Combustion Instability in the Project Morpheus Liquid Oxygen/Liquid Methane Main Engine

PROPULSION SYSTEMS

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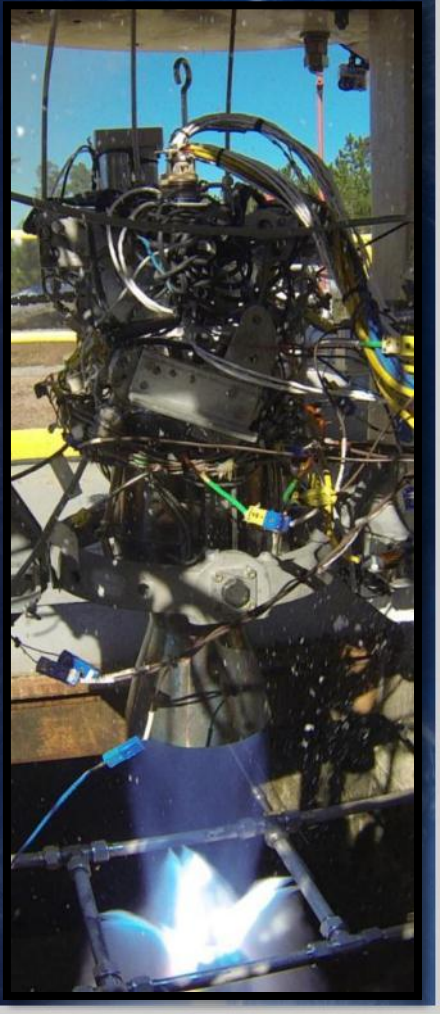
Agenda

- Executive summary
- Project Morpheus Propulsion Overview
- Morpheus Main Engine Overview
- Combustion Instability background
- Overview of Instability signatures and spectral analysis
- Overview of Instability Working Theory
- Discussion on vehicle applicability, redline



HD4-LT in test at SSC
Stennis Stand E-3

Executive Summary

- The Project Morpheus Liquid Oxygen (LOX)/Liquid Methane HD4-LT and HD5 demonstrated acoustic-coupled combustion instabilities during testing at Stennis Space Center (SSC).
- The instabilities have two causes and signatures
  - Overchilled CH4 with high CH4 injection velocity causes a high-amplitude, 1T, 1R, 1T1R (and higher order R harmonics). This instability usually manifests during low-throttle startup conditions and can propagate through mainstage throttle-up. It has never been shown to start after mainstage throtte-up.
  - Warm LOX causes transient, self-limiting instabilities that appear as 1T-1L or 1R (with harmonics). These instabilities typically happen at ignition (or shortly thereafter) and dampen out once the LOX injector chills in.
- Vehicle-HD4 tests at JSC typically only demonstrate low-amplitude transient tones near ignition, which are probably due to "warm" LOX type instabilities which always dampen
- The explanation for the lack of vehicle-test instabilities are theories in work:
  - The vehicle tests demonstrate a faster fuel injector pressurization fill compared to SSC, and the vehicle tests also have a higher frequency, more quickly dampened start water hammer.
- To protect for the possibility of instability occurrence on the Morpheus vehicle, a new high-speed redline cutoff system has been designed, tested, and installed.

Project Morpheus Overview

- Morpheus is an autonomous, reusable rocket powered terrestrial Vertical Take-off /Vertical Landing (VTVL) vehicle for testing integrated spacecraft and planetary lander technologies
- Autonomous Landing and Hazard Avoidance Technology (ALHAT) Project has advanced the technologies for autonomous precision landing and hazard avoidance.
- In FY13, the Morpheus vehicle will provide a flying platform to test the ALHAT system for the first time

Morpheus Vehicle – Tether Test TT19, July 17, 2012

Project Morpheus Main Engine Overview

- Morpheus Propulsion uses integrated Main Engine / Reaction Control System (RCS) with LOX/methane propellants
  - – Historical First: demonstrated integrated LOX/Methane propulsion, 5/1/2013
- The JSC Propulsion & Power Division developed 3 inexpensive development prototype LOX/Methane engines for Project Morpheus from 2010-2012
  - HD3,4,5: 3800, 4200, 5200 lbf max thrust; all designed and built at JSC

HD3: Yr2011, 27 tests (incl. 8 vehicle tests), 363 sec total run time, burnthrough-damaged

HD4: Yr2011-2012, 20 vehicle tests, 923 sec total run time, damaged in Morpheus crash at KSC

Yr2012-2013, rebuilt as HD4-LT (large throat), 36 starts (incl. 12 vehicle tests), 285 sec total run time, current Morpheus engine

HD5: Yr2012-2013 , 67 tests at SSC, >160 sec total run time. Instability, thermal issues.

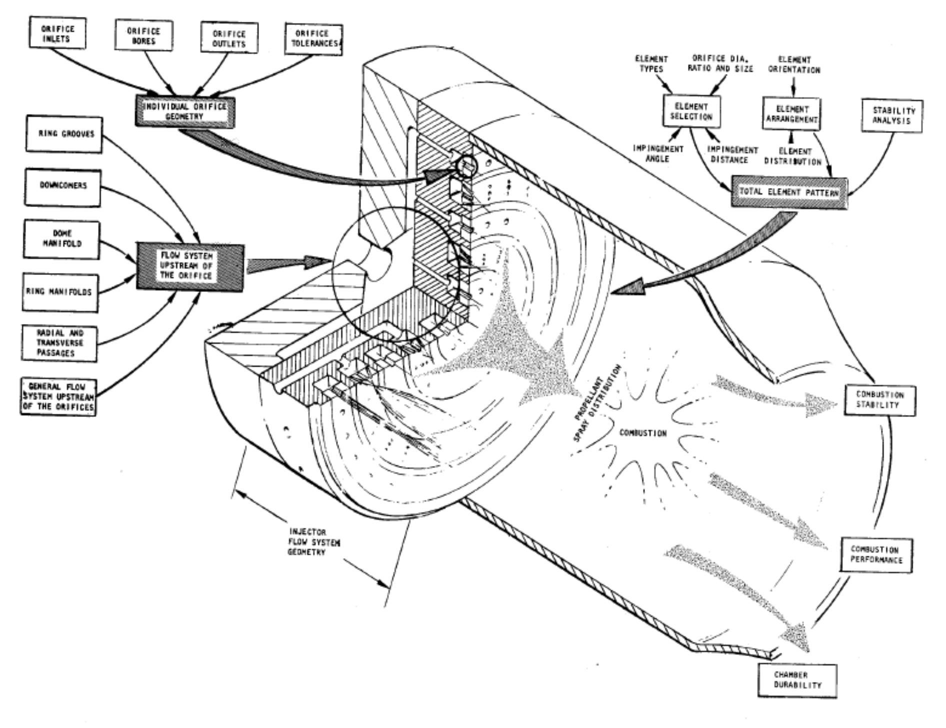
Morpheus HD4 Main Engine Design

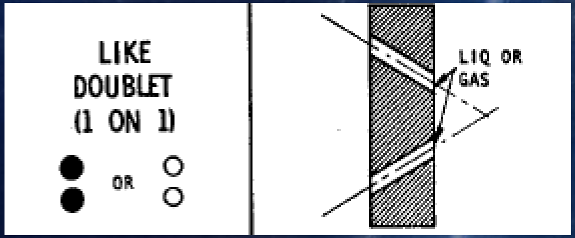
- Requirements: (Demonstrated on Morpheus)
  - 4,200 lbf thrust max (4,350 lbf)
  - 4:1 throttle range (5:1 w/minimal chug on vehicle)
  - 215 sec ISP avg (sea-level) (221 sec max, 204 sec mid thrust flight avg)
  - 210+ sec duration per flight (126 sec, steady state thermal)
- Impinging element injector
  - Like doublets, arranged in pairs and triplets
- Methane film cooling
- Adjustable acoustic cavities allow engine to be tuned between firings

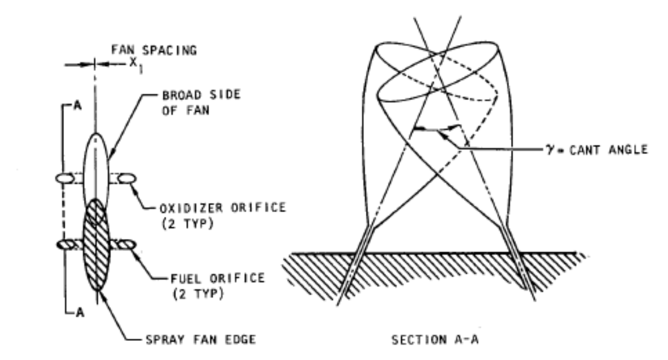
HD4-LT installed
in SSC stand E-3

Like Doublet Injector Element Design

- Like-on-Like (LOL) double design chosen for improved mixing and stability compared to unlike doublet design (e.g., RS-18 3500 lbf Apollo lunar module ascent engine)





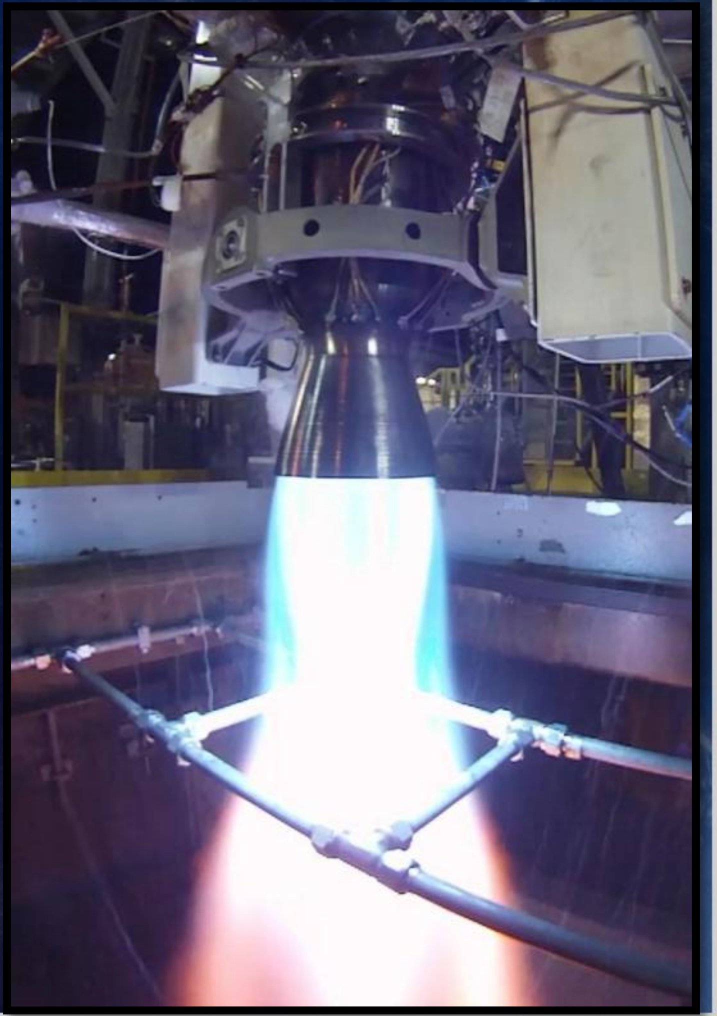


NASA-SP-8089 (1976)

HD4-LT SSC Test #19

HD4/HD5 Combustion Instability Problems at SSC

- HD3 showed no instability problems, until a 1T-related burn-through during a vehicle test (triggered at ignition)
  - Suspect cold-CH4 issue
- HD4 was tested 20 times on Morpheus vehicle with no detected instability problems in 2012
  - Any acoustic tones were low-amplitude and auto-damped after ignition
- HD5 testing at SSC in 2012-2013 revealed significant combustion instability issues (1T, 1R, 1T1R, etc.)
- HD4-LT rebuilt following KSC crash, and SSC revealed significant combustion instability problems in 2012-2013



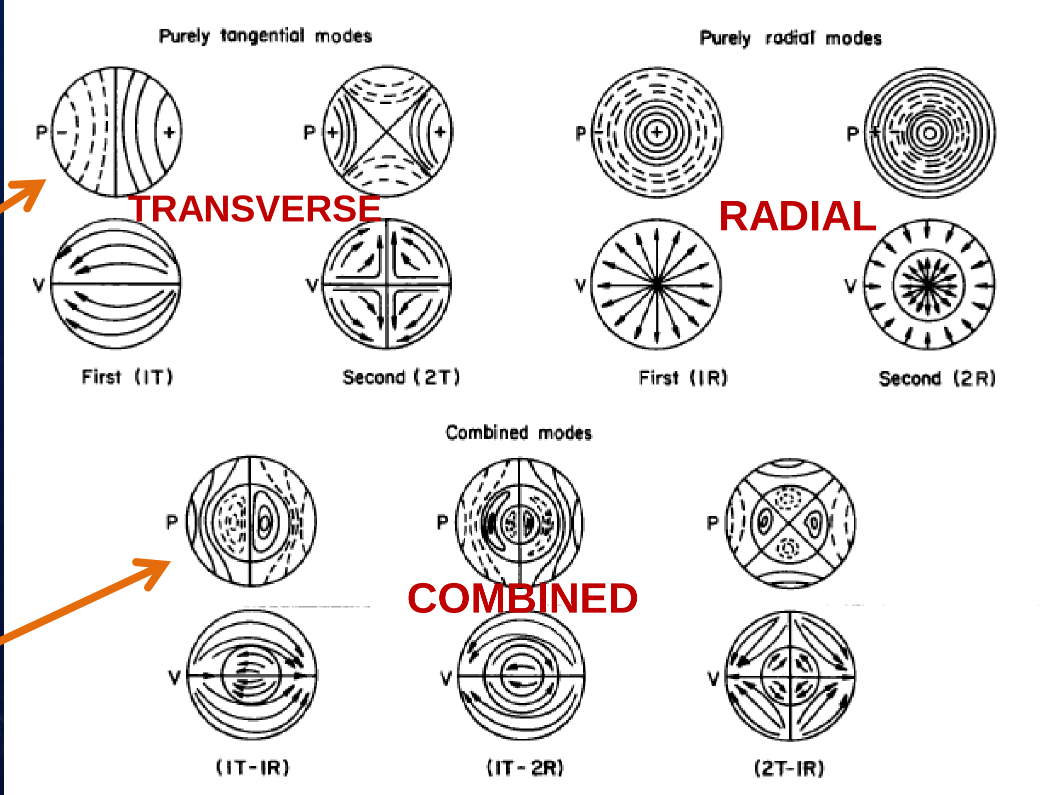
HD5 installed in
SSC stand E-3

Predicted Combustion Chamber Acoustic Modes

- Chamber L-modes behave similar to organ-pipe (coke-bottle) tone
- Chamber T, R modes act on the chamber diameter
- Predictions for HD4:
  - 1L ~ 1,600 Hz
  - 2L ~ 3,200 Hz
  - 1T ~ 3,150 Hz
  - 2T ~ 5,200 Hz
  - 1R ~ 6,550 Hz
  - 2R ~ 12,000 Hz
  - 1T1R ~ 9,100 Hz
  - 1T2R ~ 15,000 Hz

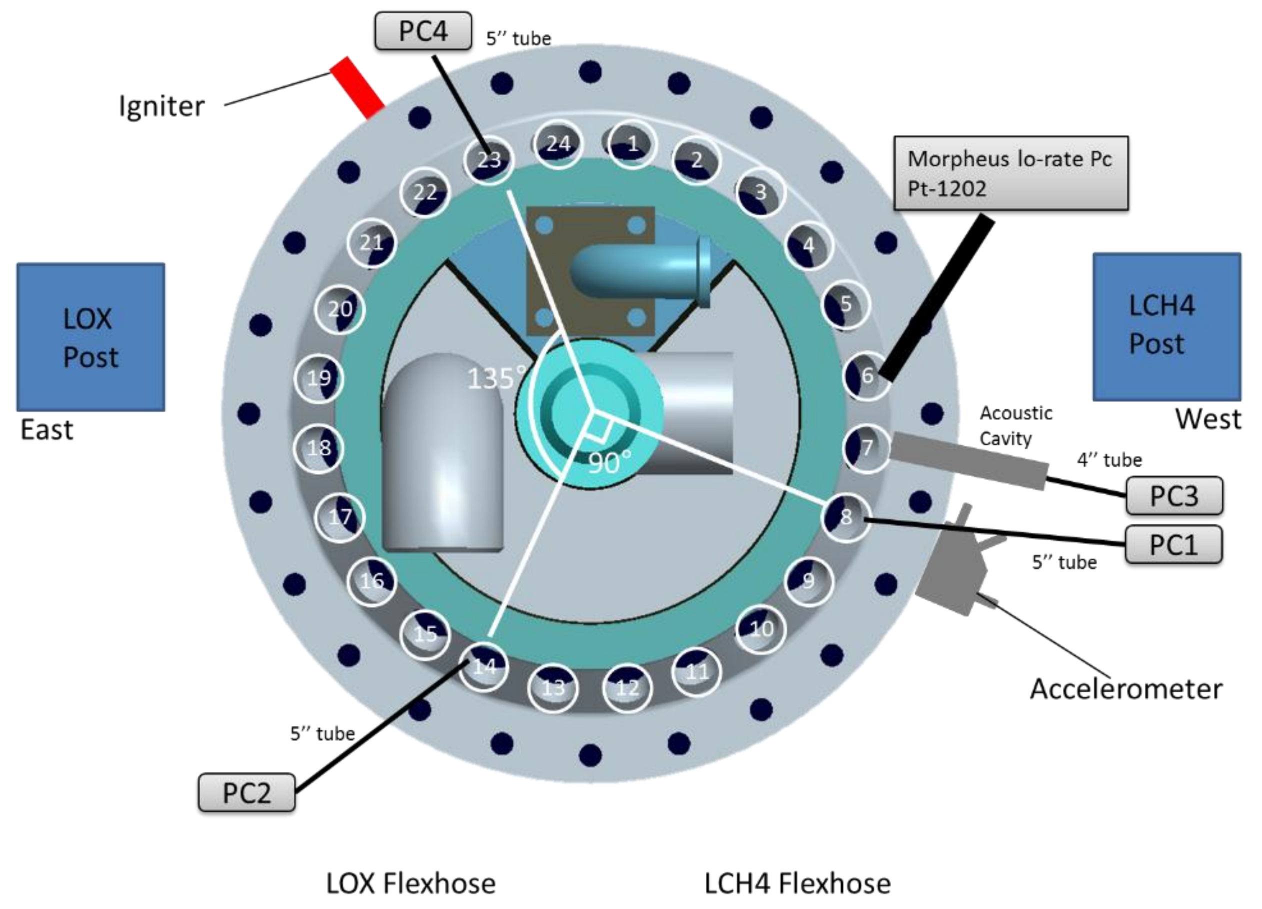
$f = C n / 2L$

$f = C E_n / D$



NASA-SP-194 (1972)

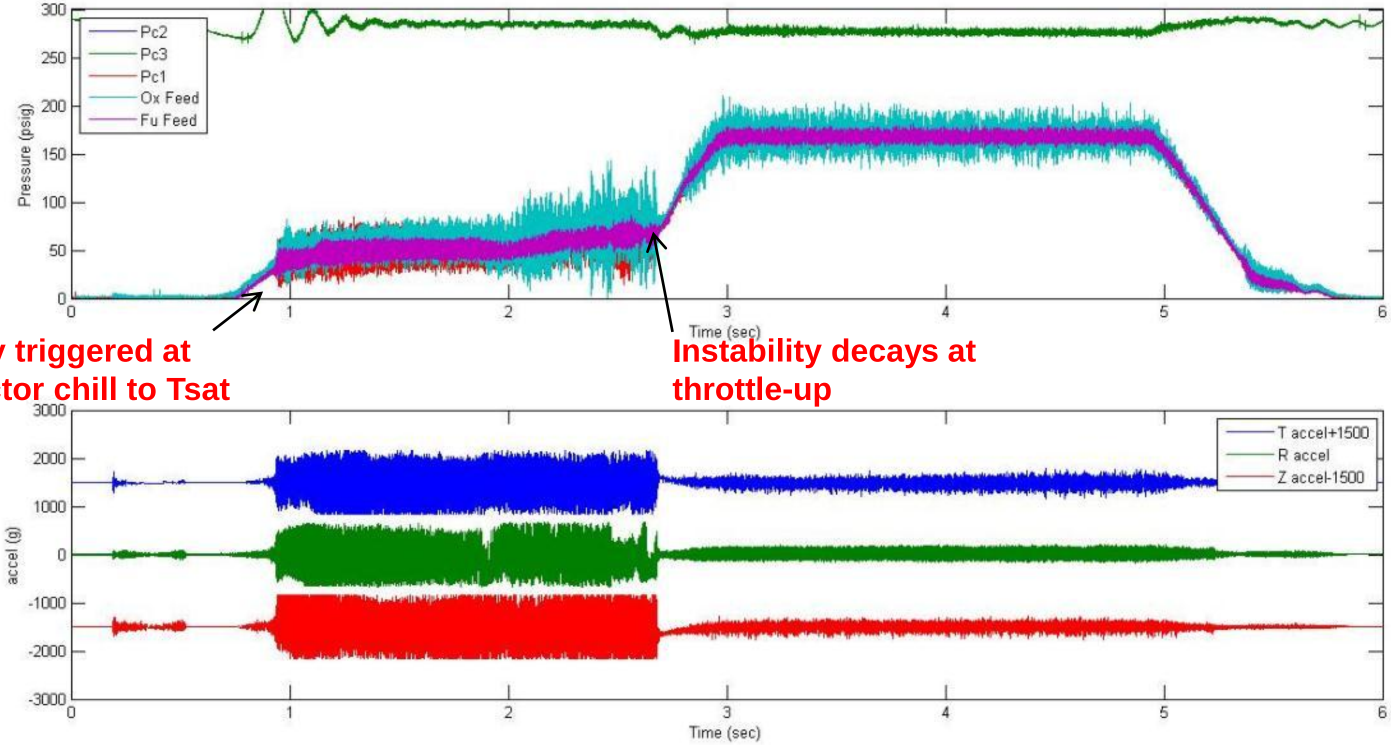
High-Speed Instrumentation Layout



Data rate typically 25 kHz for all high-speed channels, some tests recorded at ~100 kHz

CH4-triggered Instability Example (High-speed Pc and Accel Data)

HD4-LT SSC Test 14 (12/11/2012)

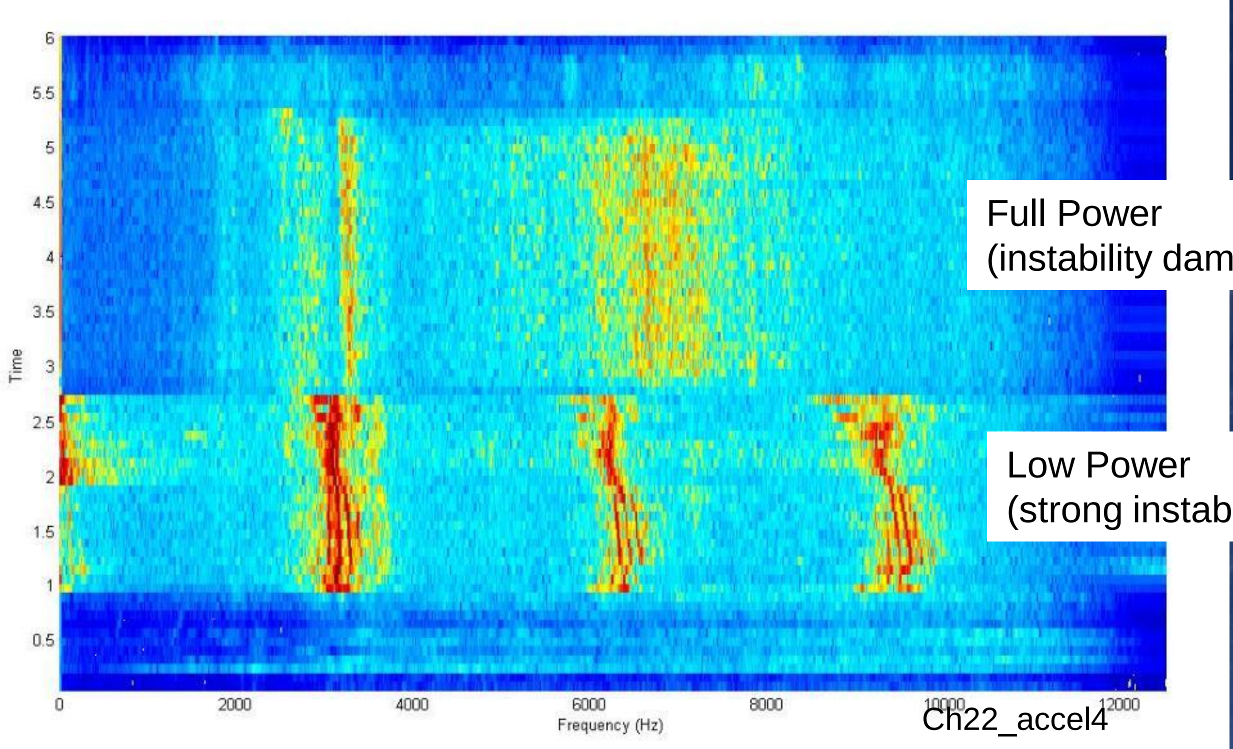


Instability triggered at CH4 injector chill to Tsat

Instability decays at throttle-up

CH4-triggered Instability Example (Accelerometer data)

HD4-LT SSC Test 14 (12/11/2012)



Ch22_accel4

Full Power
(instability damped)

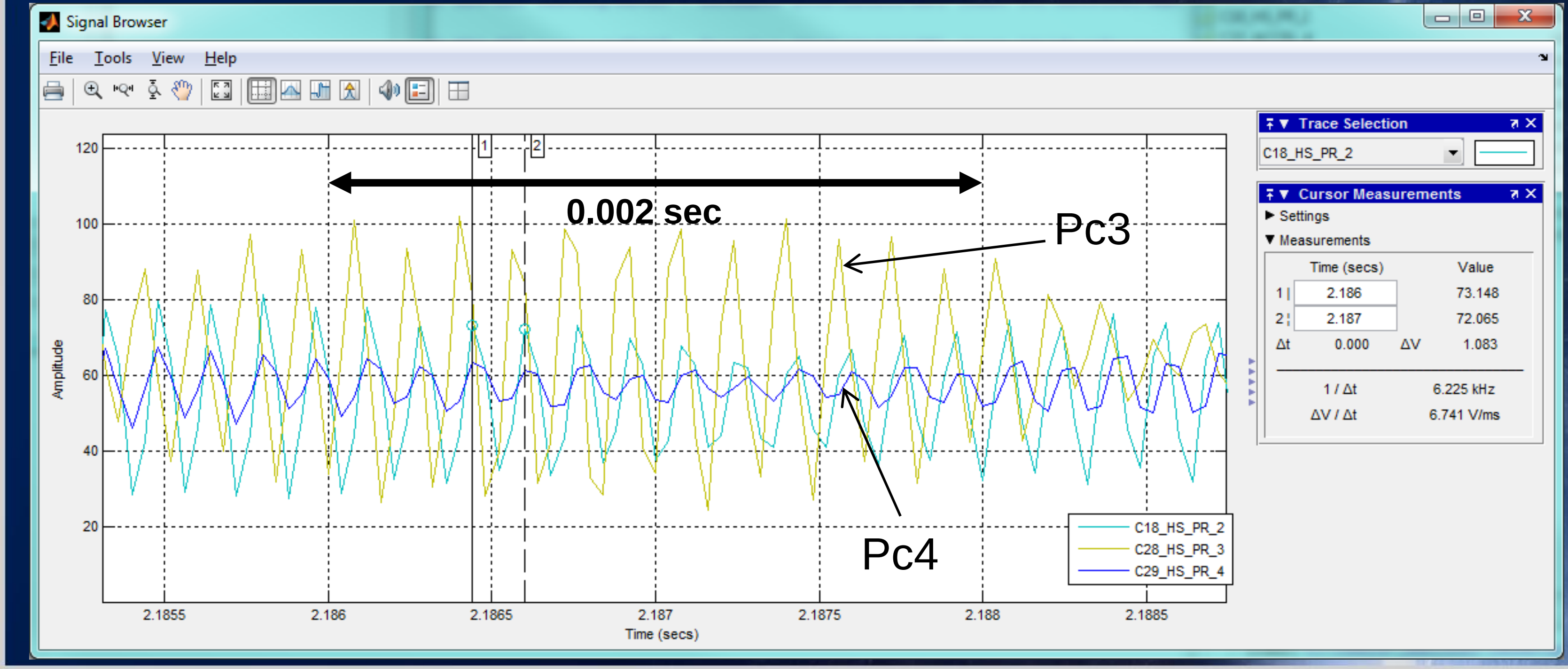
PSD units
arbitrary

Low Power
(strong instability)

- Characteristic 3K/6K/9K pattern seen on both HD4-LT and HD5 instabilities: 3125Hz, 6250 Hz, 9400Hz
- Believed to be 1T, 1R, and 1T1R

HD4-LT SSC Test 14 (12/11/2012)

- Pc 2,3,4 at 25 kHz sampling
- Pc2 and Pc4 are mostly in phase at 6225 Hz
  - There is some minor transient variable phasing (possibly due to signal noise interference)
  - Pc3 slightly out of phase, but Pc3 is on the back of a 5-6” long acoustic cavity
  - Pc3 also has a large amplitude noise at ~6000 Hz
- Interpret 6225 Hz as 1R modulated to 2x 1T frequency



Trace Selection: C18_HS_PR_2

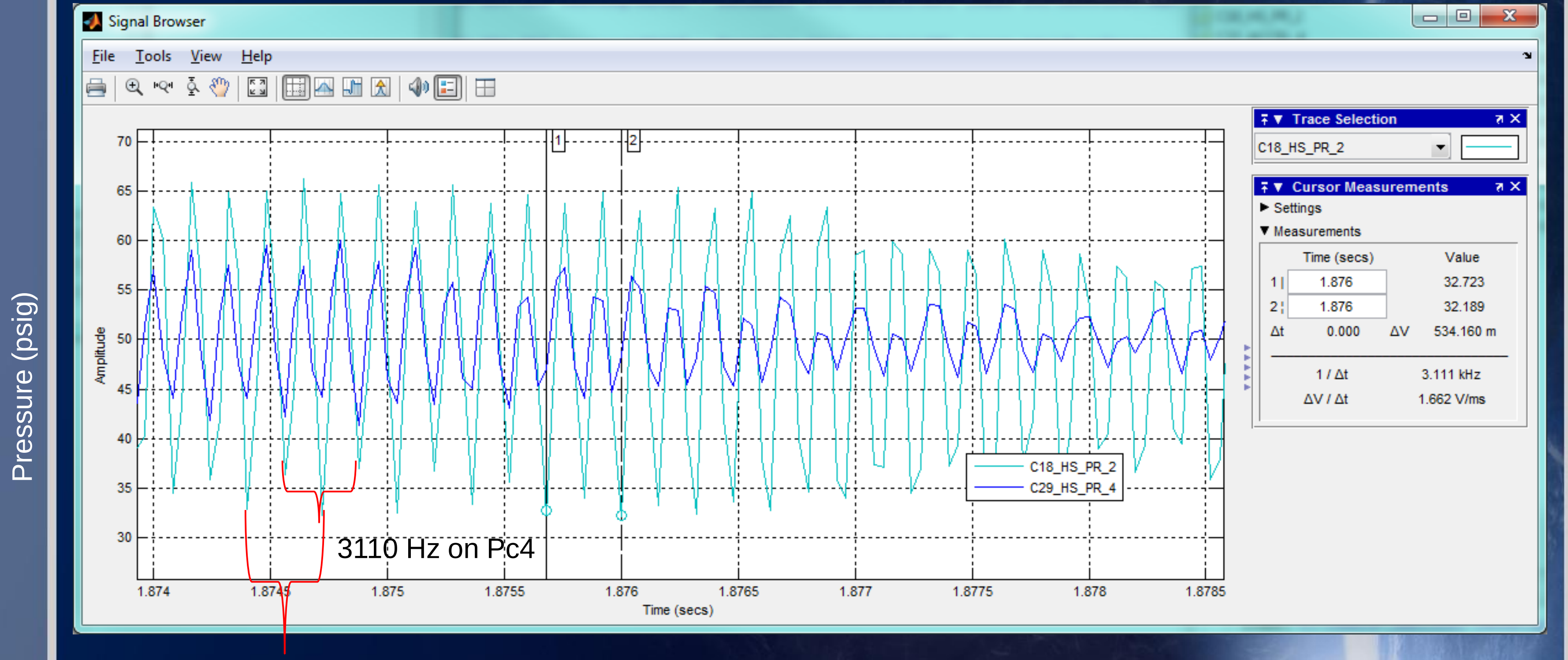
	Time (secs)		Value
1	2.186		73.148
2	2.187		72.065
Δt	0.000	ΔV	1.083

1 / Δt 6.225 kHz

ΔV / Δt 6.741 V/ms

HD4LT SSC Test 14 (12/11/2012)

- PC2 and Pc4 are 180 deg out of phase at 3110 Hz
  - Sensors mounted 135 deg apart
- Interpret 3110 Hz as 1T mode



Trace Selection: C18_HS_PR_2

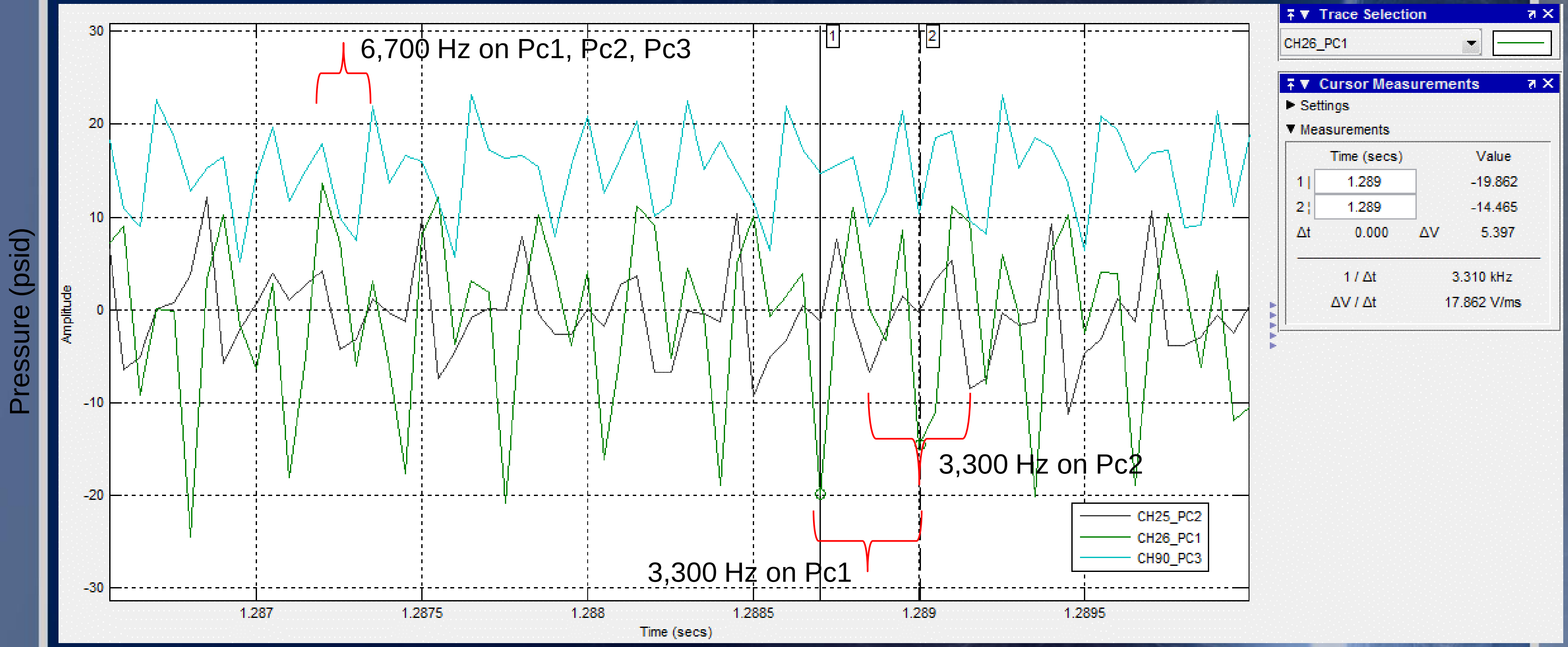
	Time (secs)	Value
1	1.876	32.723
2	1.876	32.189
Δt	0.000	ΔV 534.160 m
1 / Δt		3.111 kHz
ΔV / Δt		1.662 V/ms

3110 Hz on Pc4

3110 Hz on Pc2

f = C En / D

GTAL2



6,700 Hz on Pc1, Pc2, Pc3

3,300 Hz on Pc2

3,300 Hz on Pc1

Trace Selection: CH26_PC1

Cursor Measurements

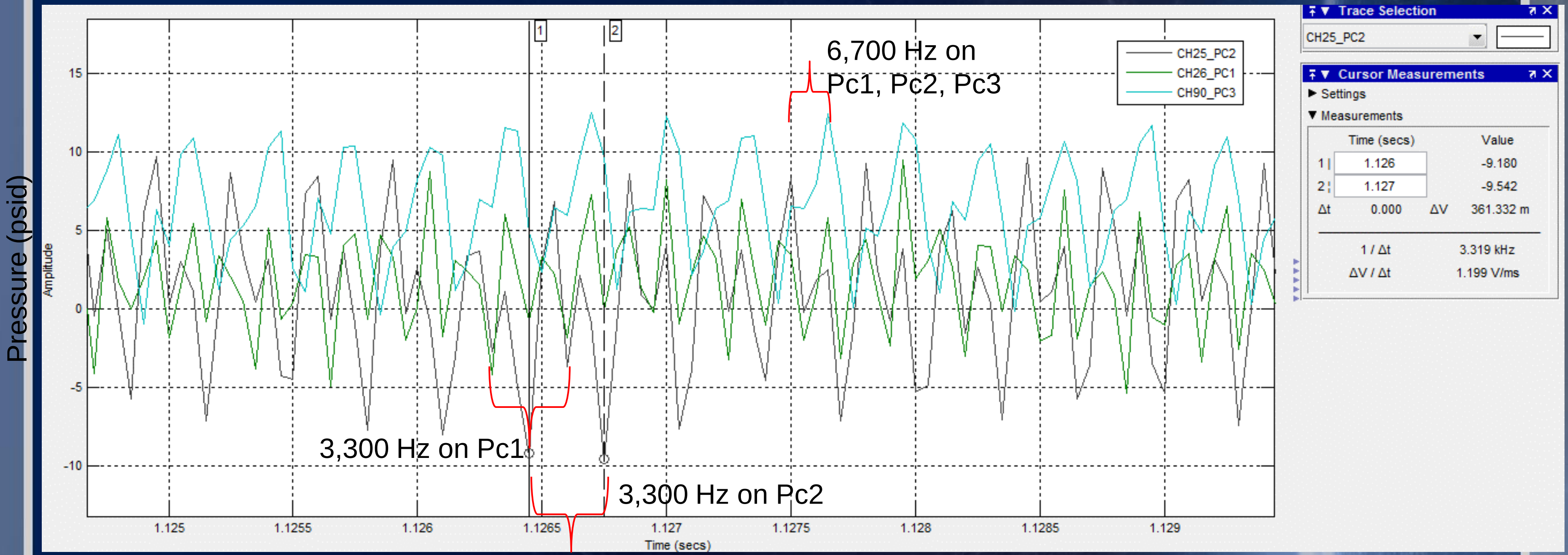
	Time (secs)		Value
1	1.289		-19.862
2	1.289		-14.465
Δt	0.000	ΔV	5.397

1 / Δt 3.310 kHz

ΔV / Δt 17.862 V/ms

3110 Hz on Pc2

HF9.1



6,700 Hz on Pc1, Pc2, Pc3

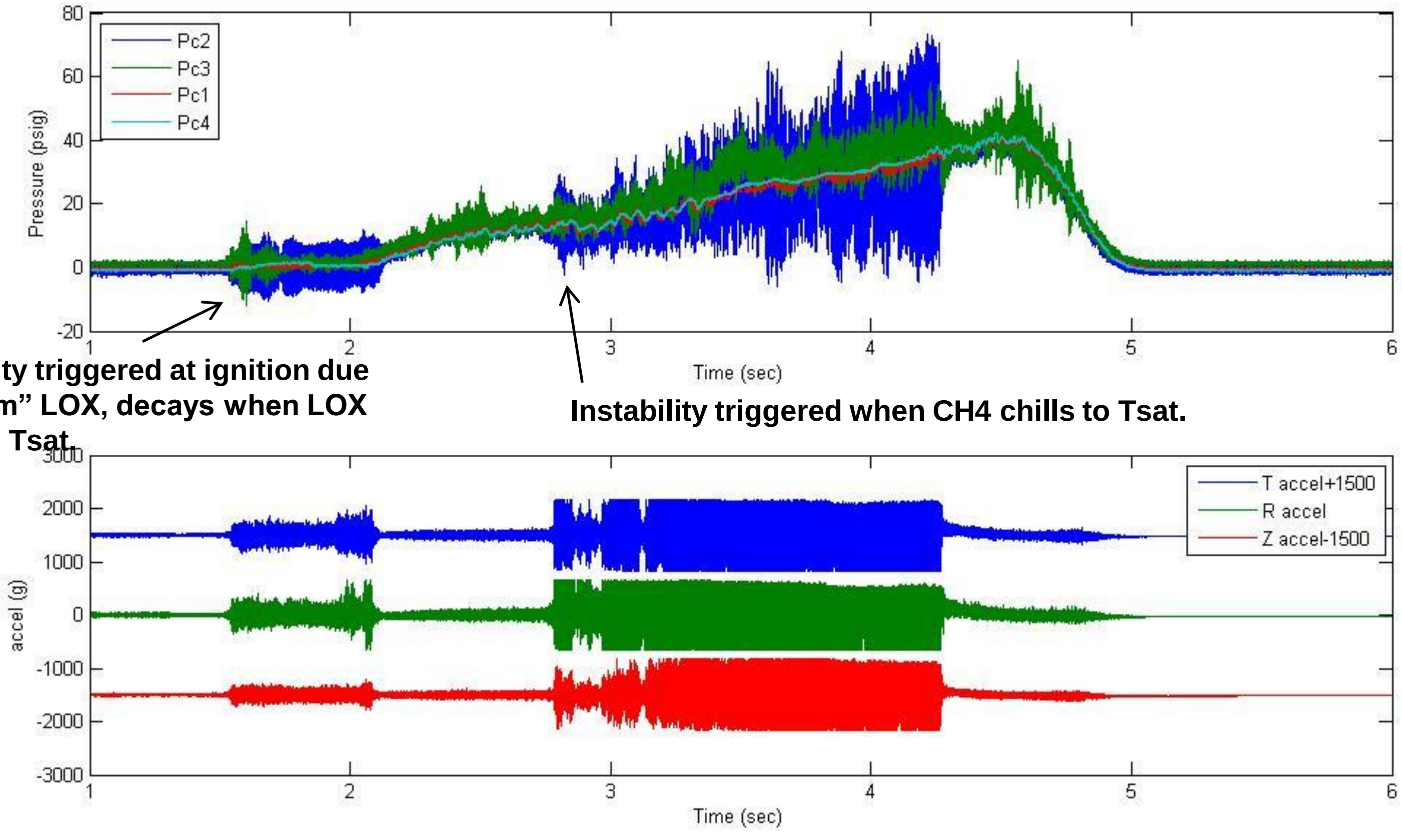
3,300 Hz on Pc1

3,300 Hz on Pc2

	Time (secs)		Value
1	1.126		-9.180
2	1.127		-9.542
Δt	0.000	ΔV	361.332 m
	1 / Δt		3.319 kHz
	ΔV / Δt		1.199 V/ms

Some HD5 tests show distinct separate causes of Instability

HD5.a, SSC Test 6, 10/15/2012

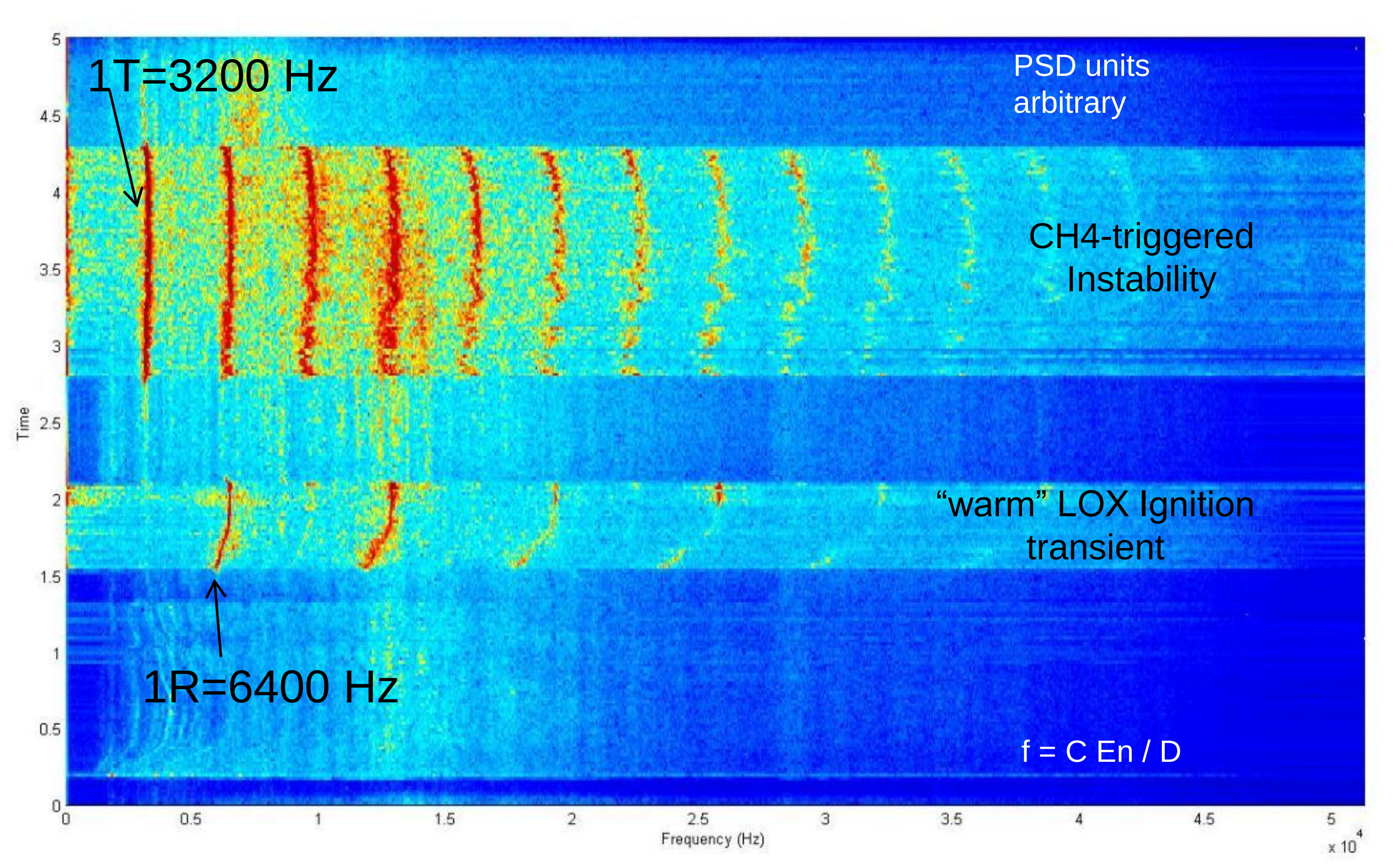


Instability triggered at ignition due to "warm" LOX, decays when LOX chills to Tsat.

Instability triggered when CH4 chills to Tsat.

HD5.a, SSC Test 6, 10/15/2012

CH22_Accel4 (accelerometer, sampling rate = 102.4 kHz)



HD5.a, SSC Test 6, 10/15/2012 (Accelerometer data)

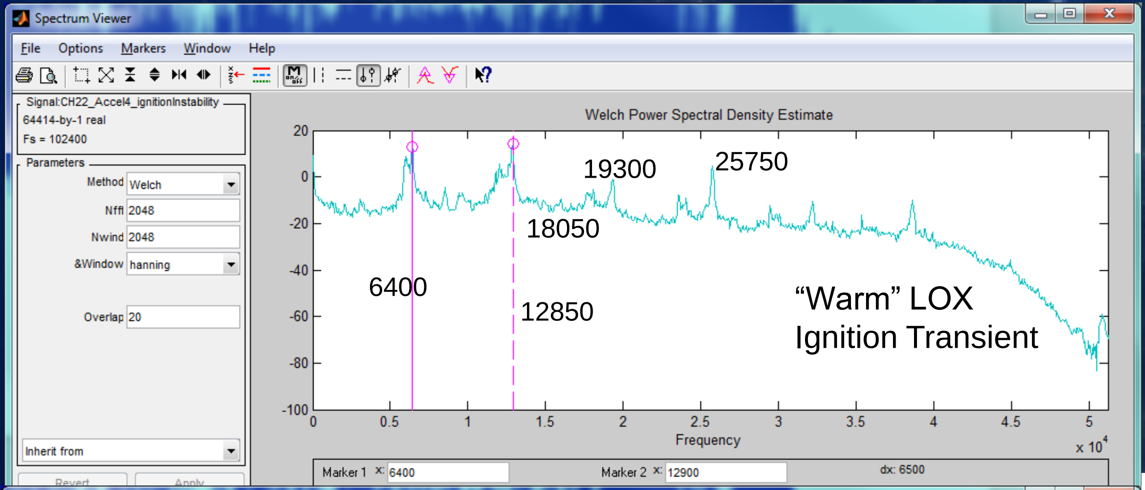
Predictions:

1R = 6,555 Hz
2R = 11,982 Hz
3R = 17,409 Hz

1T = 3,150 Hz
1T1R = 9,134 Hz
1T2R = 14,561 Hz
1T3R = 20,042 Hz

Conclusions:

- Ignition transient tones related to 1R, 2R
- CH4 triggered instability related to 1T, 1R, 1T1R, 2R, 3R, 1T2R

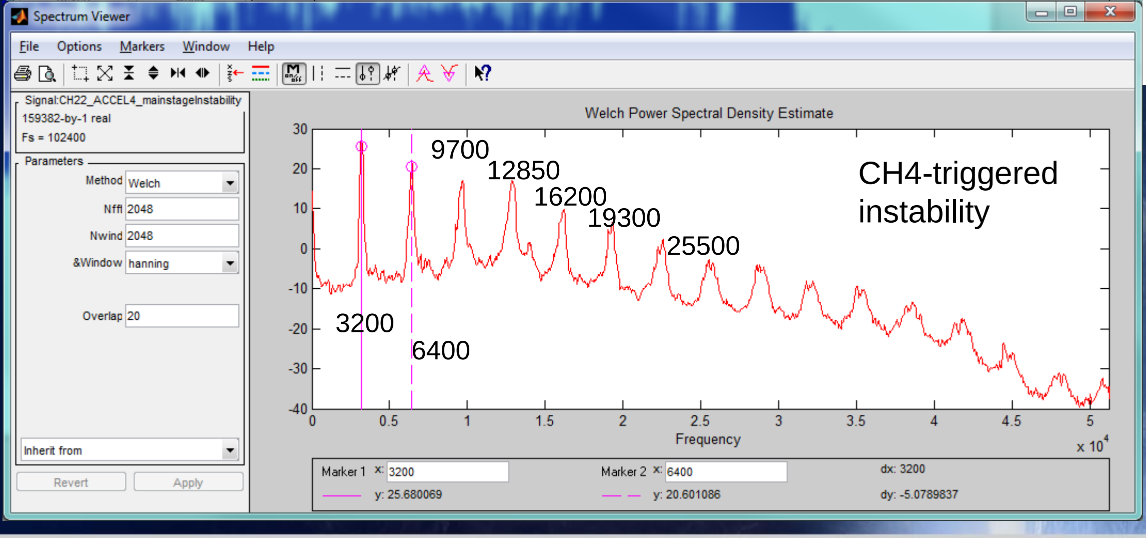


Signal:CH22_Accel4_ignitionInstability
64414-by-1 real
Fs = 102400

Method: Welch
Nfft: 2048
Nwind: 2048
&Window: hanning
Overlap: 20

Marker 1 x: 6400
Marker 2 x: 12900
dx: 6500

"Warm" LOX Ignition Transient



Signal:CH22_ACCEL4_mainstageInstability
159382-by-1 real
Fs = 102400

Method: Welch
Nfft: 2048
Nwind: 2048
&Window: hanning
Overlap: 20

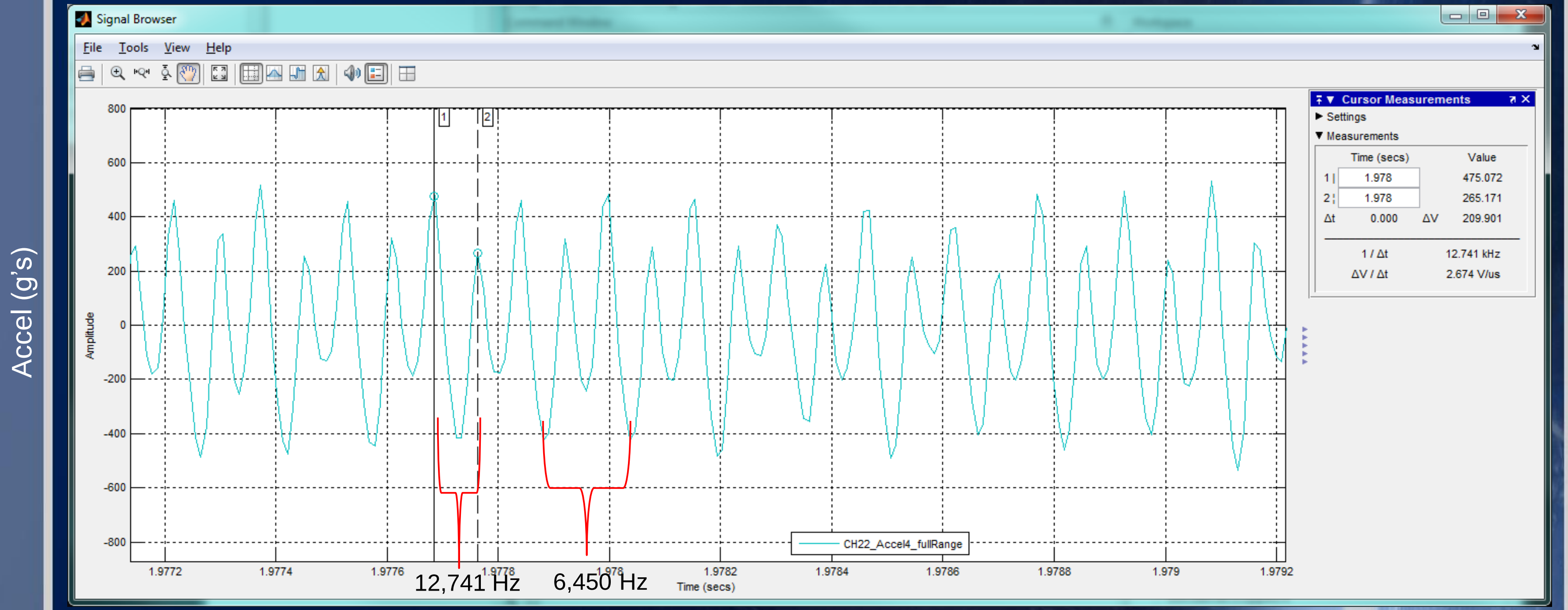
Marker 1 x: 3200
y: 25.680069
Marker 2 x: 6400
y: 20.601086
dx: 3200
dy: -5.0789837

CH4-triggered instability

PSD units arbitrary

HD5.a, SSC Test 6, 10/15/2012 (Accelerometer data)

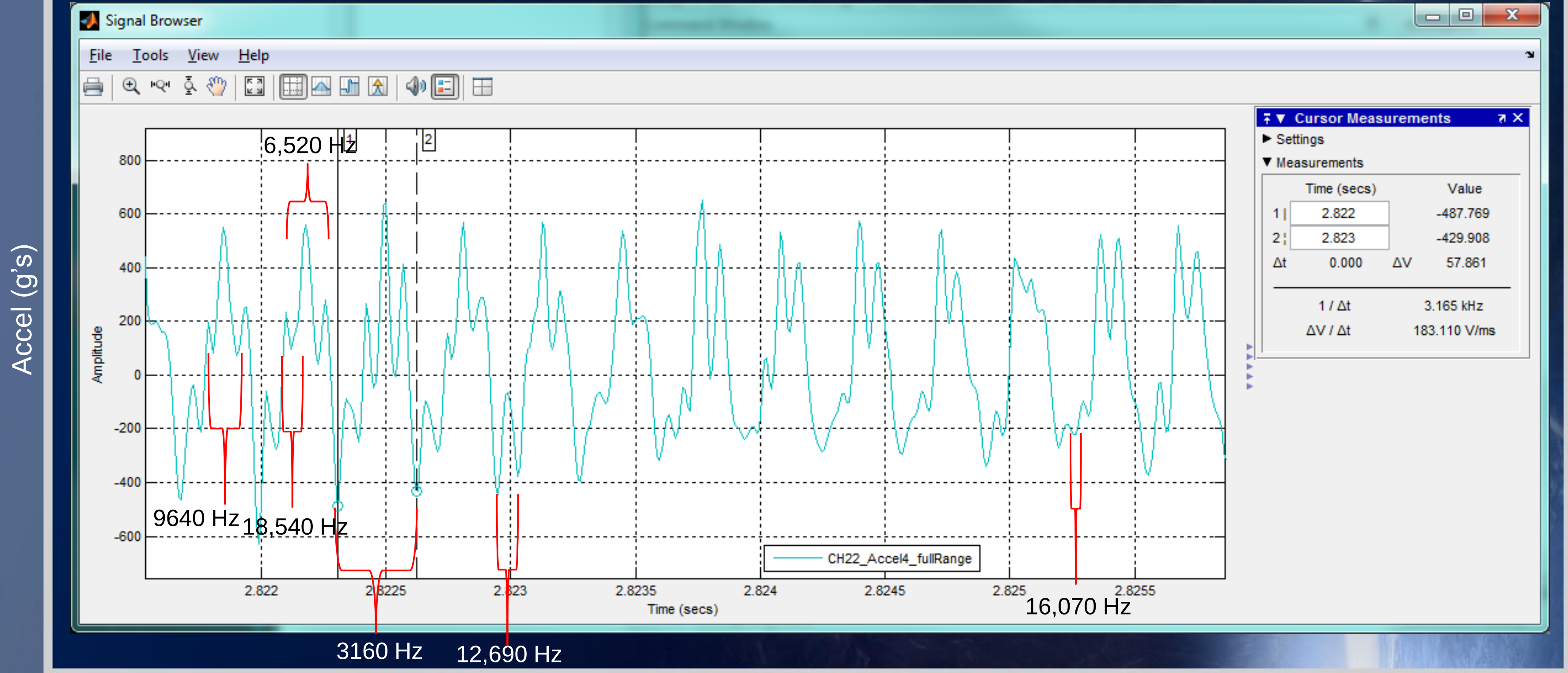
- Accelerometer Data, sampling rate 102.4 kHz data
- During Ignition instability, 1R, 2R signals evident
  - Blips at 3R or above (17 kHz) not easily measured



	Time (secs)		Value
1	1.978		475.072
2	1.978		265.171
Δt	0.000	ΔV	209.901
	1 / Δt		12.741 kHz
	ΔV / Δt		2.674 V/us

HD5.a, SSC Test 6, 10/15/2012 (Accelerometer data)

- Accelerometer Data, sampling rate 102.4 kHz data
- During Mainstage instability, 1T, 1R, 1T1R, 2R, 3R, 1T2R signals evident
  - Blips at 1T3R (20 kHz) and higher difficult to distinguish



	Time (secs)		Value
1	2.822		-487.769
2	2.823		-429.908
Δt	0.000	ΔV	57.861

1 / Δt 3.165 kHz
ΔV / Δt 183.110 V/ms

Is the measured signal 1T, 1R or something else?

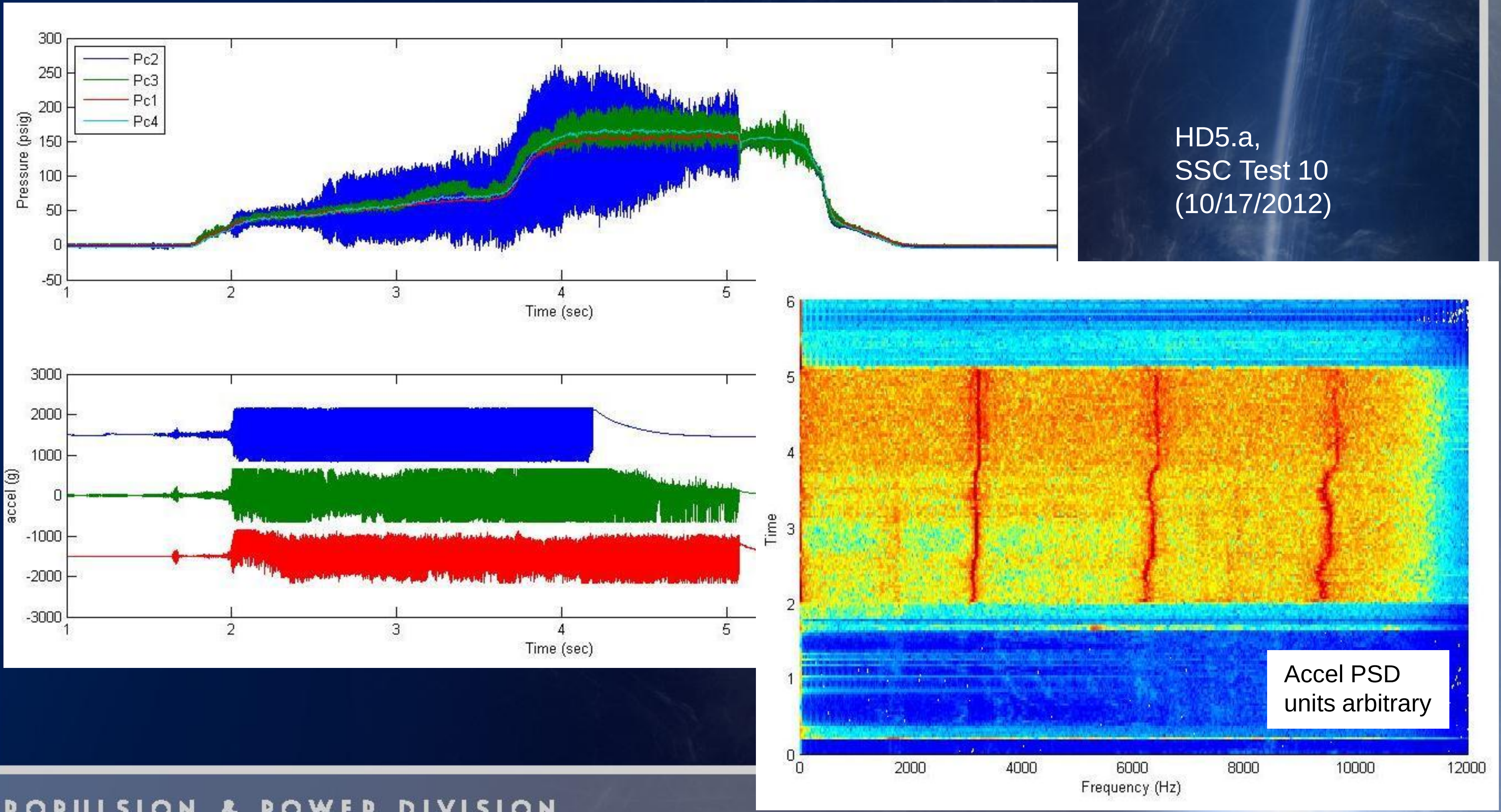
- NASA-internal peer review have raised the possibility that the ~3100-3200 Hz tone is actually a 2L
  - Changes the interpretation of the 6 kHz tones to being 4L instead of 1R
- Evidence against 1R cause:
  - Measured harmonics (3kHz / 6 kHz / 9 kHz pattern) suggests L-modes
  - Variable phasing of the Pc signals at ~6 kHz suggests the tone is not Radial mode
- Evidence for 1R cause:
  - HD4 and HD5 measurements are consistently in the 6200 – 6700 Hz range for this tone, most likely to be 1R based on predictions.
  - Variable phasing between the Pc signals would have to be explained by known sense line interference for the high-speed Pc ducers
  - Published theory shows that non-linear coupling can modulate both 1R and 2T to oscillate at exactly 2x 1T frequency, with 1R higher amplitude (Vigor Yang, AIAA Prog. Vol 169)

Bottom Line:

6 kHz Instability may be longitudinal (4L), or radial (1R)

Instability propagation through a throttle transition

- The instability has been shown to propagate through a throttle-transition, but it has never been demonstrated to initiate after main-stage throttle-up



HD5.a,
SSC Test 10
(10/17/2012)

Accel PSD
units arbitrary

CH4-triggered instabilities: Working Theory

- CH4-triggered Instabilities coupled to high CH4 injection velocity
  - Calculations for injection velocity (not shown here) are higher than originally predicted during startup
  - CH4 injection velocity driven high by orifice flow detachment in CH4 injector during startup high injector pressure drop
  - CH4 orifice flow detachment caused by start surge (Water hammer) combined with or because of “cold” CH4
- Instability appears to “trigger” at moment of injector chill in to CH4 Tsat
  - Unknown: how the CH4-chill-in triggers the instability
- Some tests do show that the instability can dampen out after CH4 flow re-attaches or at throttle-up.
- Issue: Working theory does not explain why Morpheus vehicle engine tests do not demonstrate the undamped instabilities seen in SSC testing

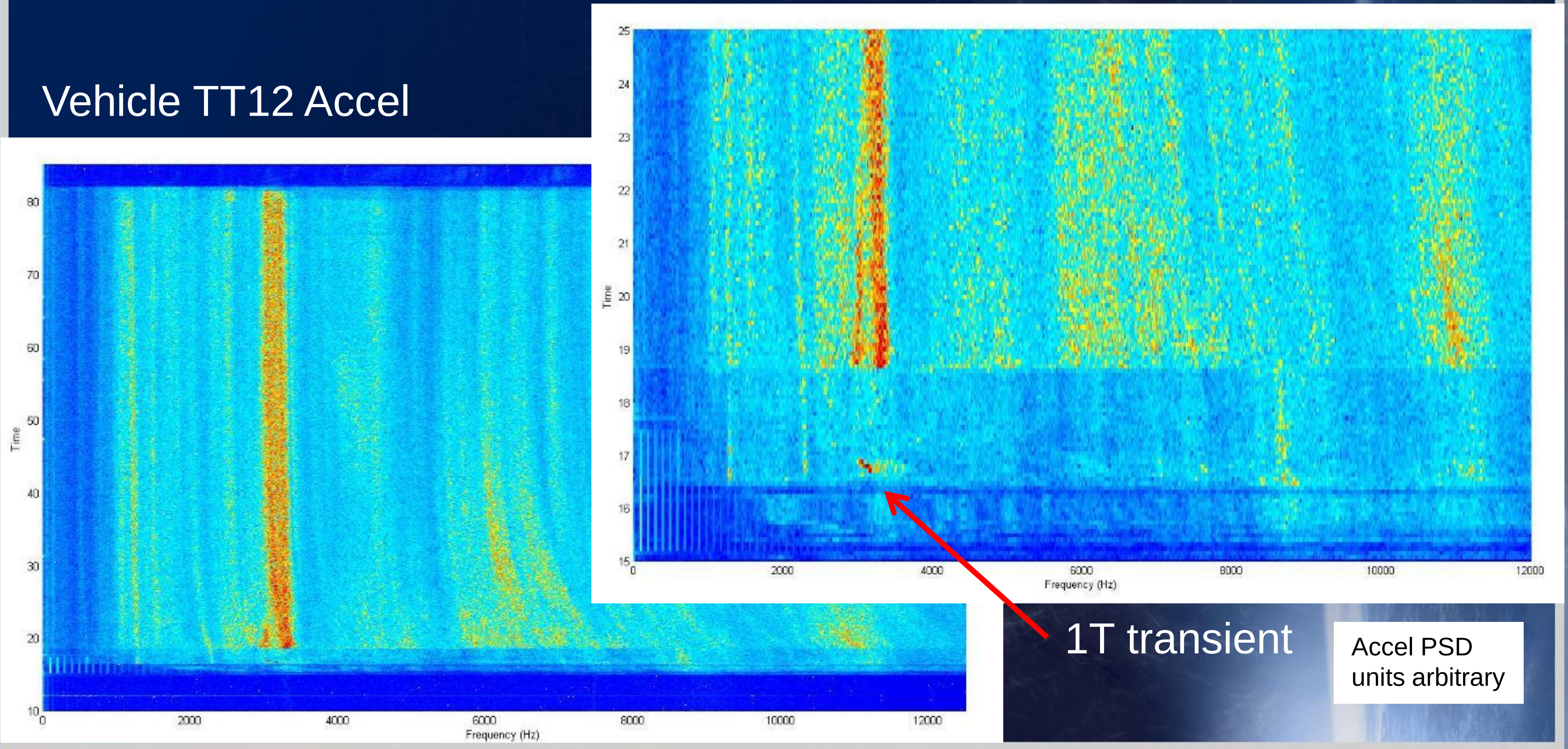
Morpheus Vehicle Tests Observations (31 tests for HD4 and HD4-LT)

- High-amplitude, undamped instabilities have been recorded on the vehicle using HD4-LT (2013), but not during tests using HD4 (2012)
  - The 3 kHz /6 kHz /9 kHz pattern has been observed, but typically at greatly reduced amplitude, and damped out prior to throttle-up
  - The HD4-LT instability was observed on a test with very cold CH4 chill-in pre-test
- New observations suggest HD4-LT injector pressurization, injection velocity profile is higher than HD4 on the vehicle
  - On the vehicle, the injector operating conditions that appear to cause instabilities at SSC are more severe for HD4-LT than HD4
  - The HD4-LT larger throat affects chamber pressurization and injector pressure drop
- Major differences between SSC and vehicle CH4 flow
  - The CH4 injector pressurizes much more quickly on the vehicle than on the SSC test stand
  - The CH4 start surge has a much shorter wavelength and dampens out quicker than the SSC config (even though magnitudes are in family)
  - These differences due to larger diameter plumbing and 10x longer line lengths

HD4 Vehicle tests are relatively stable

- The HD4 vehicle tests are all relatively stable with minor low-amplitude transients on some tests

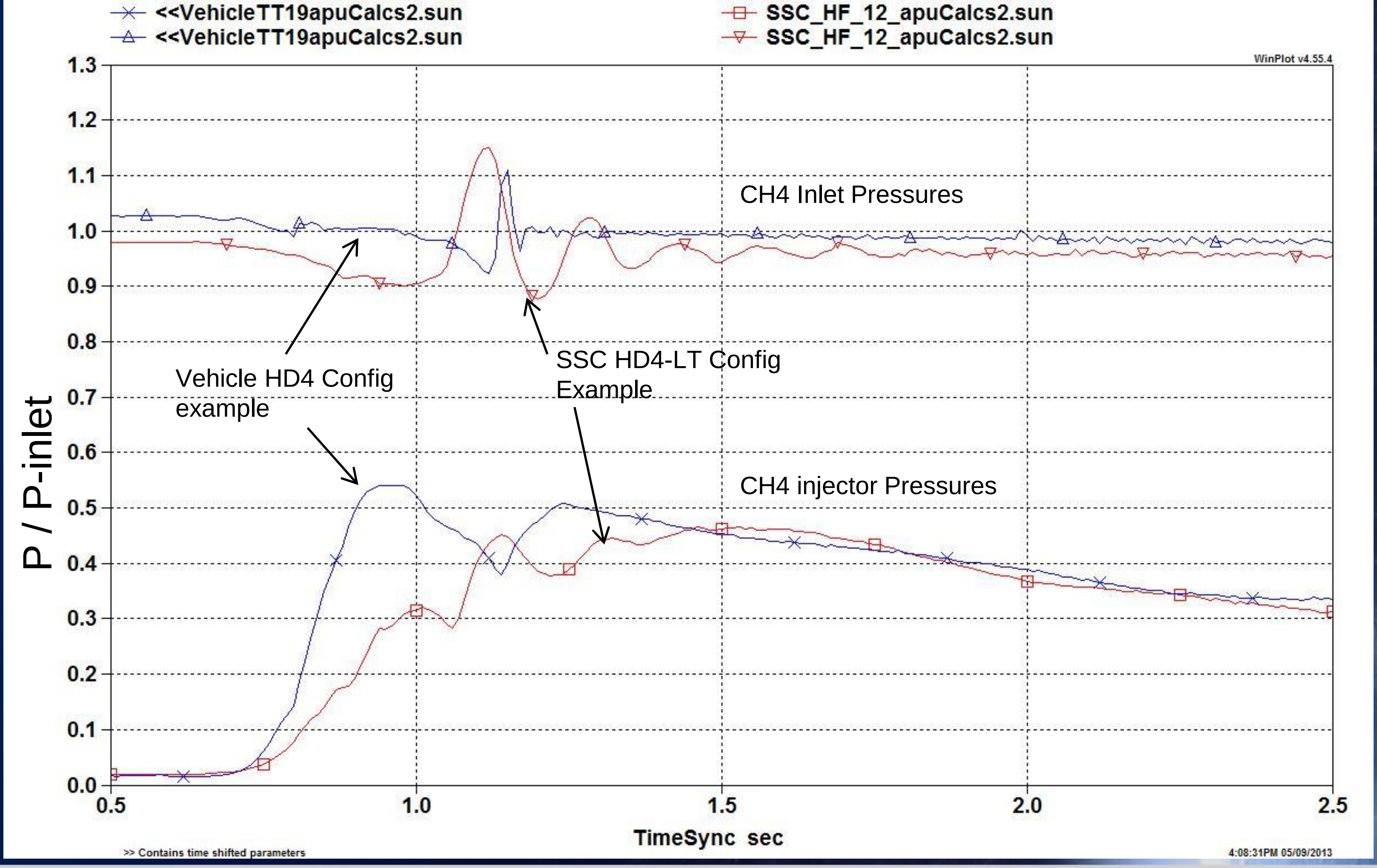
Vehicle TT12 Accel



1T transient

Accel PSD units arbitrary

Vehicle vs. SSC Config differences on CH4 flow
(startup transient pressure)



CH4 Inlet Pressures

Vehicle HD4 Config example

SSC HD4-LT Config Example

CH4 injector Pressures

PROPULSION & POWER DIVISION

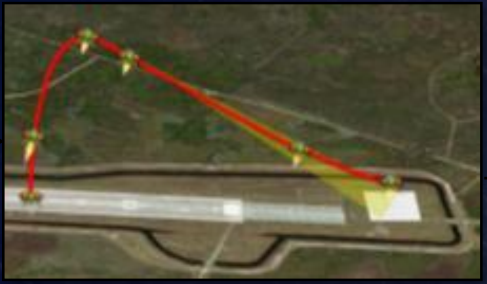
Instability Detection Redline Implementation

- A new redline system has been designed, tested, and installed on the vehicle
- The system was developed during SSC testing, and demonstrated successful shutdown of the engine during high-amplitude instabilities
  - Vehicle hot-fire test with instability limits has demonstrated cut-off capability
  - SSC recorded instability data played back through vehicle cutoff system to demonstrate cut
- Because the high-amplitude instability recorded at SSC was always observed to initiate prior to throttle-up (and never after), the greatest risk to the vehicle is during engine startup, prior to liftoff.
- Future Vehicle Flight Ops:
  - Detection prior to liftoff results in an engine shutdown
  - Detection after lift-off results in a soft abort and landing followed by engine shutdown

Tether Test

Vertical, Slant Hops, Traverse Hops

Flight Envelope Expansion:



Full Hazard Detection Phase

Autonomous Hazard Avoidance
Identify and land at safe site in landing field with hazards (rocks, craters, slopes)