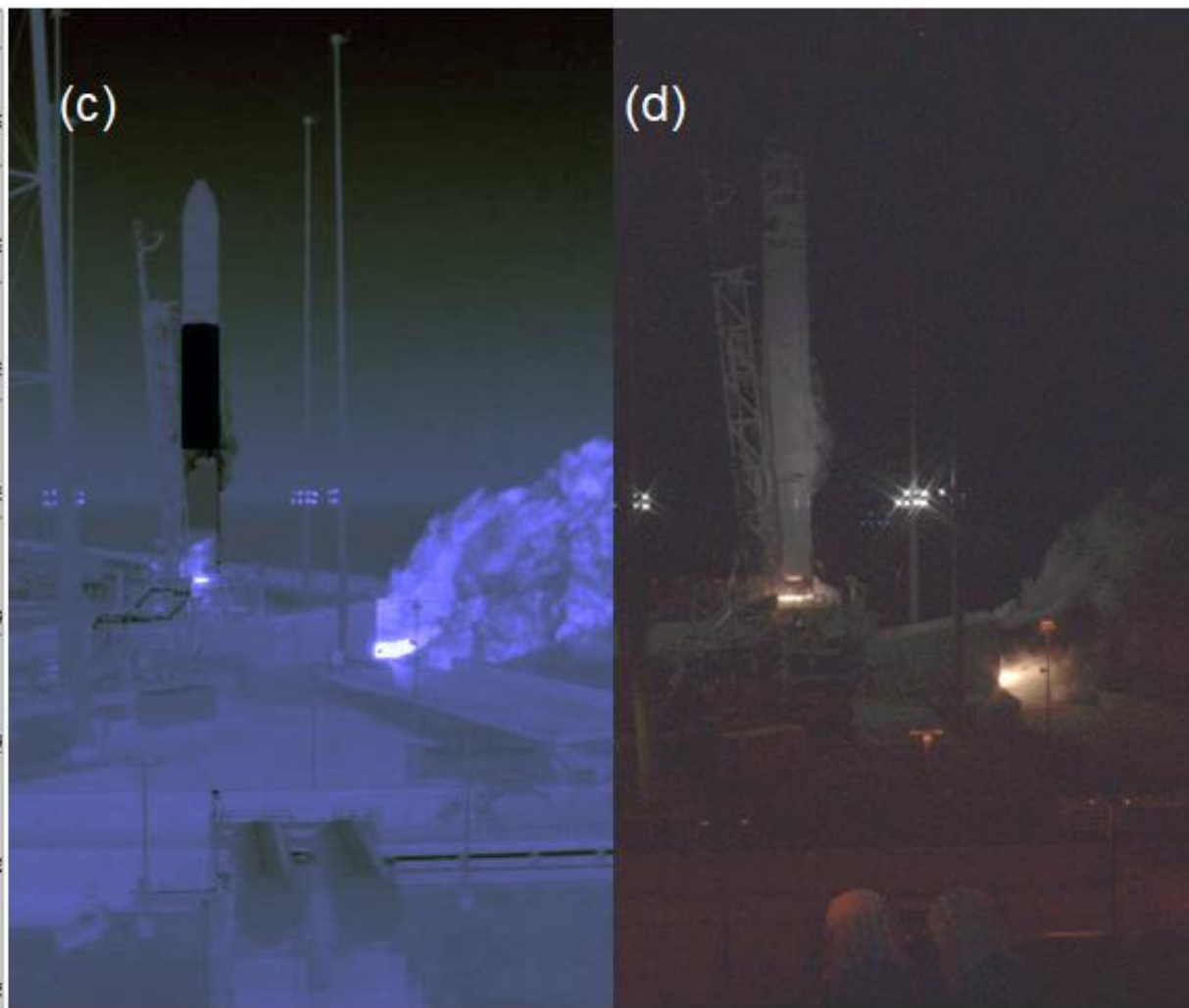
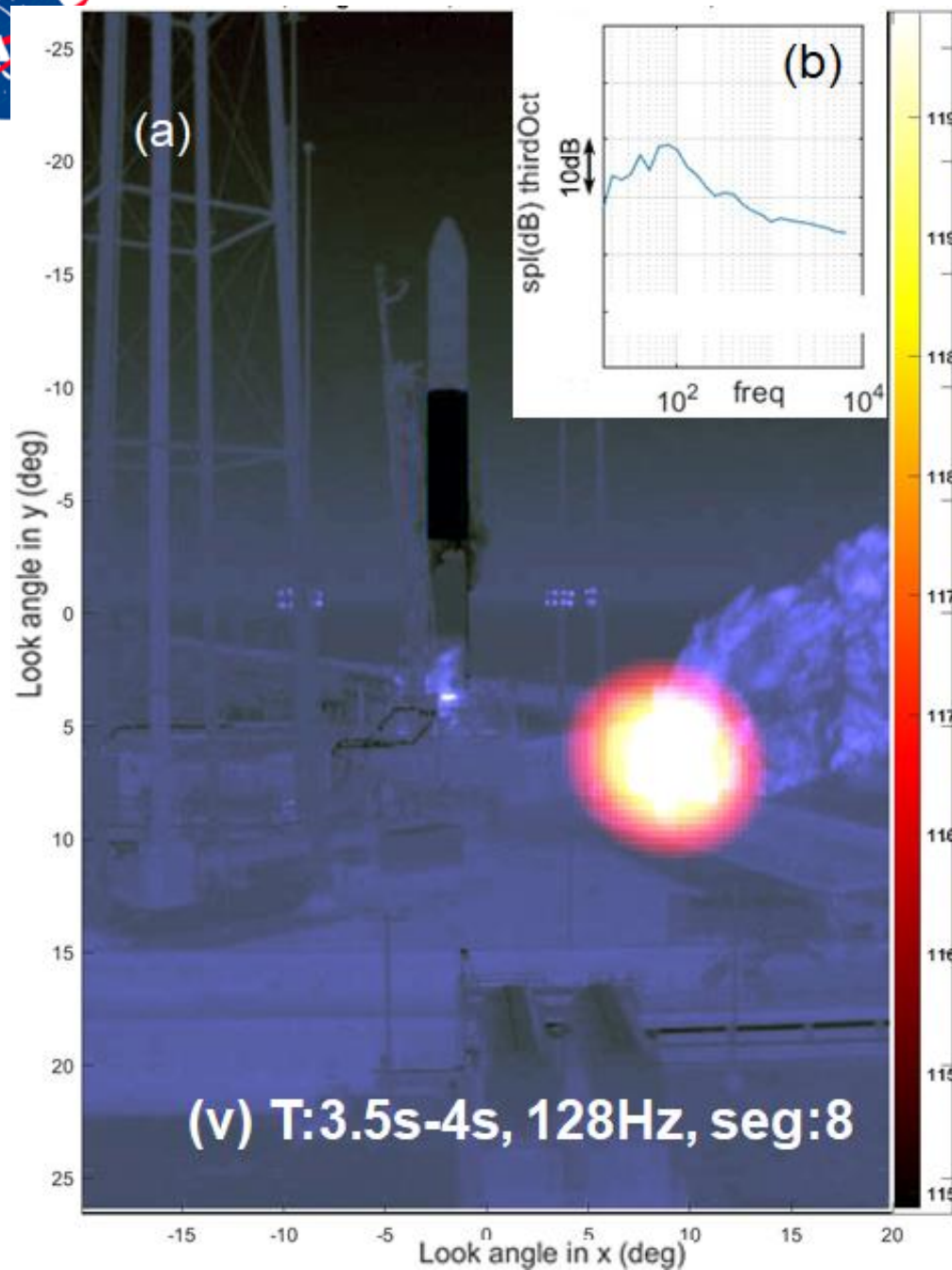


Examine multiple frequencies, T:3s-3.5s, seg:7



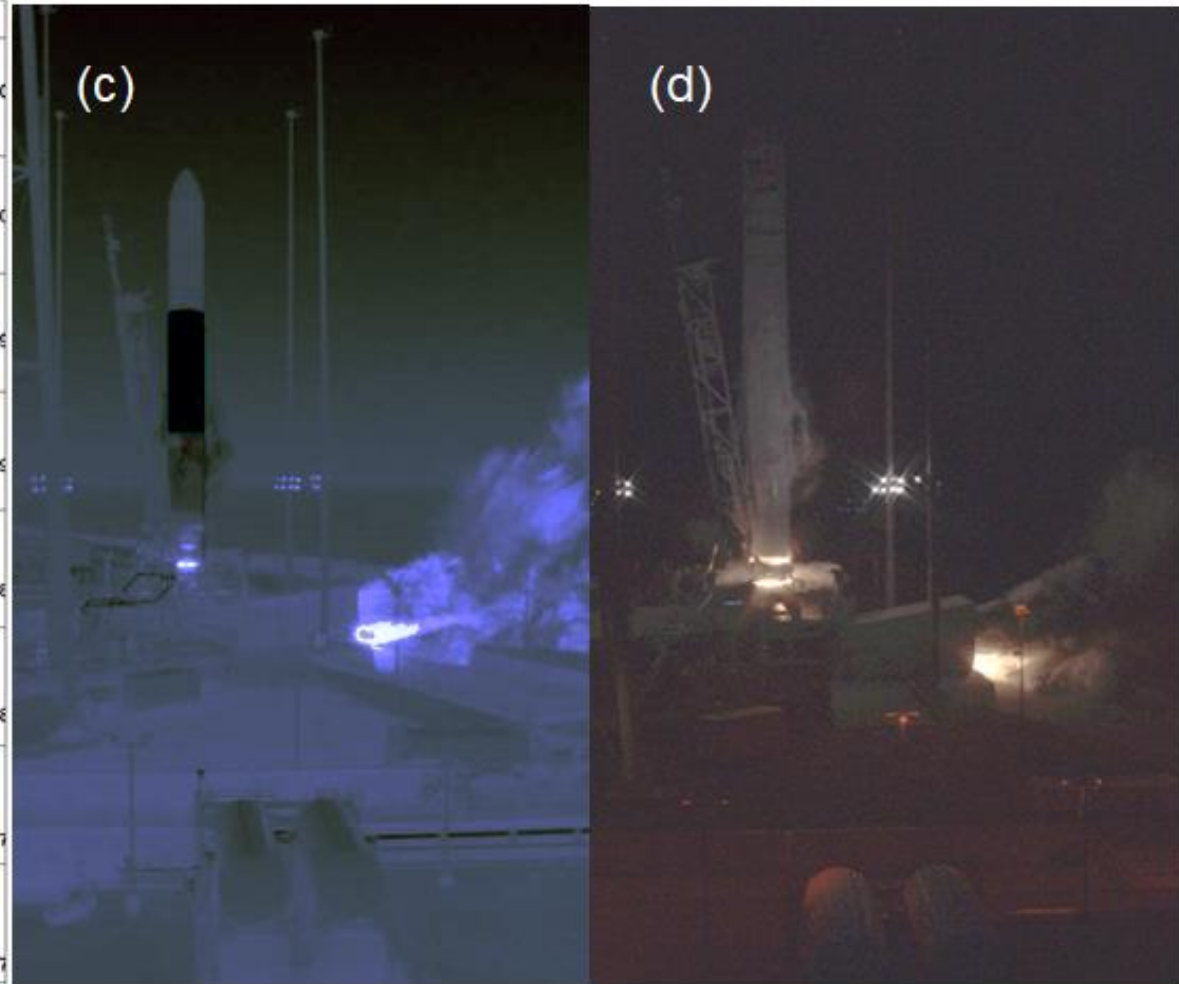
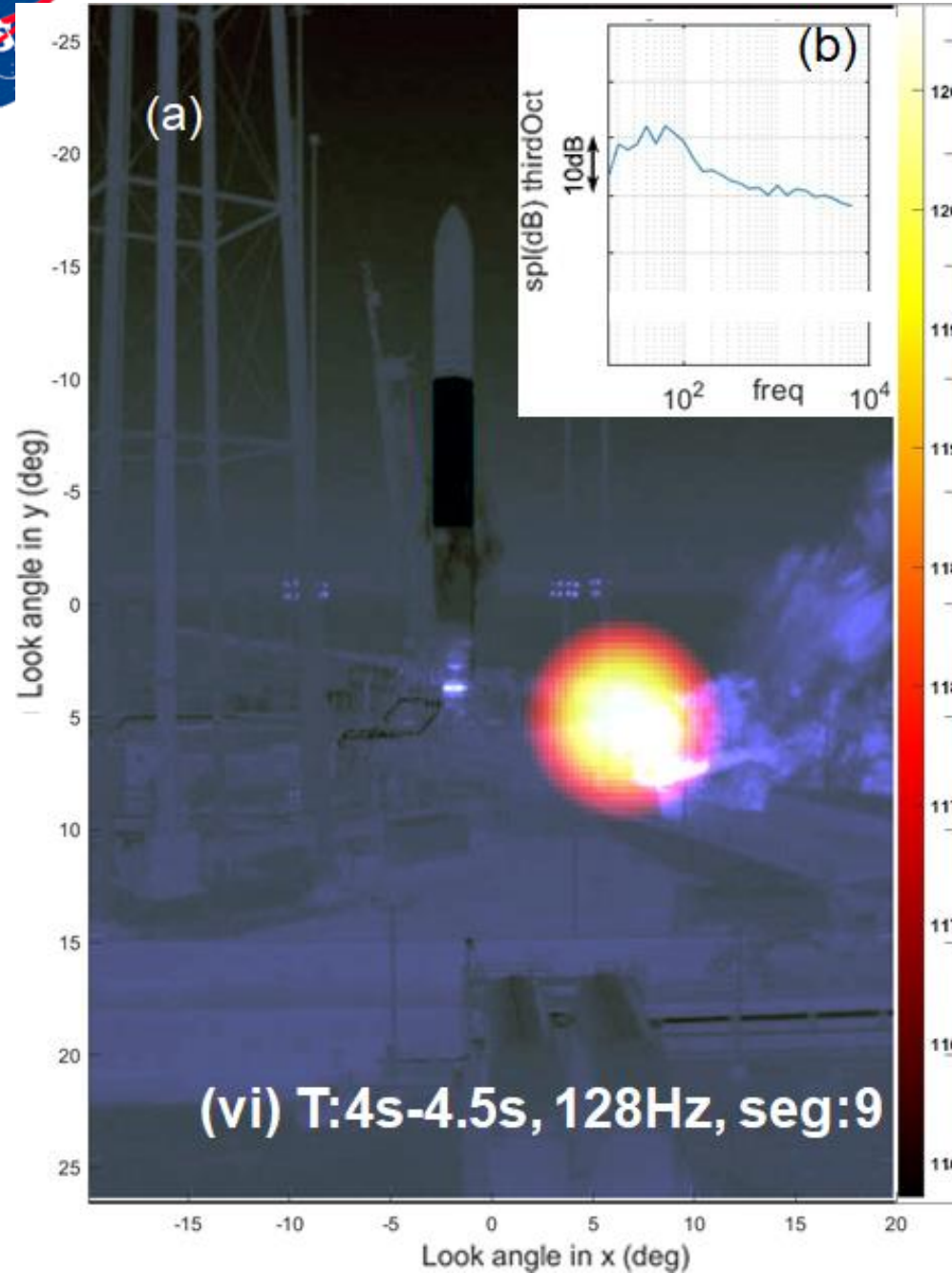
- For most frequencies the gap at engine mount is the primary noise source
- Lower frequency waves coming out of the duct exit

T:3.5s-4s, 128Hz, seg:8



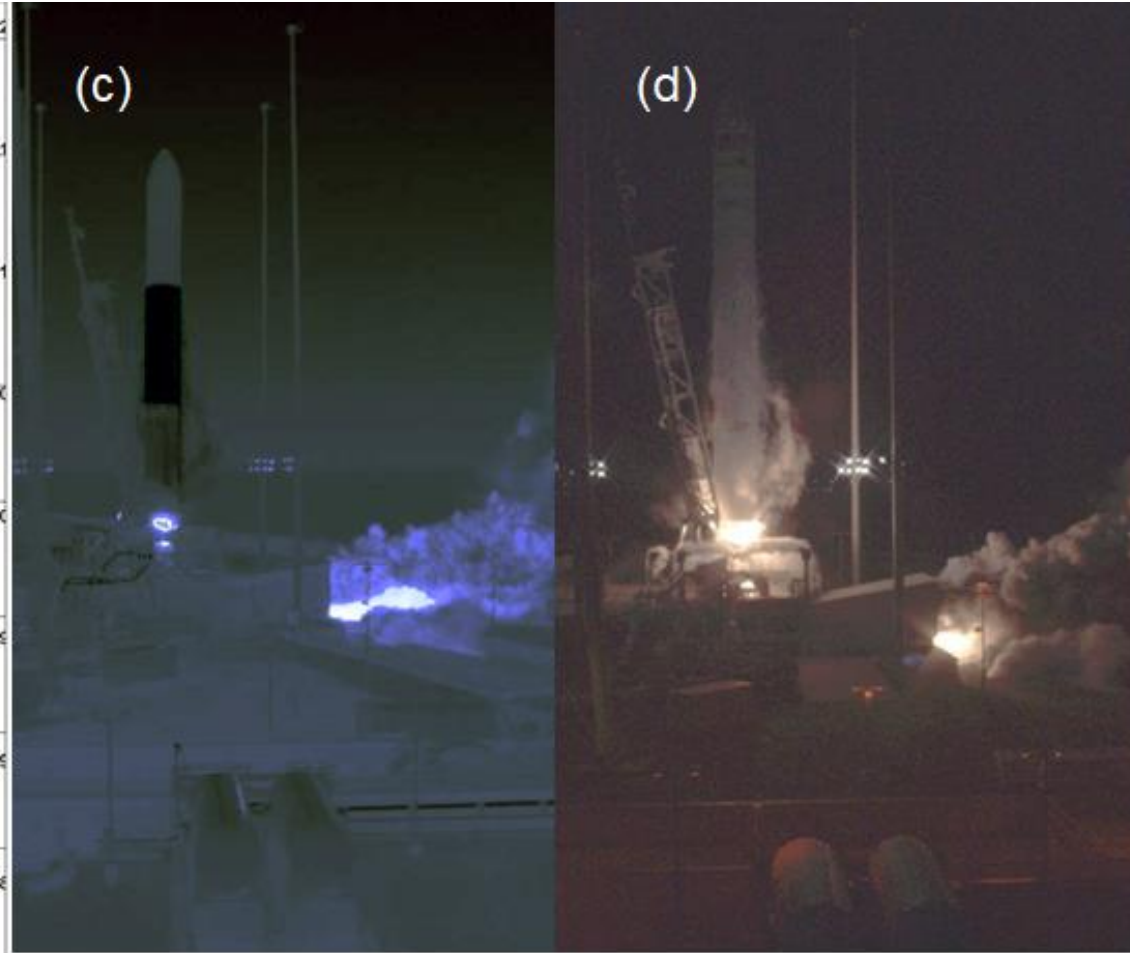
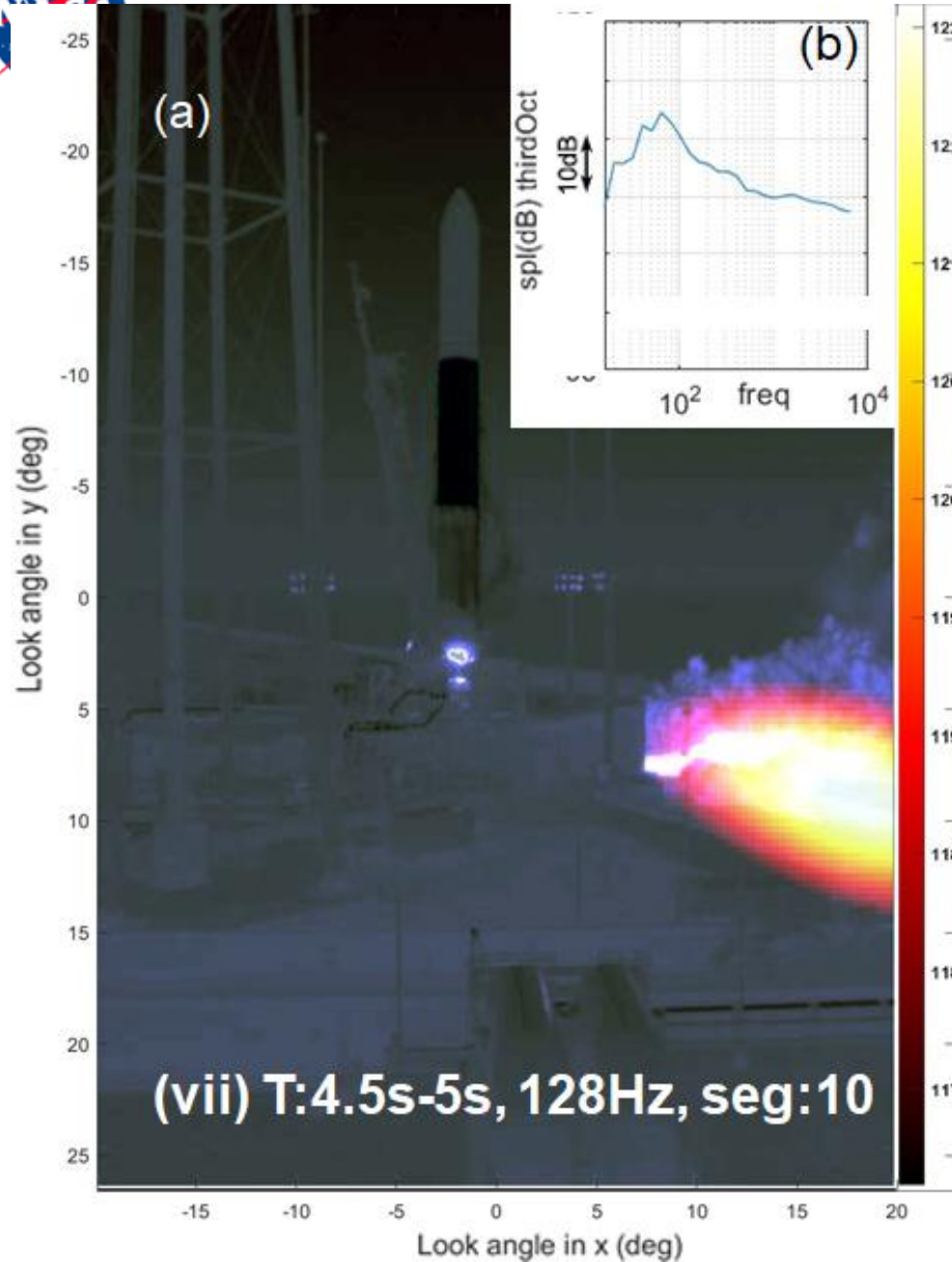
- Increasing low frequency content
- Such sounds are mostly coming out of the duct exit
- Uncooled flame is showing up at the bottom of the duct exit

T:4s-4.5s, 128Hz, seg:9



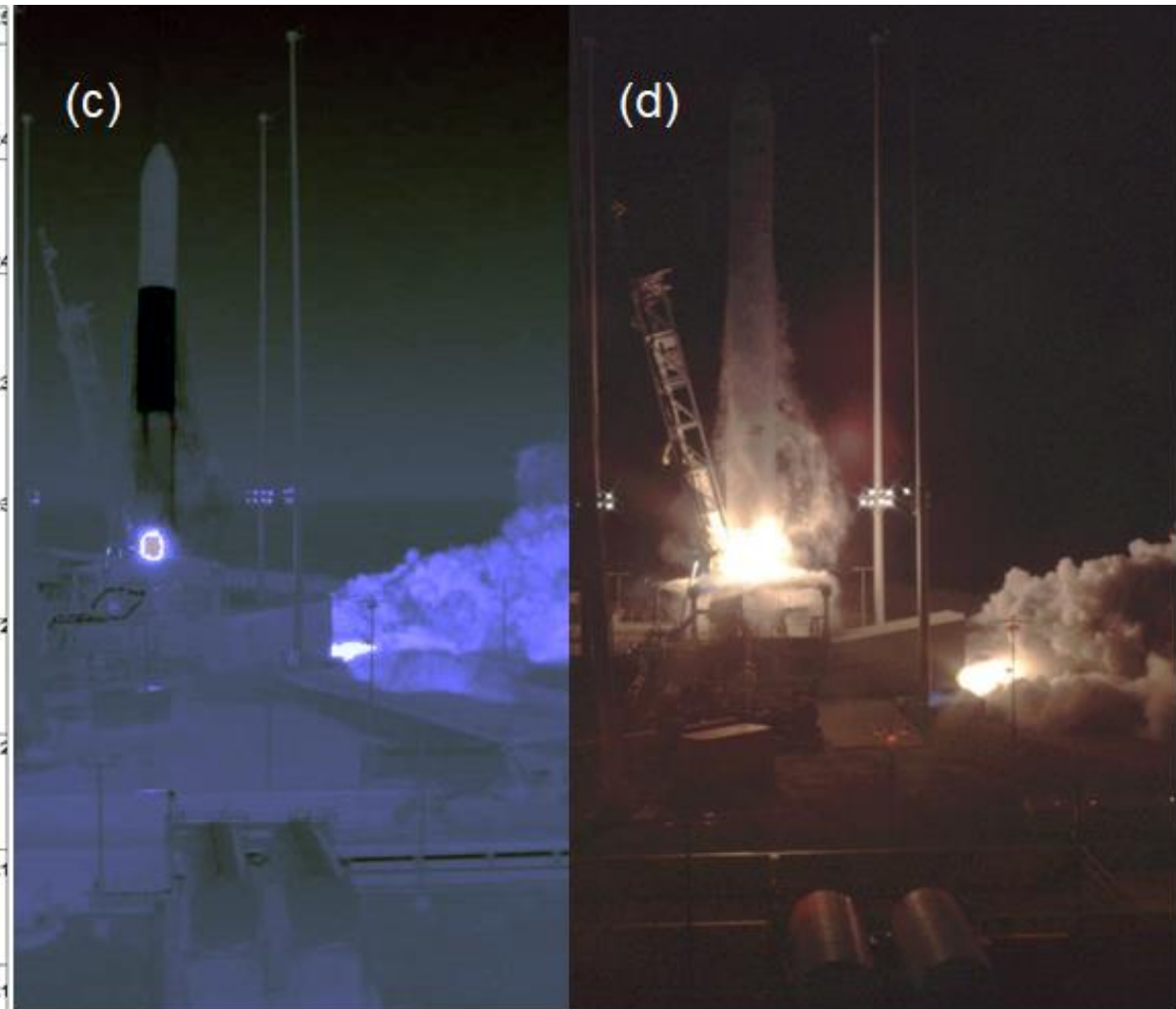
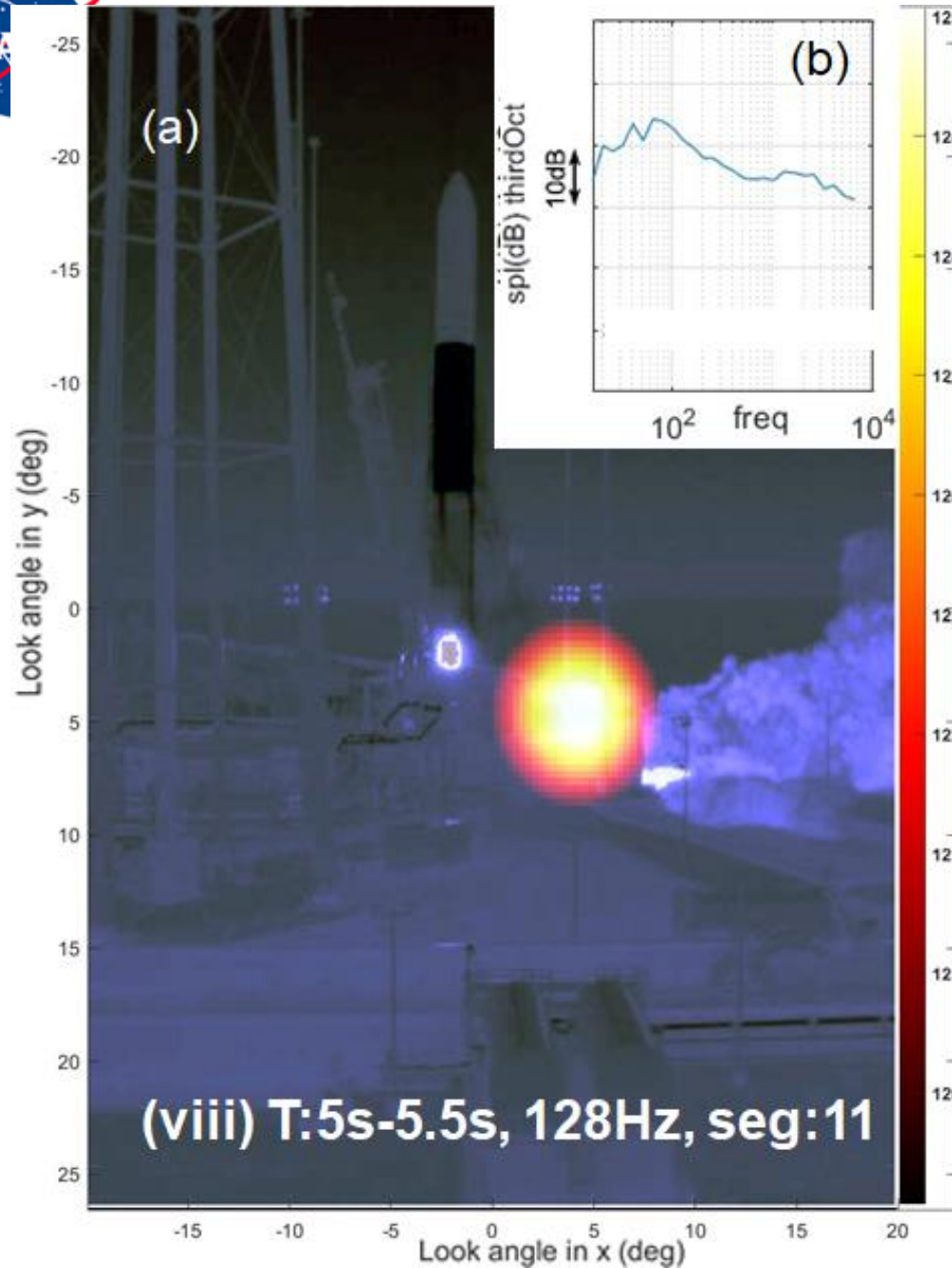
- Further increase in low frequency
- Duct exit is the primary source

T:4.5s-5s, 128Hz, seg:10



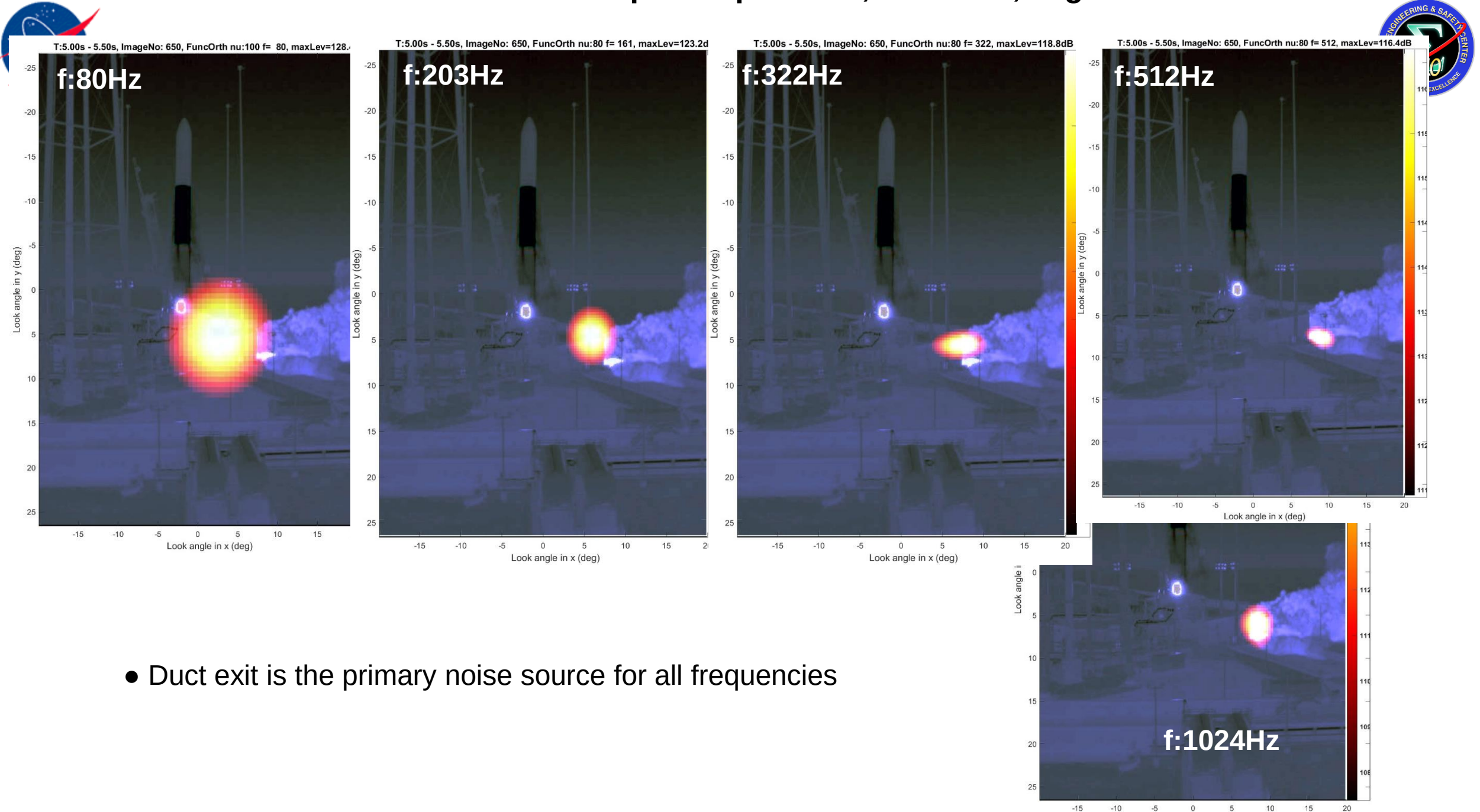
- More uncooled flame coming out of the duct exit – stronger noise source

T:5s-5.5s, 128Hz, seg:11

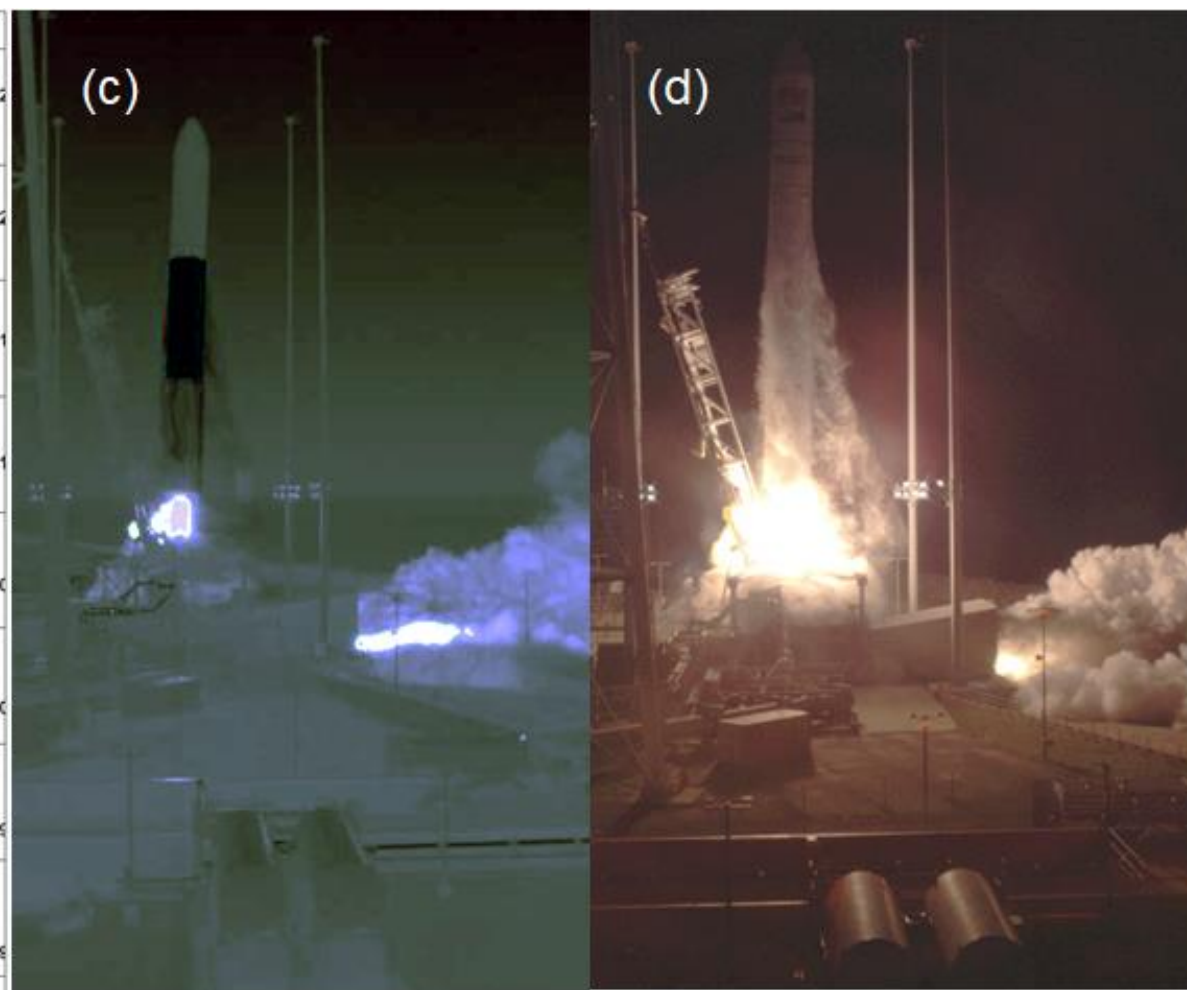
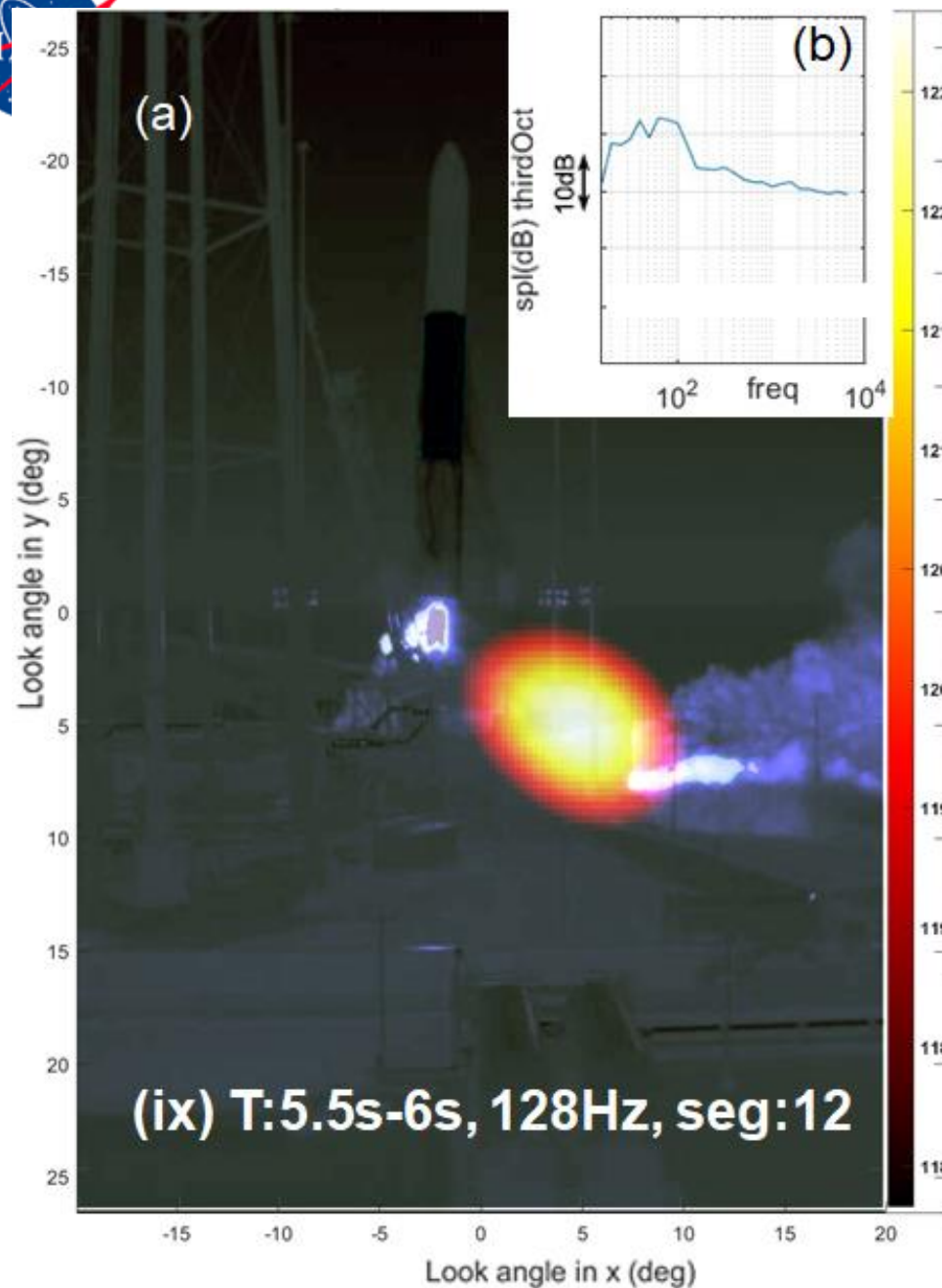


- same as before
- Rainbird flow rates are increasing

Examine multiple frequencies, T:5s-5.5s, seg:11

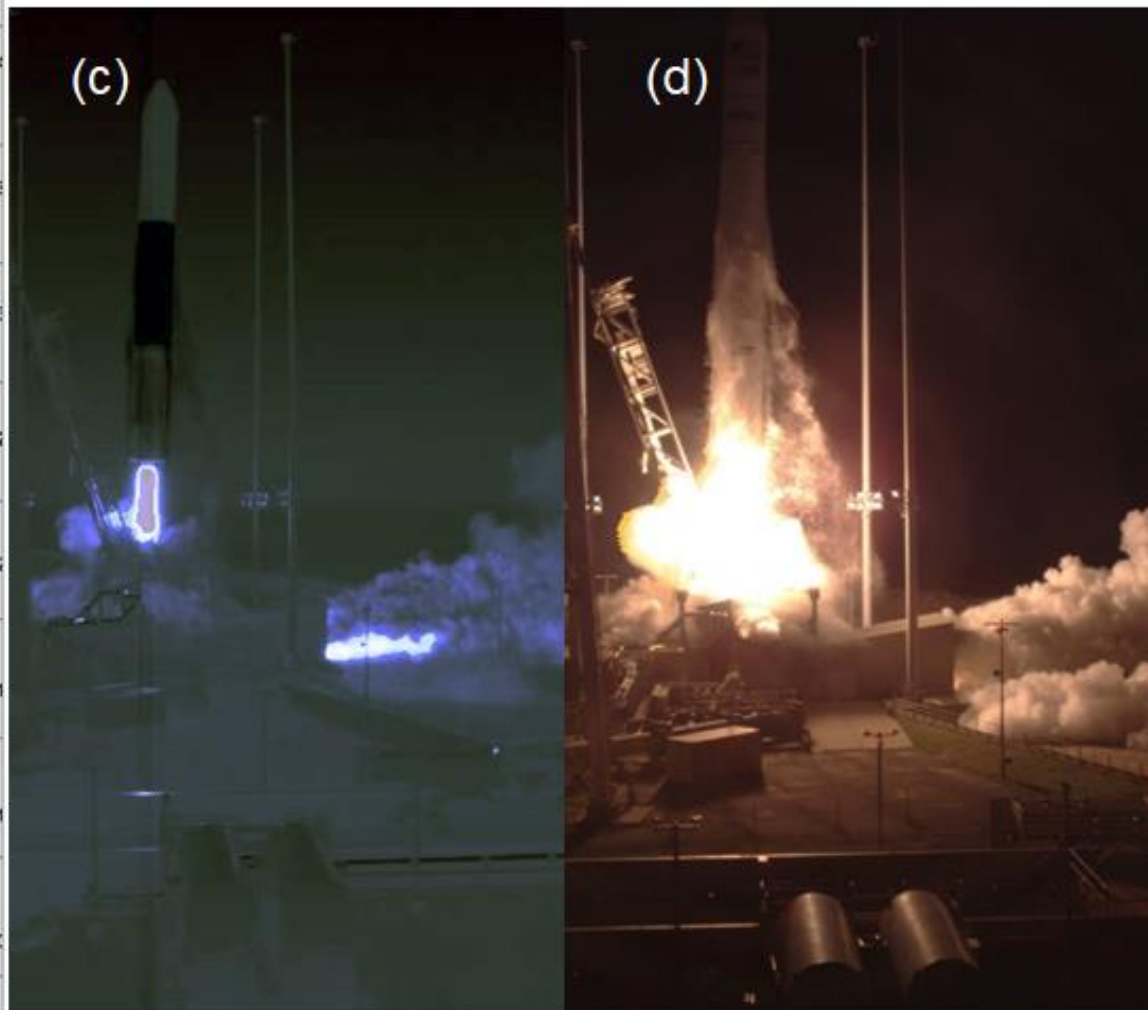
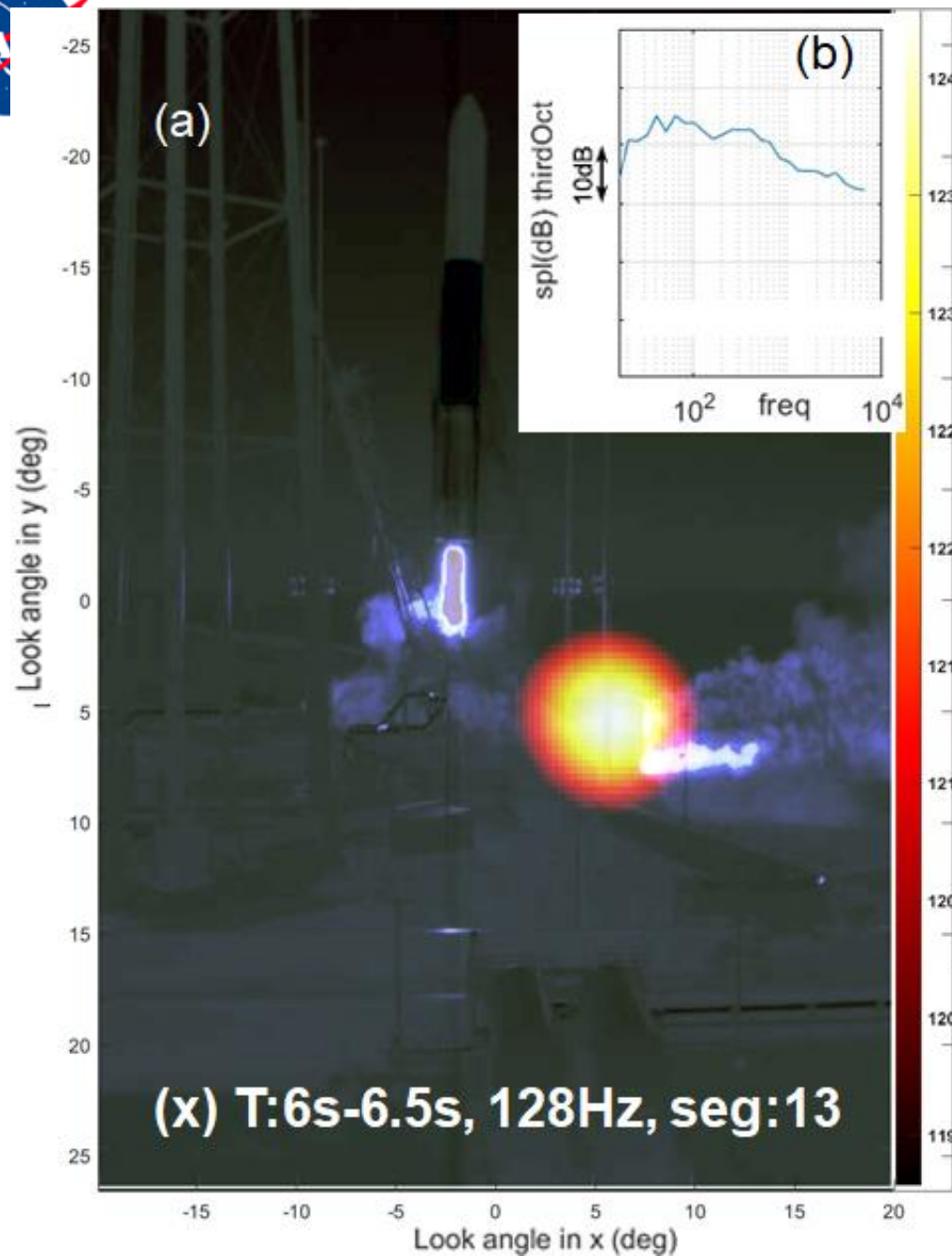


T:5.5s-6s, 128Hz, seg:12



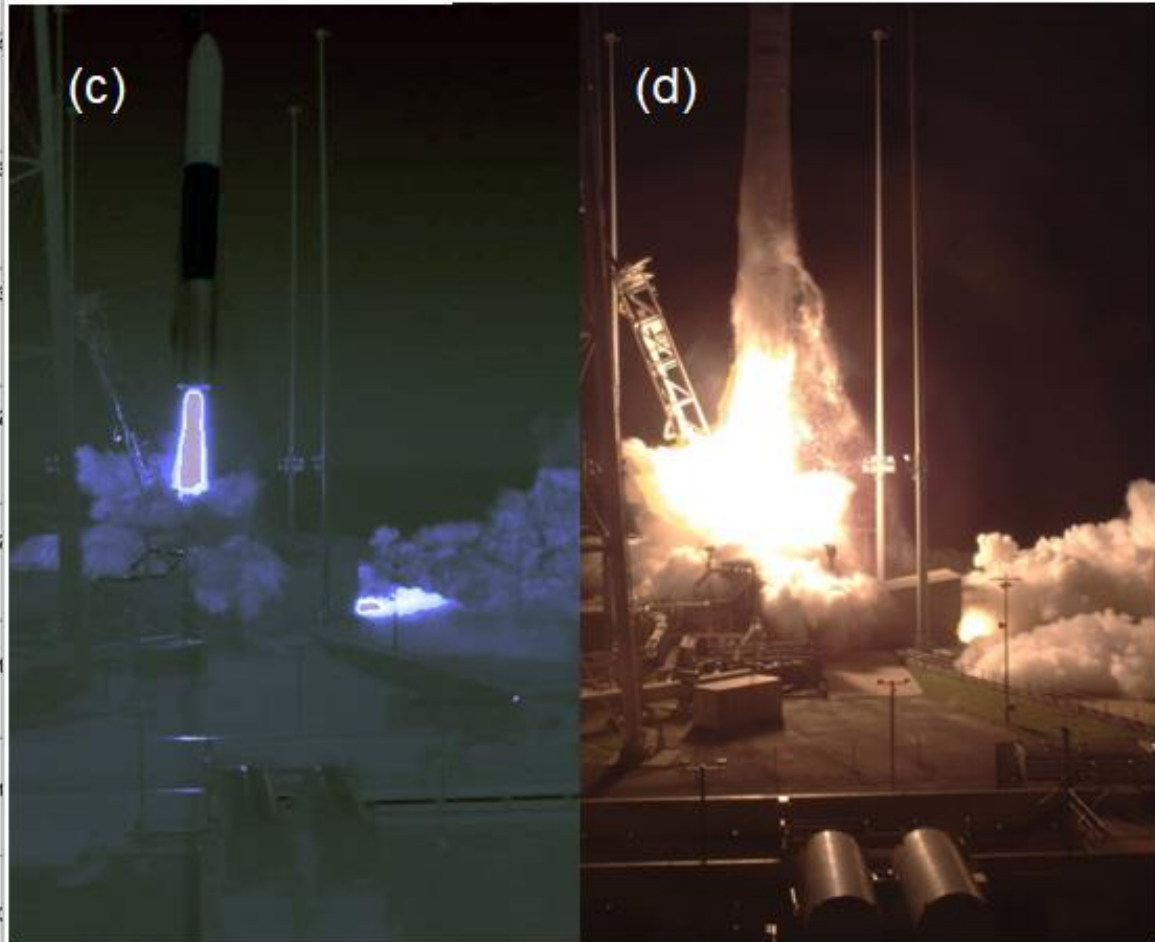
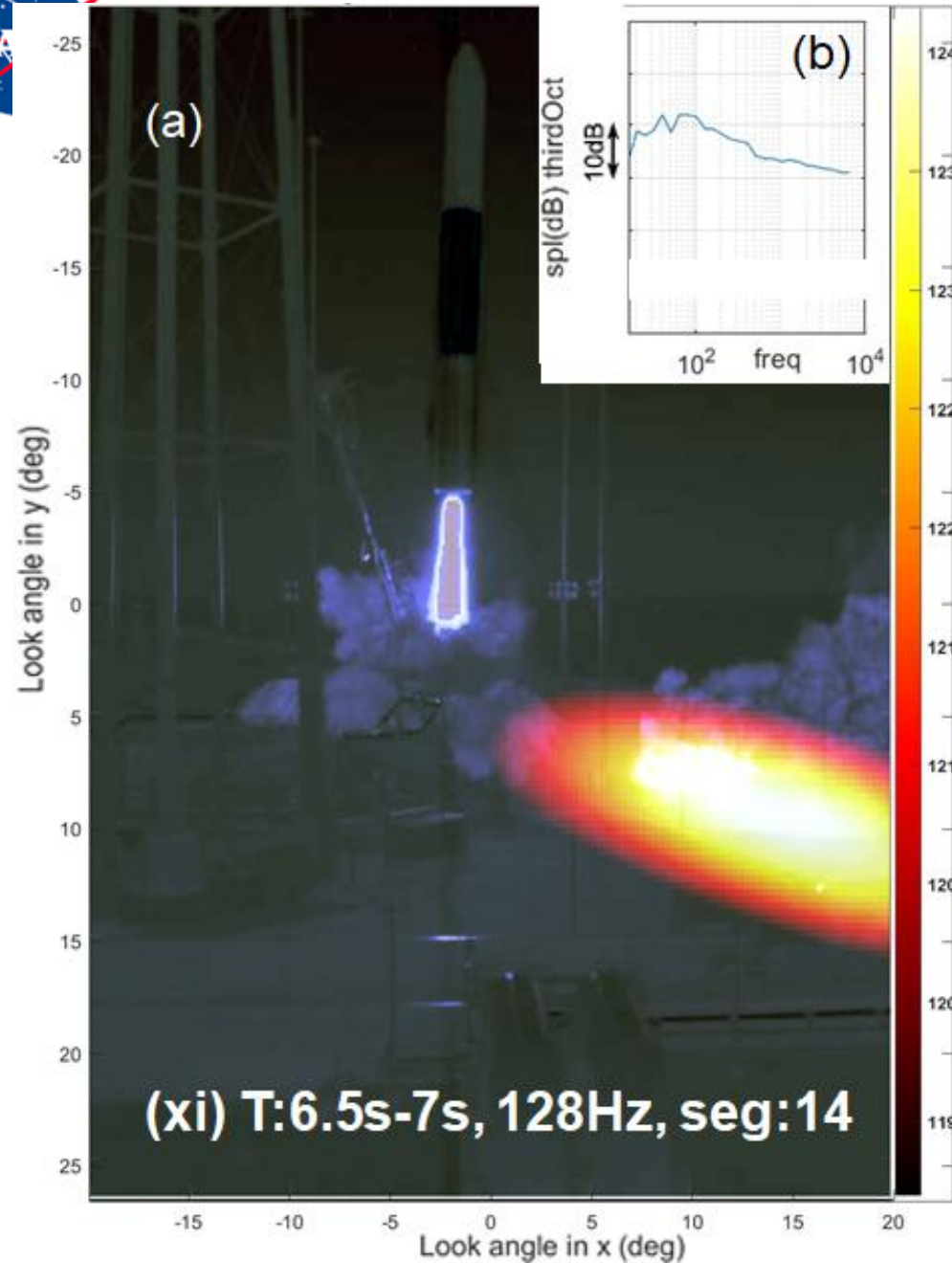
- Rainbirds are effective in cooling the spilled plume on the pad
- Decrease in the acoustic level
- The Duct exit has remained the primary source

T:6s-6.5s, 128Hz, seg:13



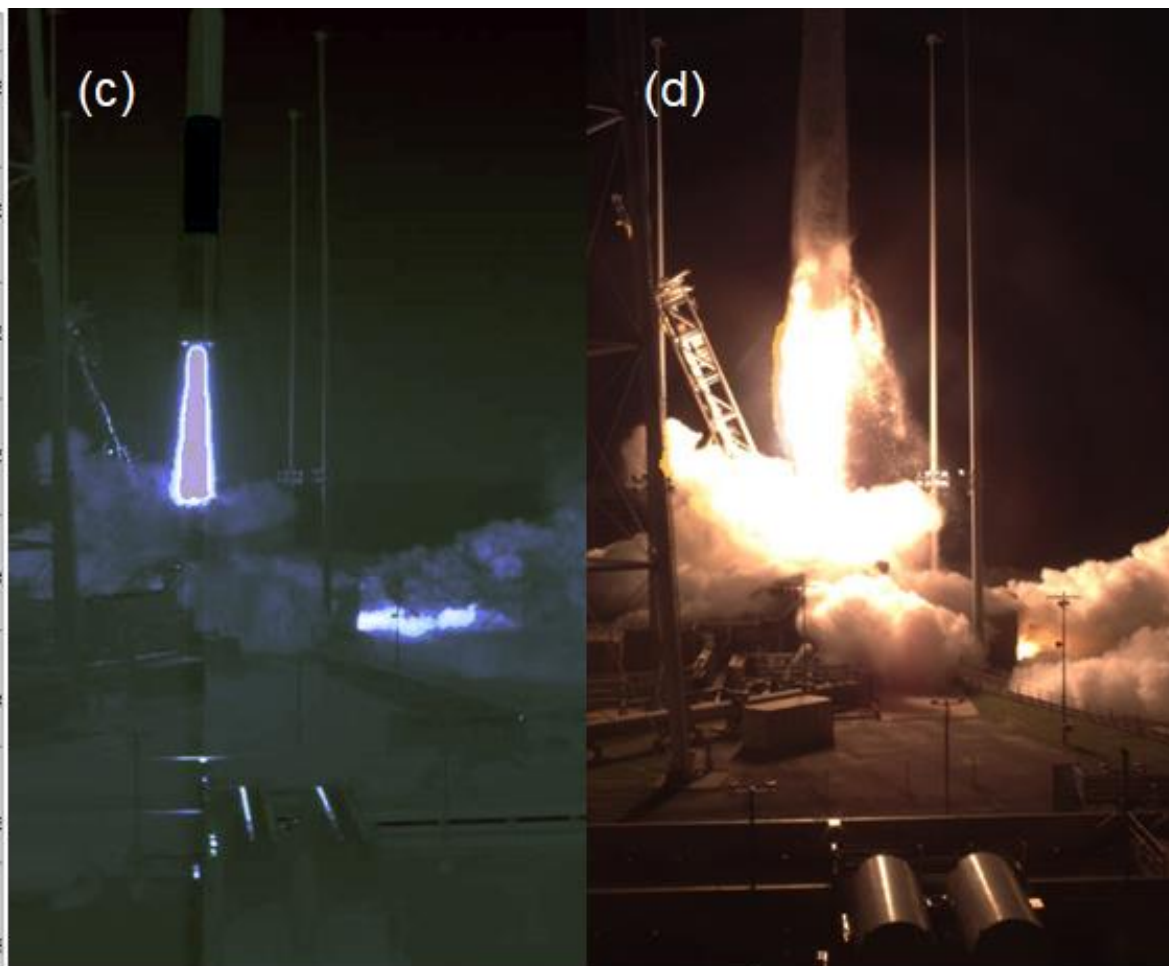
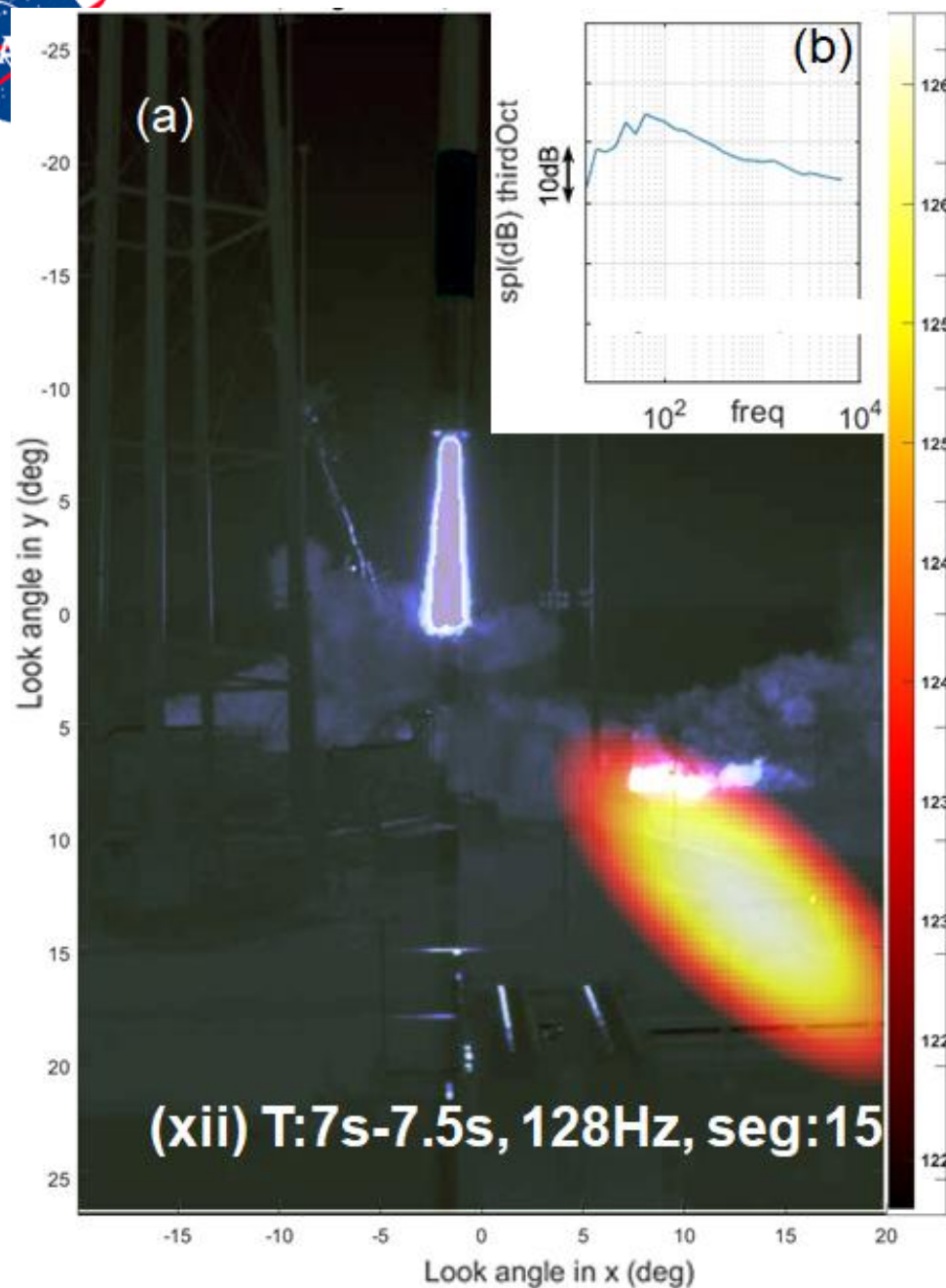
- same as before

T:6.5s-7s, 128Hz, seg:14



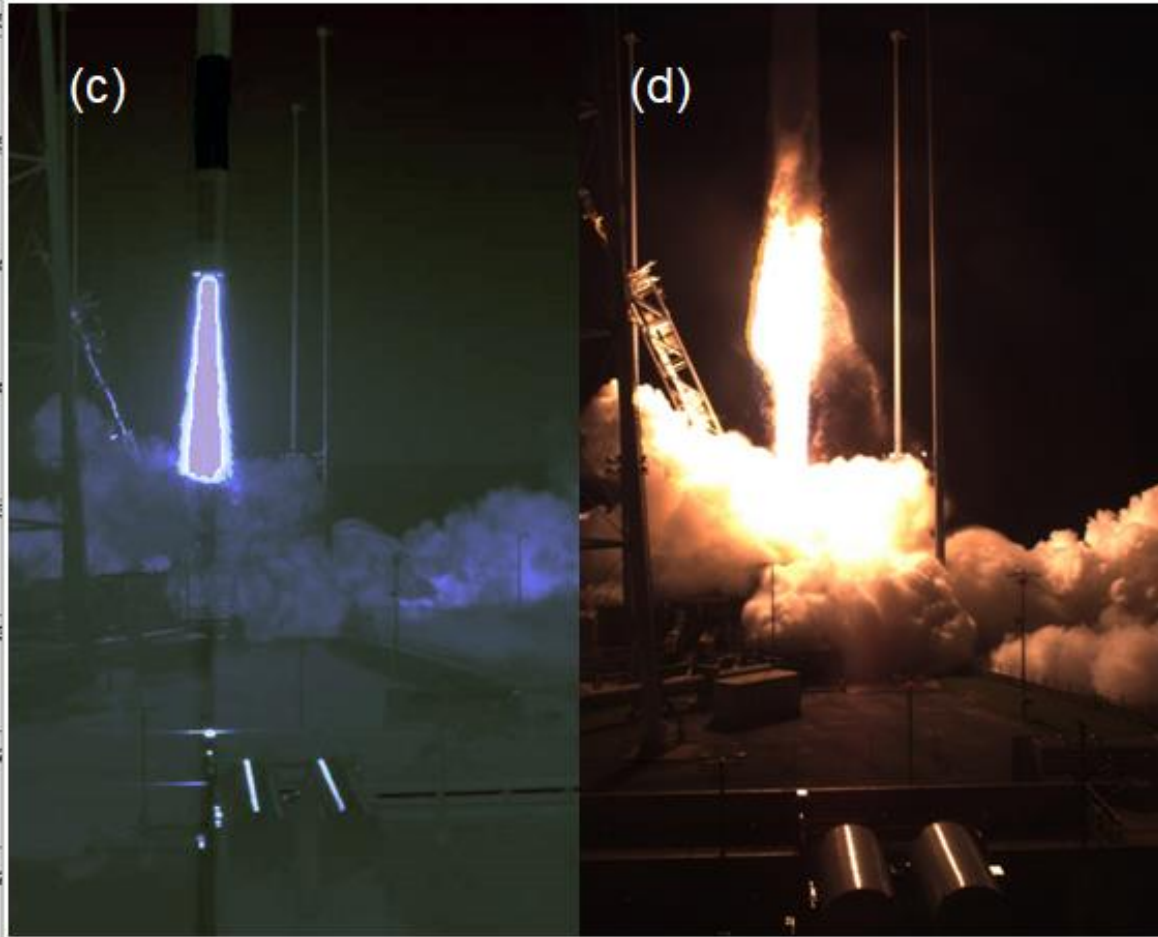
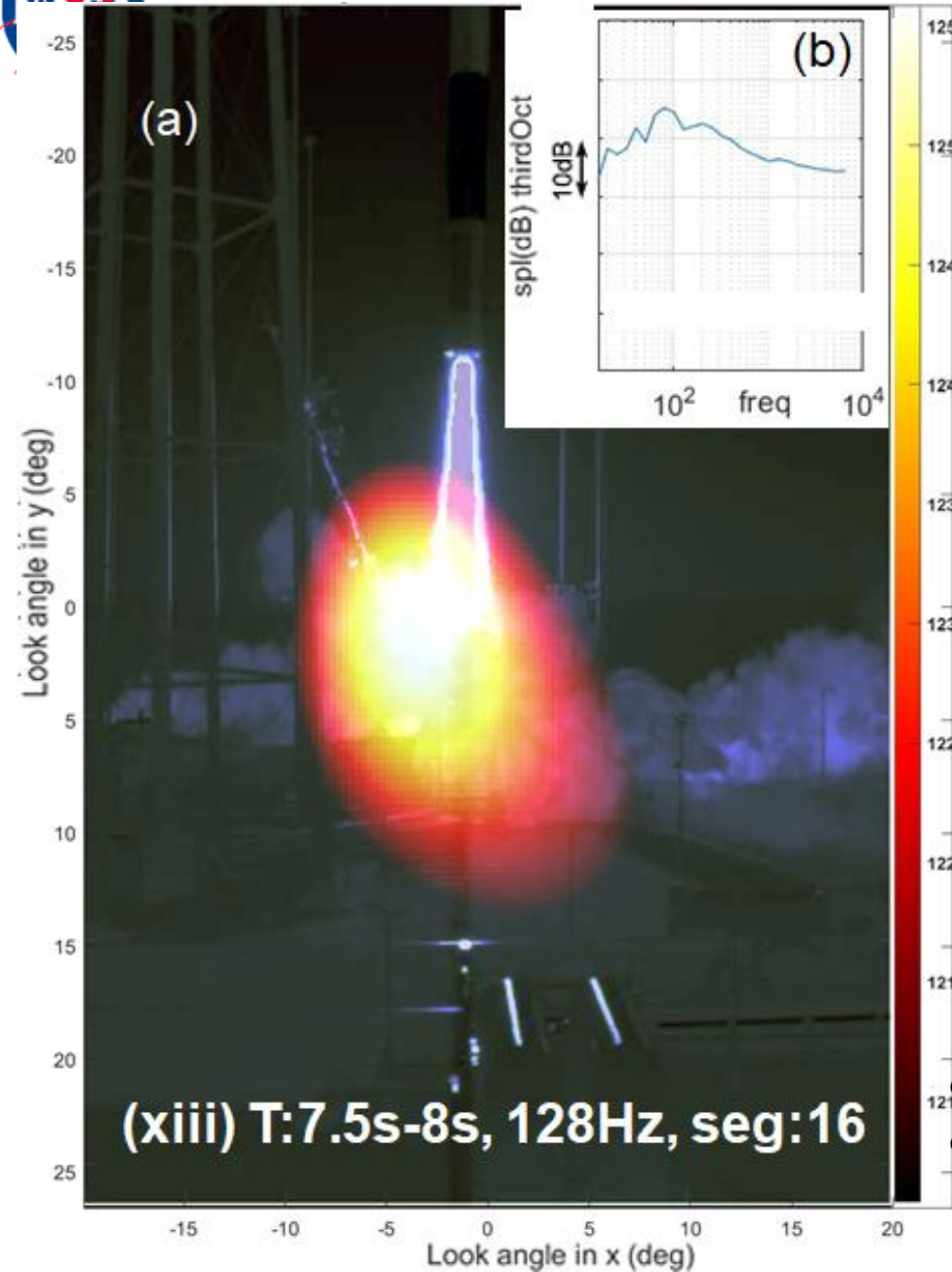
- Duct exit as noise source

T:7s-7.5s, 128Hz, seg:15



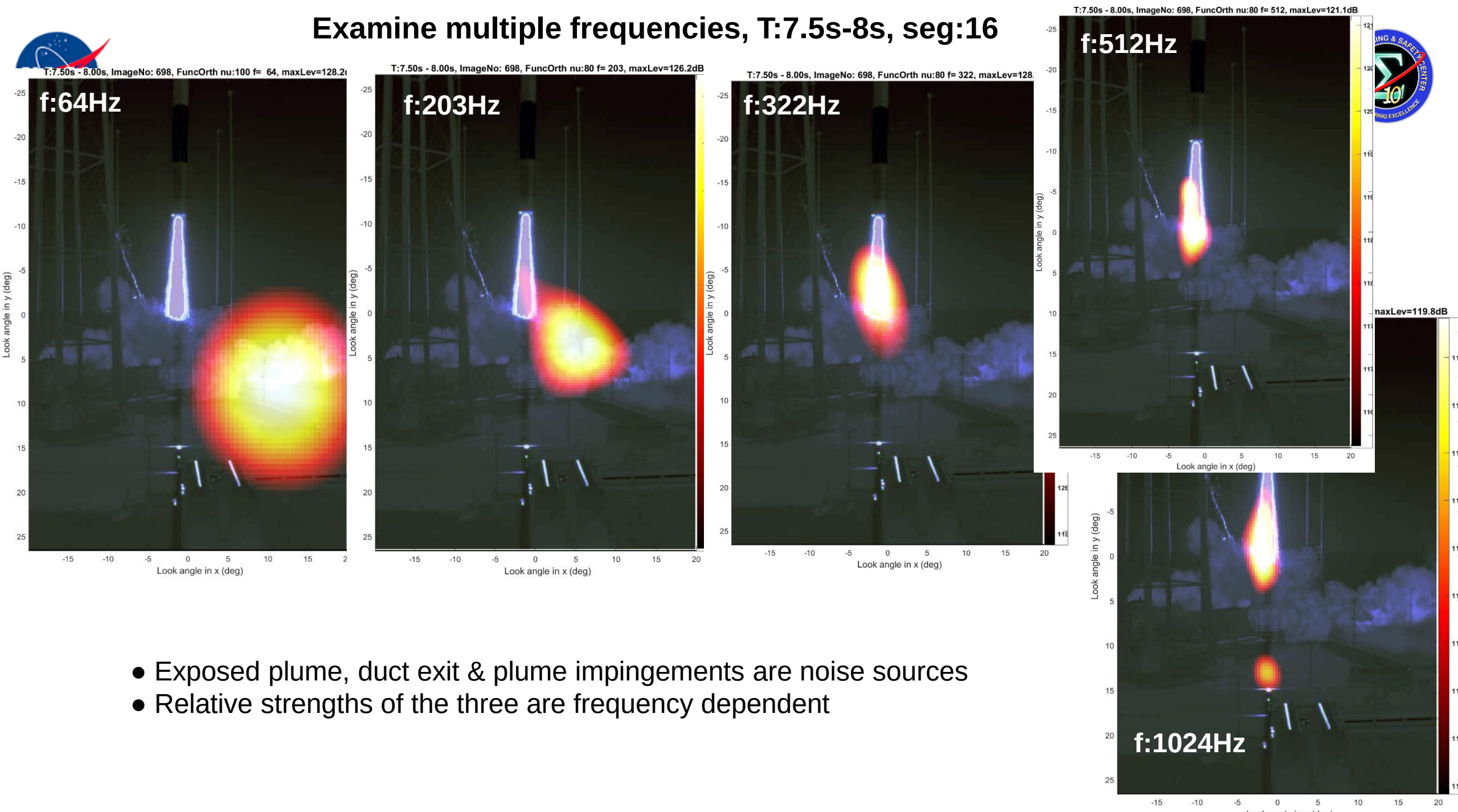
- Plume impingement on the pad
- Effective cooling by rainbirds has limited the source strength
- Reduced gas flow out of the duct exit, still primary noise source

T:7.5s-8s, 128Hz, seg:16



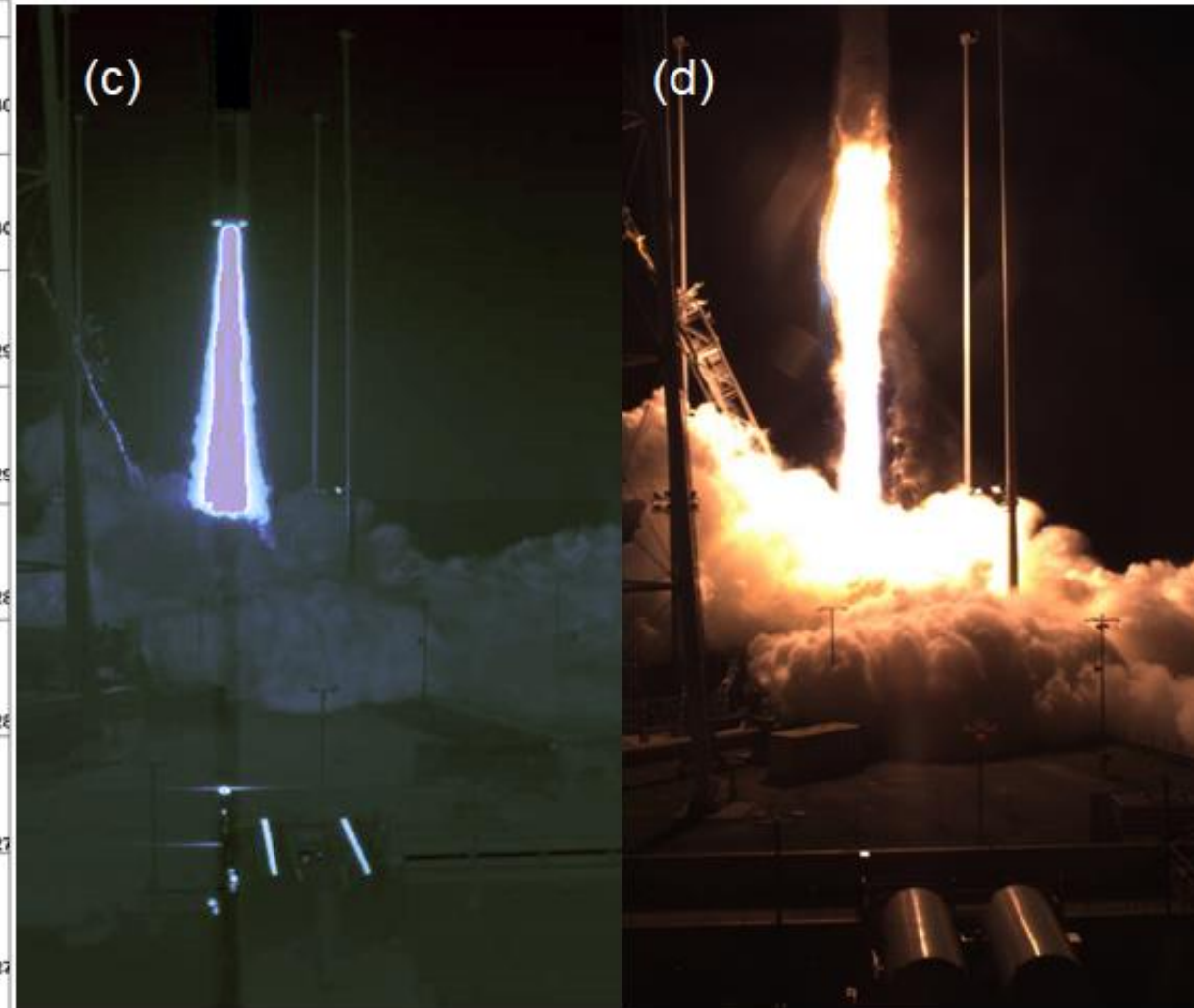
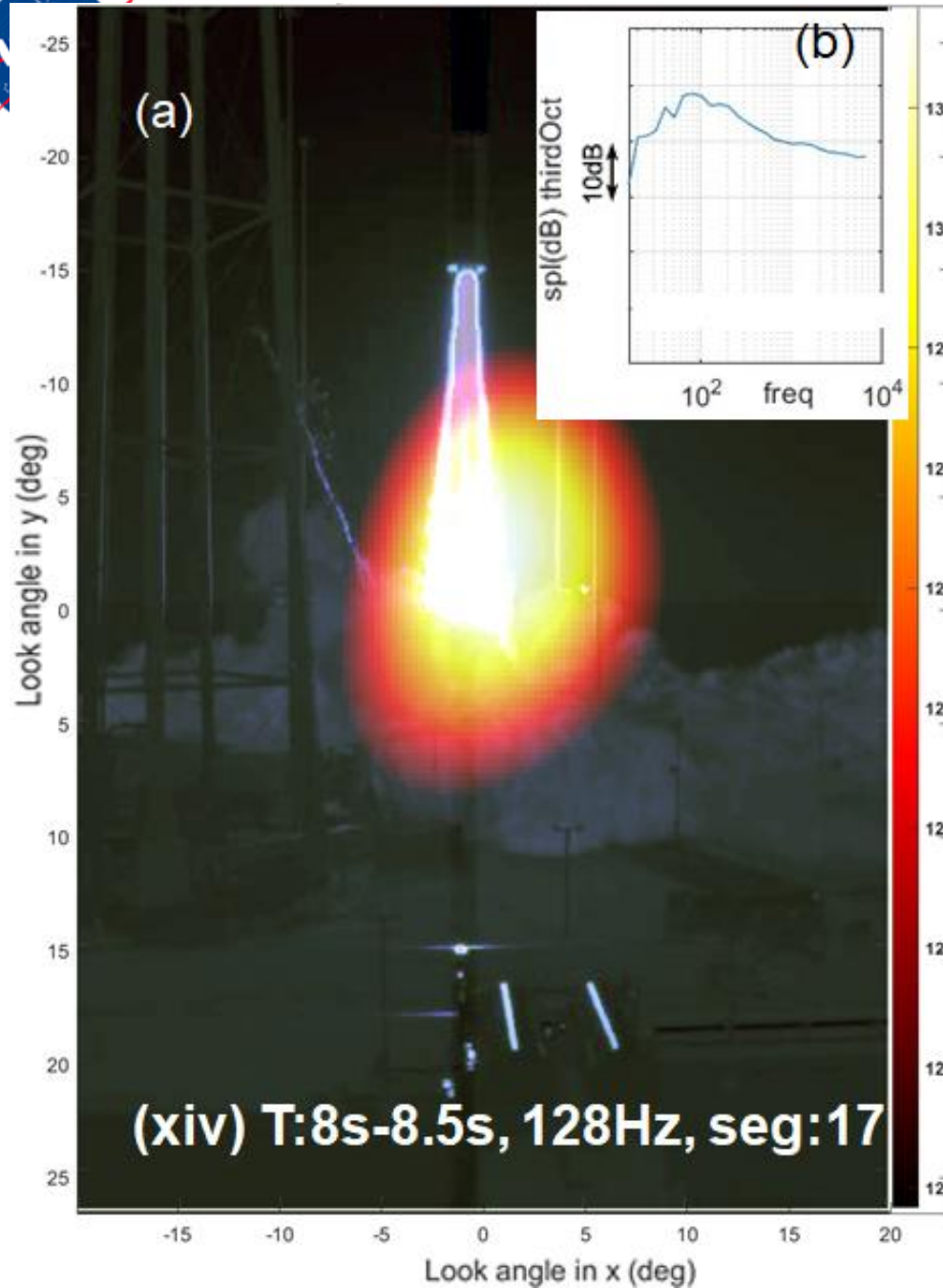
- The exposed plume and the top of the pad are stronger noise source
- Plume impingement on pad is the noise source

Examine multiple frequencies, T:7.5s-8s, seg:16



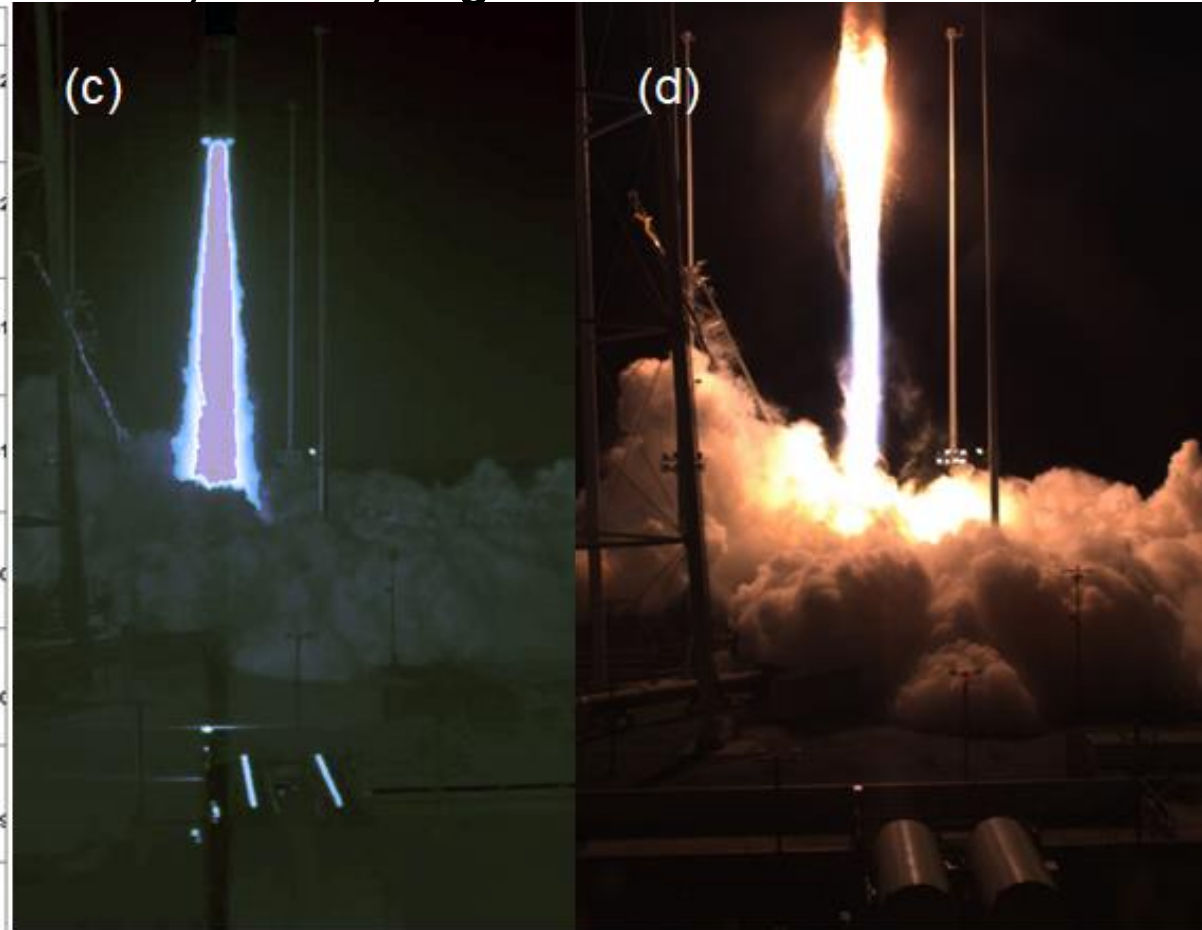
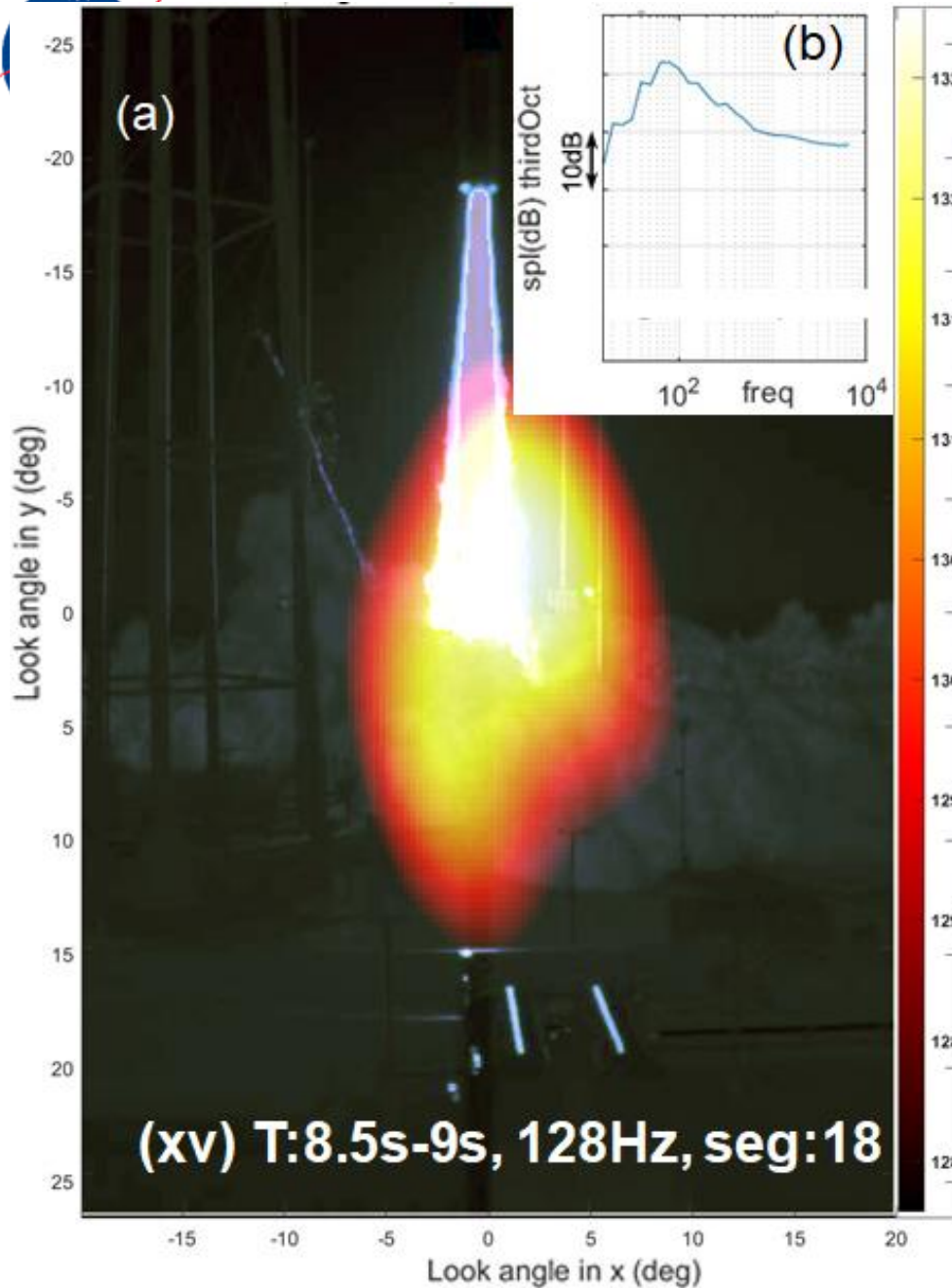
- Exposed plume, duct exit & plume impingements are noise sources
- Relative strengths of the three are frequency dependent

T:8s-8.5s, 128Hz, seg:17



- Exposed plume & impingement on pad are the noise sources
- Effective cooling weakened the source on the top of the launch pad

T:8.5s-9s, 128Hz, seg:18



- Exposed plume & impingement on pad are noise sources



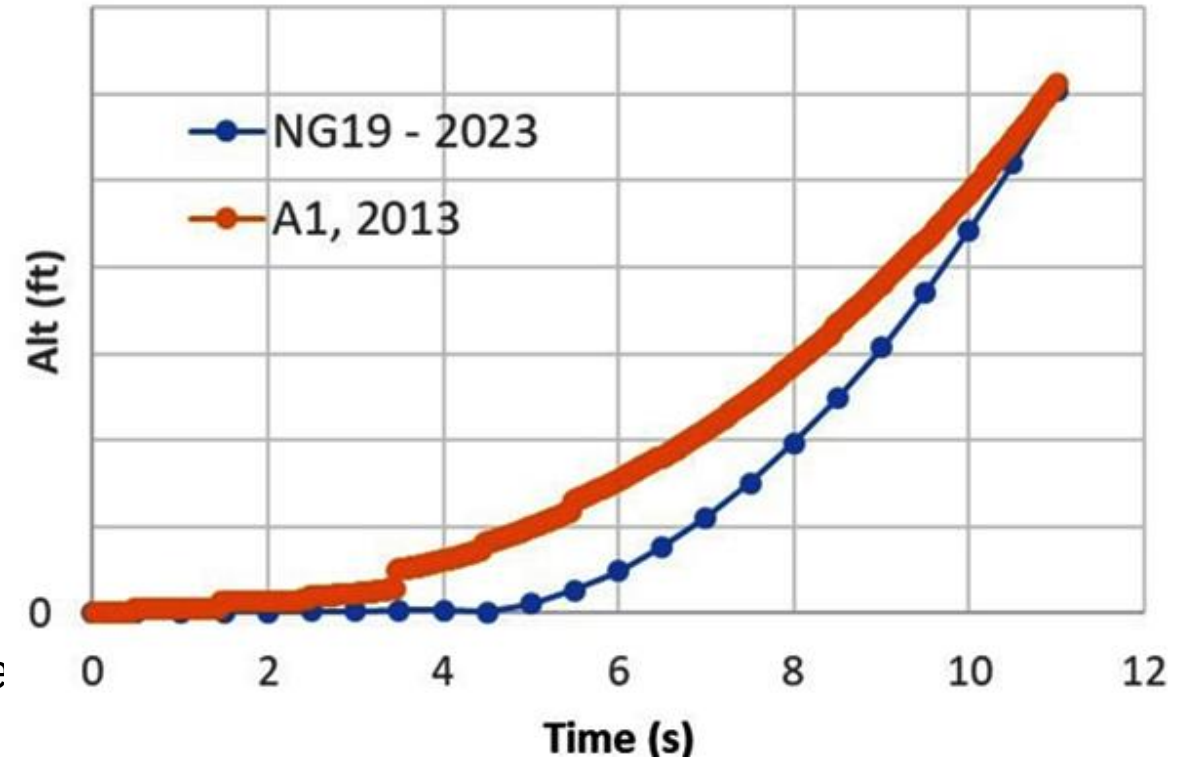
Change in noise sources between Antares A1 (2012) and NG19 (2023)



Trajectory etc.: Antares A1 (2012) vs. NG19 (2023)

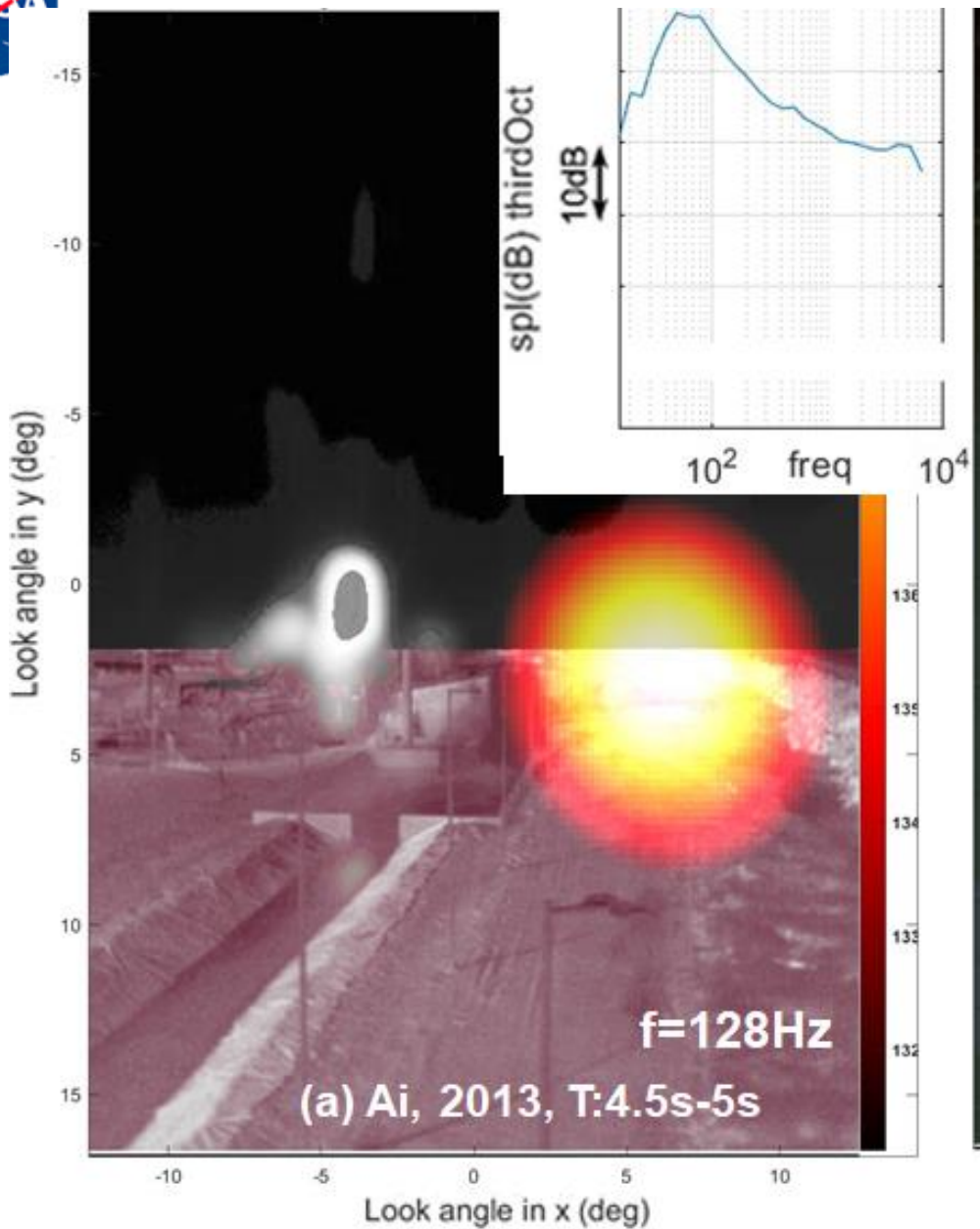


- A1 was the first flight from pad 0A
 - somewhat different trajectory (earlier elevation from pad) - **makes for a difficult study**
 - Two AJ26 engines
 - only 4 rainbirds
 - much later start of rainbirds
- NG19
 - Two RD-181 engines
 - Northrop added rainbird #5
- *Our recommendation from 2012 phased array work*
 - *Excess noise source from spilling of hot plume over the pad between T:5s-8s*
 - *Move railbird timing for increased water flow to cool the spilled plume*
- **Compare noise sources from approximately same vehicle height from pad**



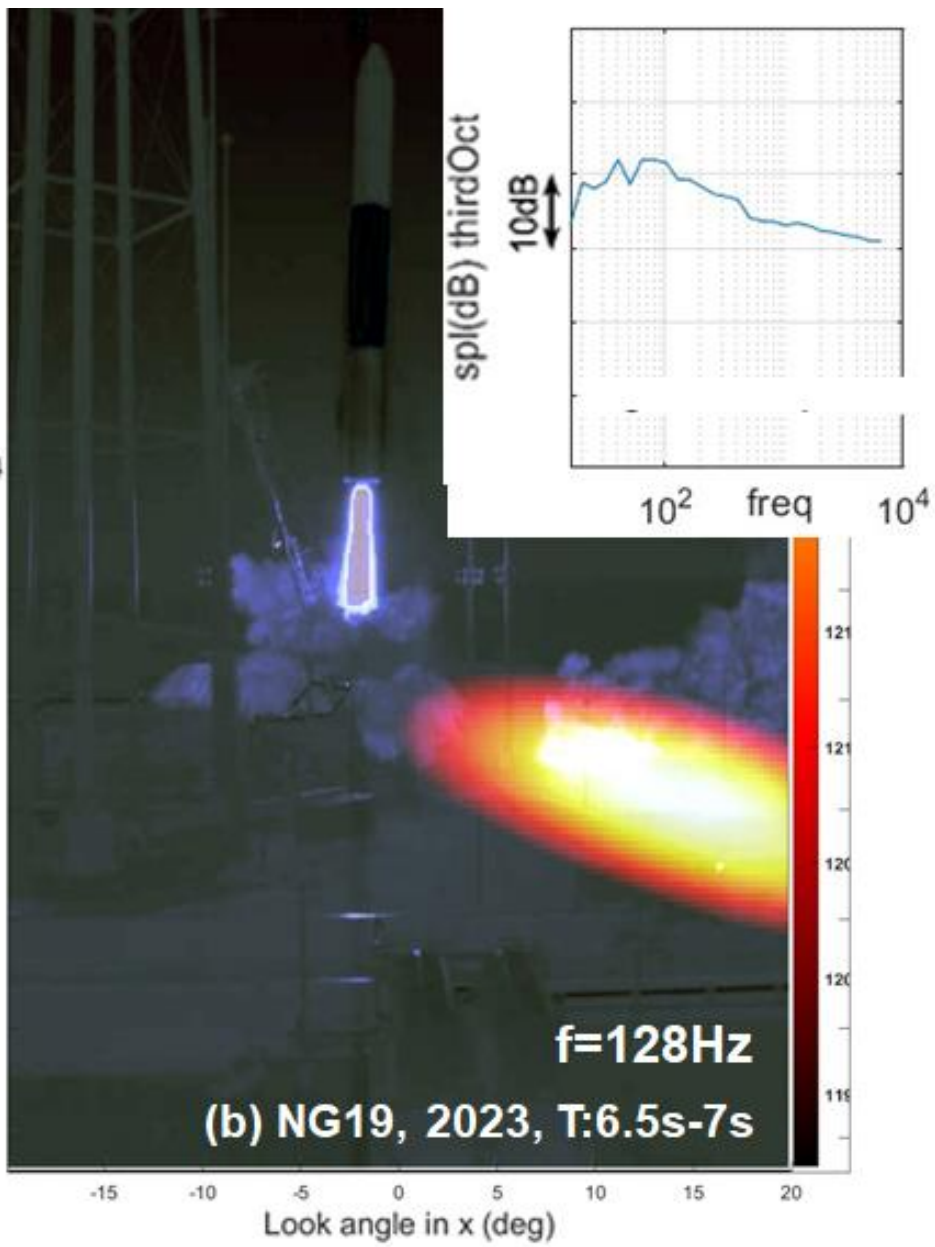


2012 A1, T:5.5s-6s



(a) Ai, 2013, T:4.5s-5s

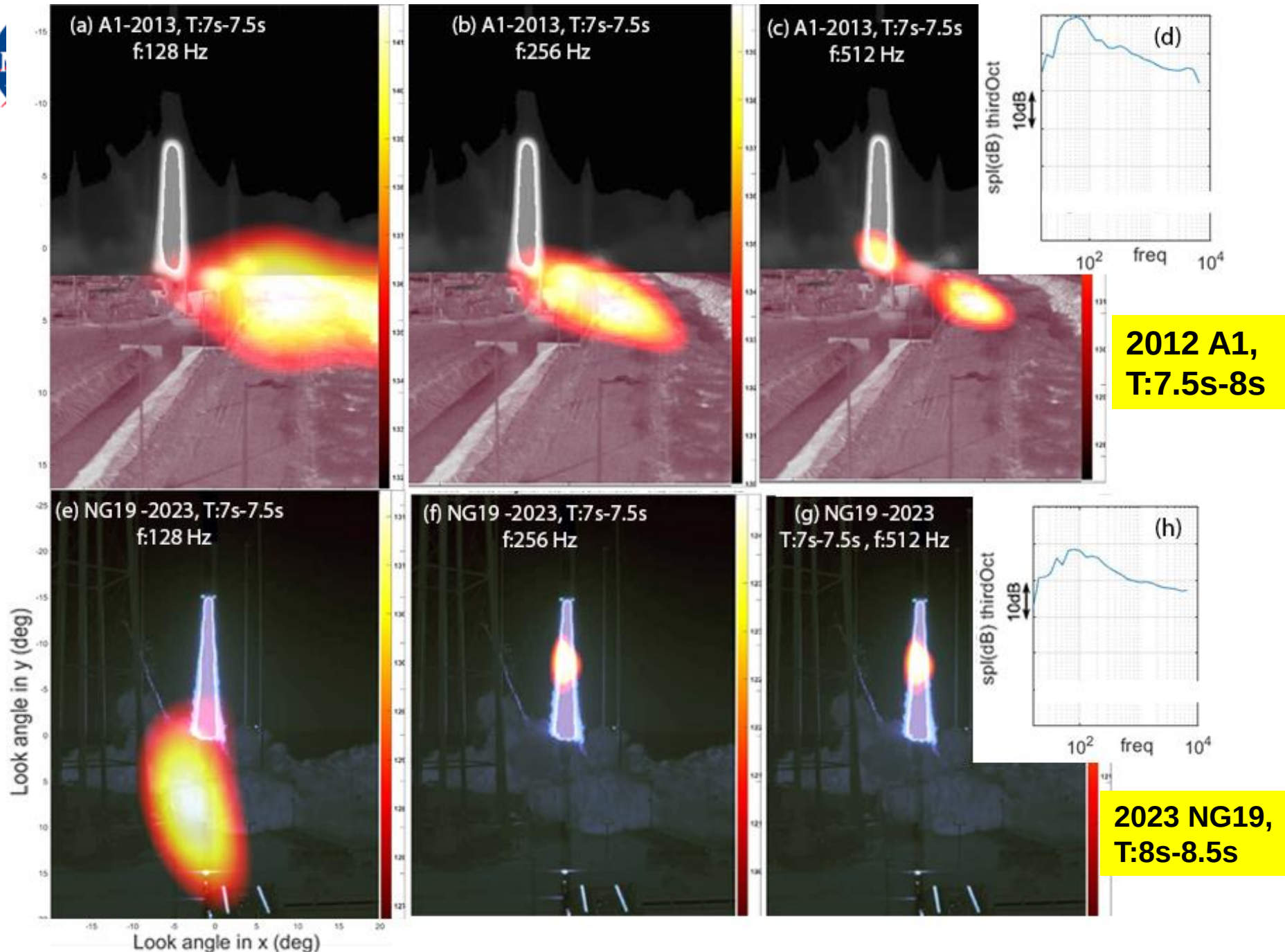
2023 NG19, T:6.5s-7s



(b) NG19, 2023, T:6.5s-7s

- Duct exit remained to be the primary noise source.
- Far stronger for A1





- Region around vehicle mount, spilled plume over the pad, duct exit all are the noise source

- Effective water injection attenuated sources on duct exit and on top of the pad
- Plume and vehicle mount are the sources

- Reduced source strength



Summary



- Good microphone data and camera images were collected
 - Survived exposures to two nights of rainstorms
- Peak vibration level $<0.4\text{grms}$
- Functional-Orthogonal math model was able to provide small spot size to 64Hz
- Noise sources varied during lift-off
- The duct exit has become the prominent noise source between T3.5s to T7.5s duration
 - Sound generated inside the duct emanates out of the duct
 - Less effective cooling of the hot gas at the bottom of the duct leads to increased noise
 - **Adding water sprays at the bottom of the duct after the deflector should help reduce acoustic level**
 - As the vehicle lifted both the exposed plume and the plume impingement regions became sources
- The five rain birds were effective in cooling the impingement regions over the pad
 - No undesirable hot streaks were found in the IR camera footage and the beamformed noise maps

Comparison between Antares A1 (2012) and NG19 (2023)

- Far less shaking of the present phased array – at least by a factor of 5
- Far more effective use of the rainbirds and the water system in 2023 compared to 2012
 - the spilled plumes on the pad were better cooled – eliminated the noise sources on the pad
 - Overall reduction of the acoustic level in the T4s to T9s duration
 - Addition of the 5th rainbird has helped with reducing the acoustics
- **The phased array is declared to reach TRL 6** – ready for use with Artemis launch
 - Some protection from high temperature blast environment is necessary

