Troubleshooting Challenges on the James Webb Space Telescope (JWST)

July 23, 2019

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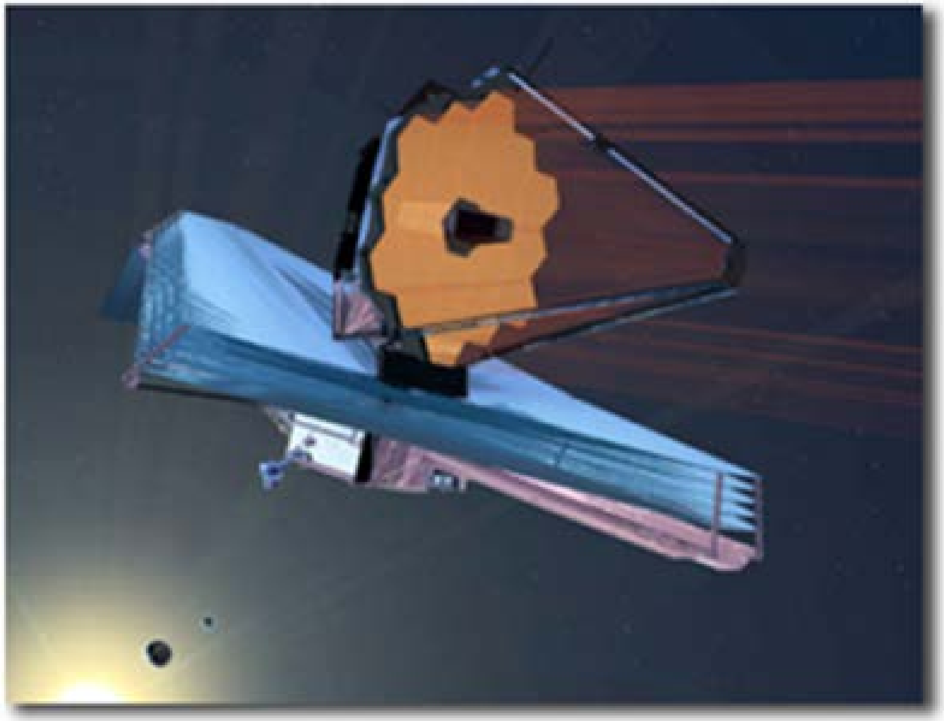
Acronyms

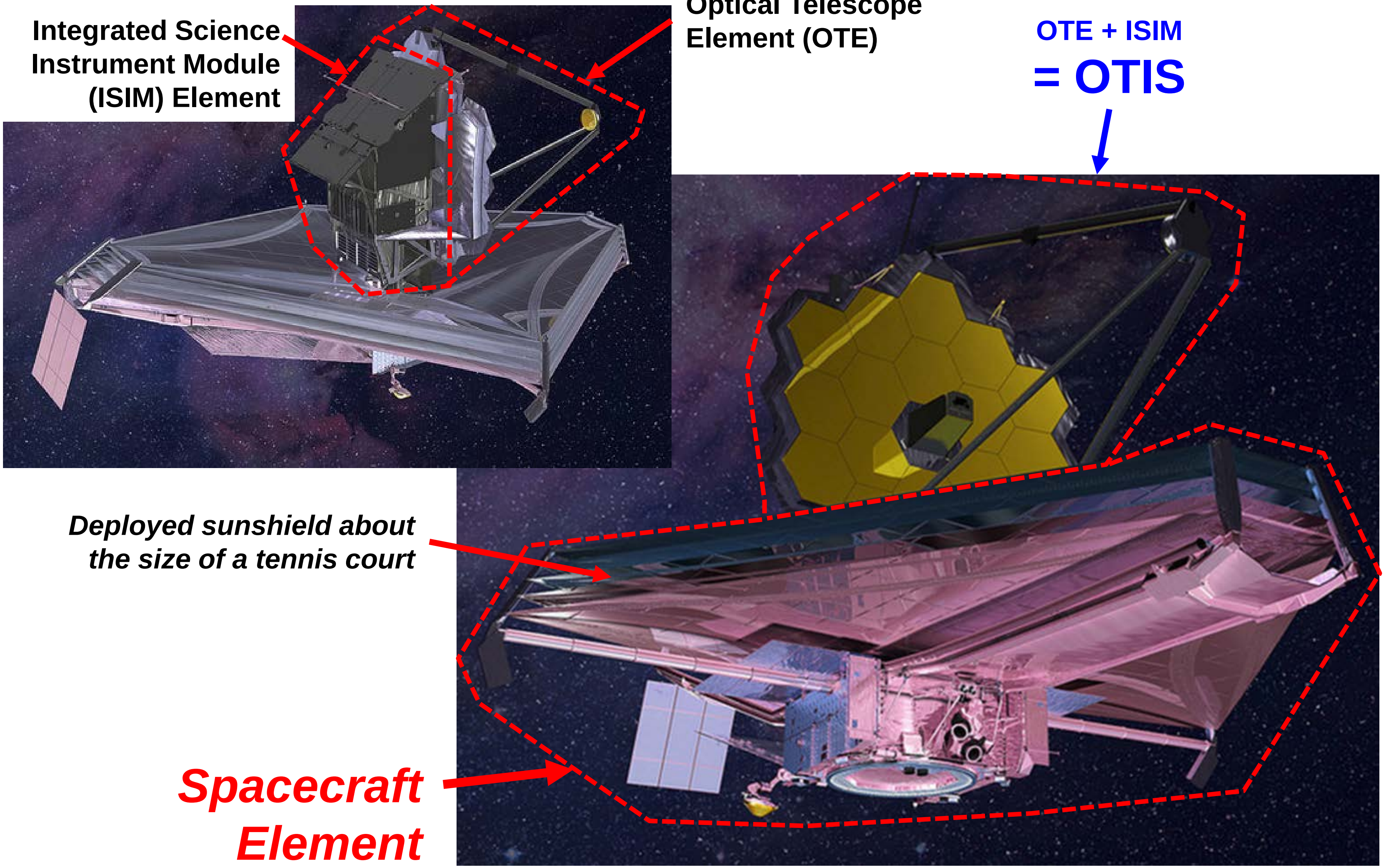
AWG	American Wire Gage
EGSE	Electrical Ground Support Equipment
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
GEVS	General Environmental Verification Specification
GSFC	Goddard Space Flight Center
I&T	Integration and Test
ICE	Instrument Control Electronics
IEC	ISIM Electronics Compartment
ISIM	Integrated Science Instrument Module
JWST	James Webb Space Telescope
JSC	Johnson Space Center
MIRI	Mid Infra-Red Instrument
NASA	National Aeronautics and Space Administration
NG	Northrop Grumman
OTE	Optical Telescope Element
OTIS	OTE + ISIM
RIVETS	Remote Interface Verification Electrical Test System
SCSim2A	Spacecraft Simulator 2A
SI	Science Instrument

Introduction

- James Webb Space Telescope (JWST) will be the premier observatory of the next decade, serving thousands of astronomers worldwide
- Follows in footsteps of Hubble Space Telescope
- It will study every phase in the history of our Universe, ranging from the first luminous glows after the Big Bang, to the formation of solar systems capable of supporting life on planets like Earth, to the evolution of our own Solar System



“Elements” of JWST



Integrated Science Instrument Module (ISIM) Element

Optical Telescope Element (OTE)

OTE + ISIM

= OTIS

Deployed sunshield about the size of a tennis court

Spacecraft Element

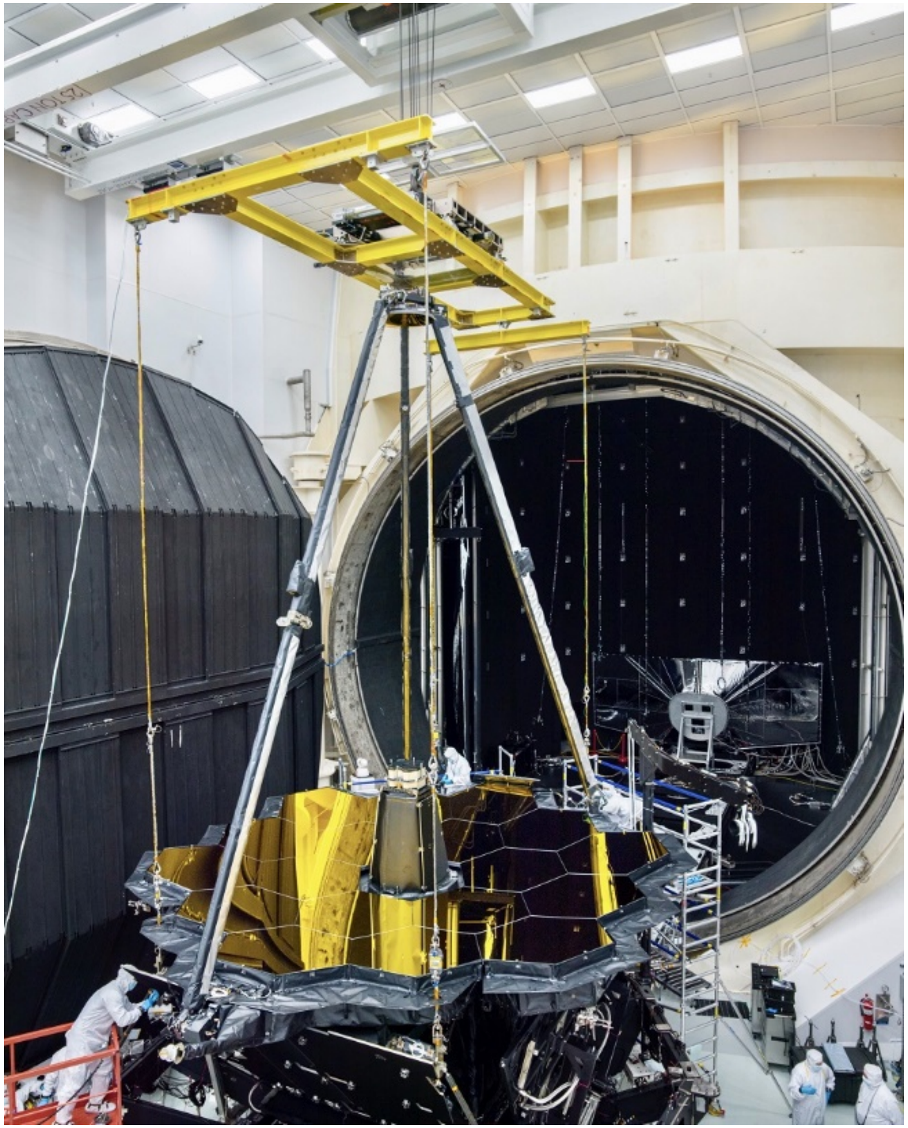
OTIS and Spacecraft Element

- **OTIS**
  - Completed cryo vacuum test campaign in large chamber at Johnson Space Center (JSC), May – Dec. 2017
  - Shipped to Northrop Grumman’s (NG’s) Space Park facility, Redondo Beach, CA, Feb. 2018
- **Spacecraft**
  - Being integrated at NG’s Space Park facility, Redondo Beach, CA
  - Final preparations in progress for environmental testing (except EMI/EMC, completed April 2017)

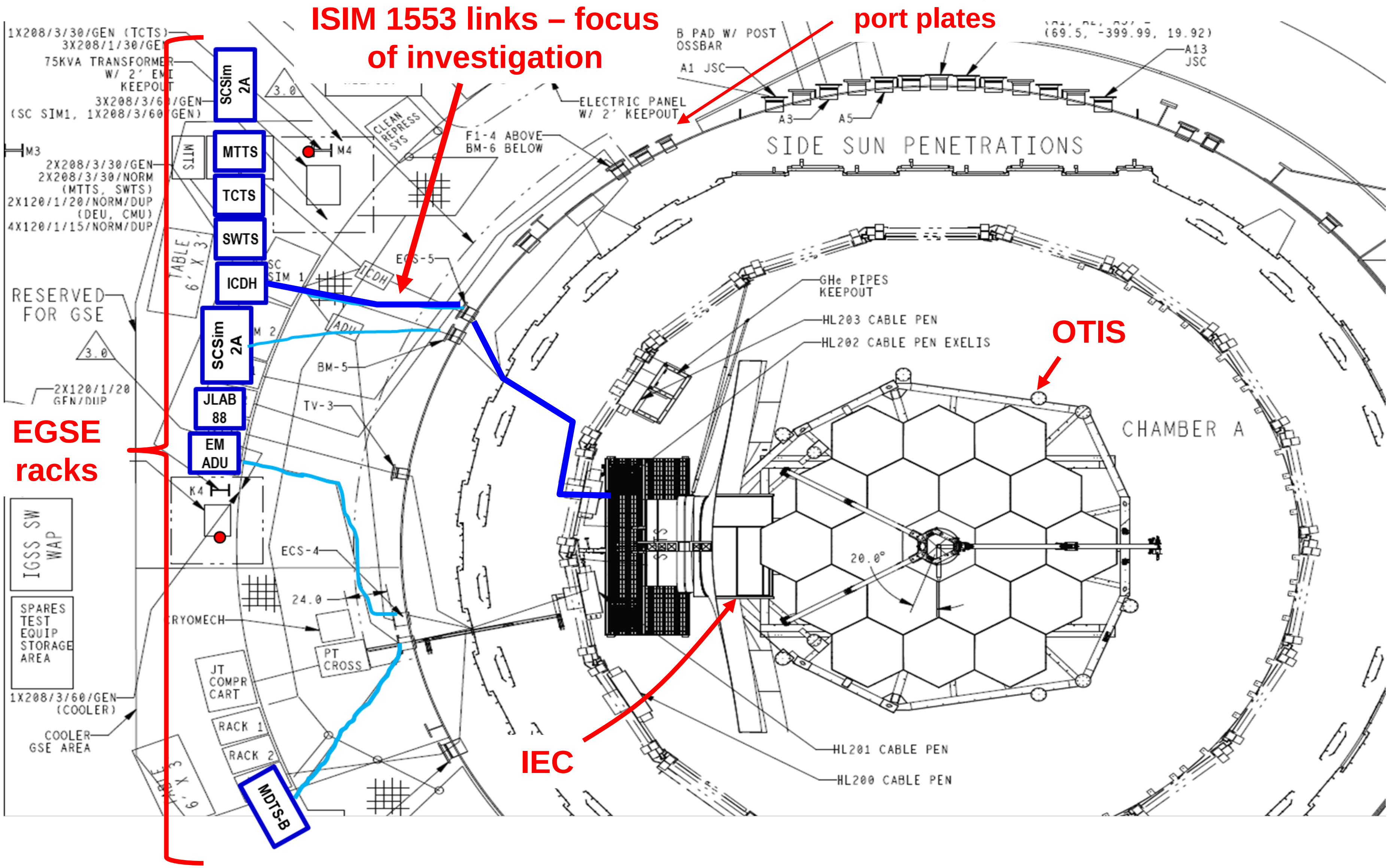
Focus of Presentation

- **This presentation summarizes recent troubleshooting on OTIS at JSC**
  - My services were requested to address any possible EMC/noise issues
  - In a previous life, I was the ISIM Electrical Systems Lead Engineer
  - Both “hats” were necessary
  - This turned out to be an investigation of power quality
- **Problem description**
  - B-Side of one of the instrument electronics boxes (MIRI ICE B) occasionally and temporarily stopped responding to 1553 commands during test
    - MIRI = Mid Infra-Red Instrument
    - ICE = Instrument Control Electronics
- **MIRI ICE (A & B)**
  - 1 of 12 electronics boxes in ISIM Electronics Compartment (IEC)
  - 1 of 4 boxes on ISIM 1553 bus

Johnson Space Center Chamber A



General Test Layout



ISIM 1553 links – focus of investigation

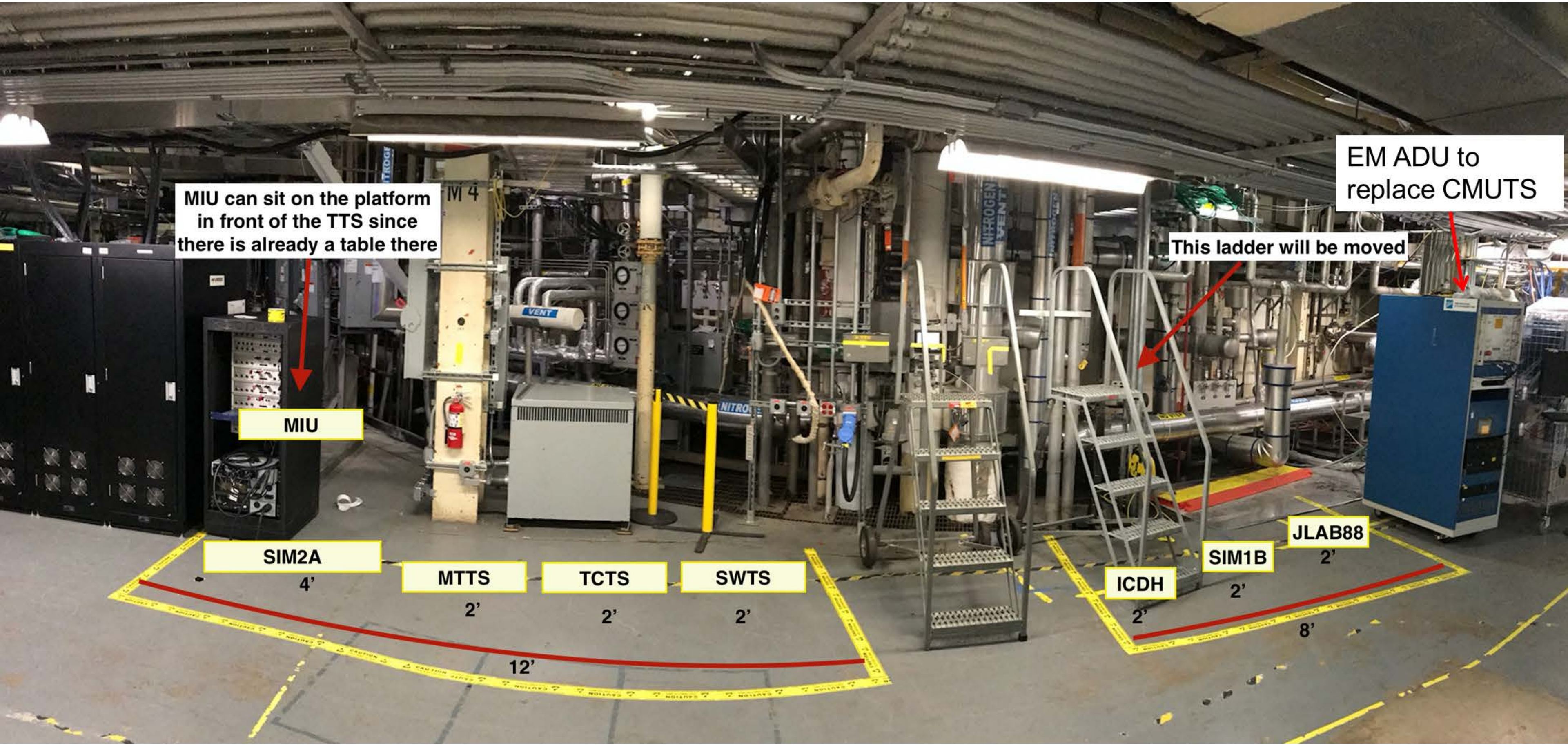
Feedthrough port plates

EGSE racks

OTIS

IEC

General Test Layout (cont.)



General Test Layout (cont.)

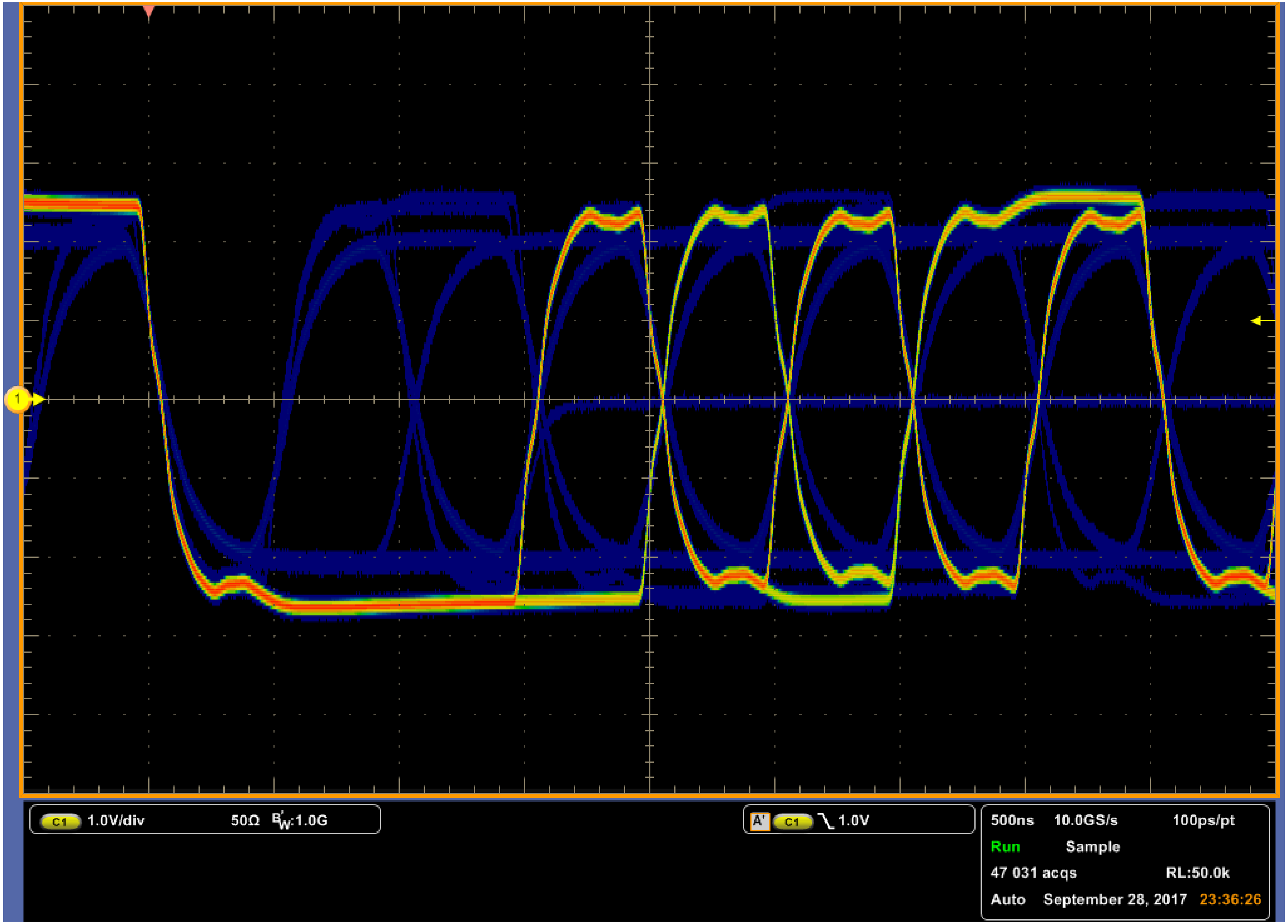
Troubleshooting Challenges

- **Lots of equipment racks, cables, etc. packed into limited space**
- **Active thermal vacuum test**
  - OTIS payload in chamber at vacuum when problem first noticed
  - No direct access to MIRI ICE-B
  - All efforts limited to outside of chamber
- **Had to schedule troubleshooting around main test activities**
  - A day here, a day there, e.g. Tuesday before Thanksgiving, week before Christmas, etc.
- **MIRI ICE built by European Space Agency (ESA) contractor**
  - No longer directly supporting JWST
  - Schematics were not required deliverable to NASA
- **Intermittent problem – handful of occurrences over a few months**

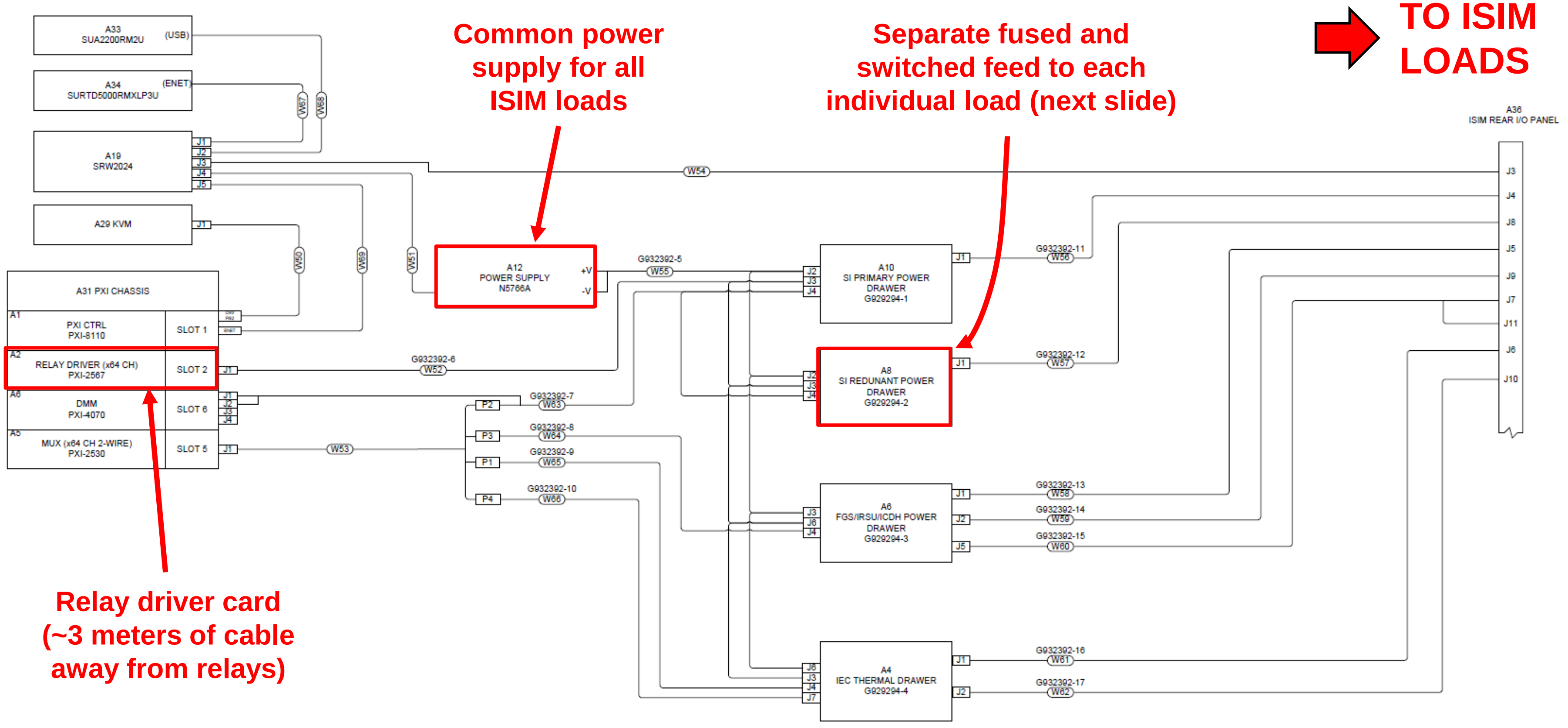
Investigation Overview

- **Possible 1553 bus problem (ruled out quickly)**
  - Bus signal quality looked good on oscilloscope (next slide)
  - All other 1553 I/F’s work fine; points away from 1553 problem
- **Combed through telemetry surrounding events for clues**
  - Correlation observed to unexpected changes on current on primary power feed to box in question (MIRI ICE-B)
- **Looked at power interface of MIRI ICE**
  - Limited e-mail and phone support from ESA contractor
  - Hardcopies of schematics provided to local ESA representative
  - Includes undervoltage shutoff function (V < ~18 V)
  - Robust multi-pole filter with roll off frequency of a few kHz
- **Took closer look at power interface between spacecraft simulator (SCSim2A) and MIRI ICE-B**
  - Focus of investigation and this presentation

1553 Bus Signals



SCSim2A Power Distribution Overview



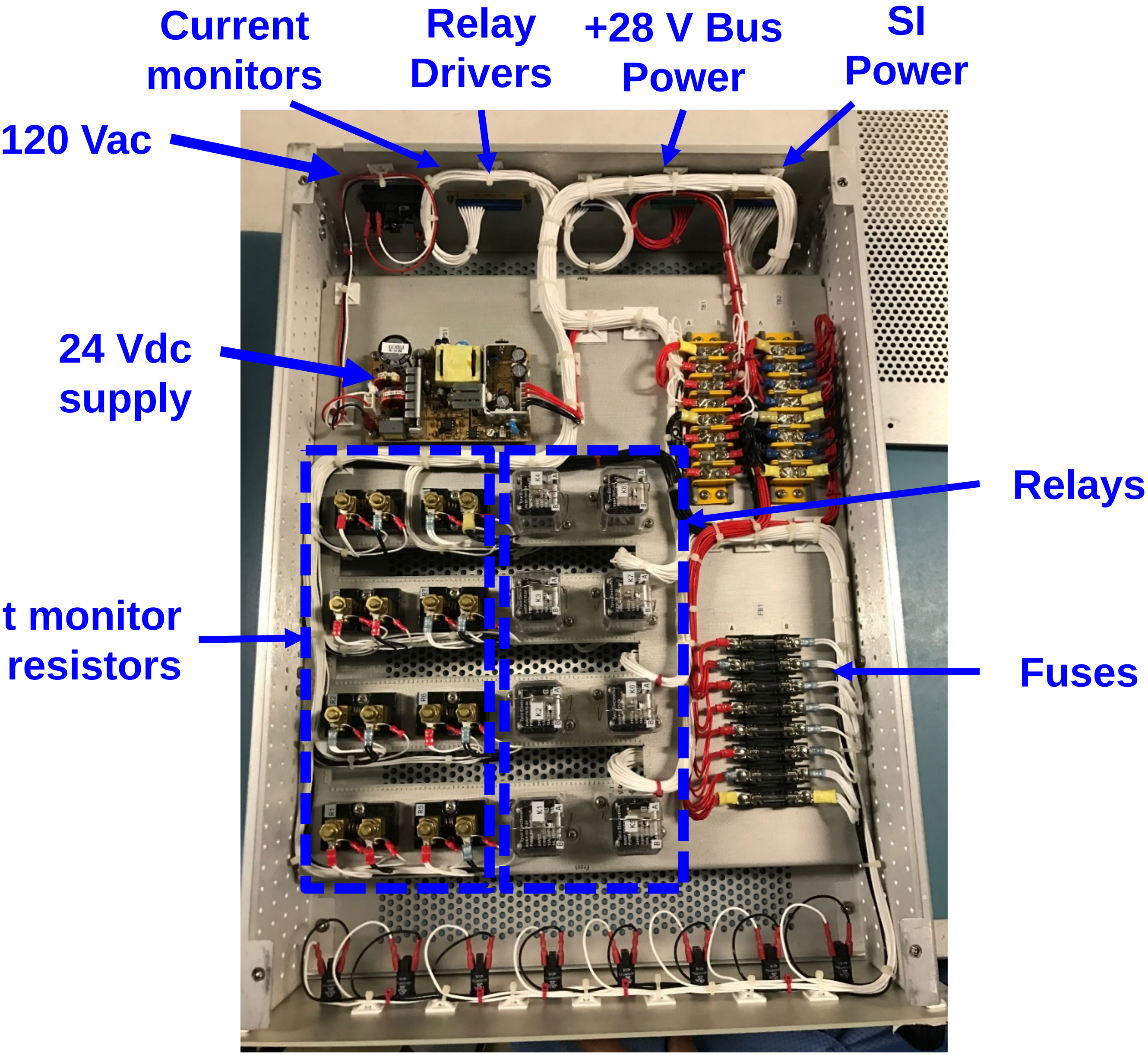
Common power supply for all ISIM loads

Separate fused and switched feed to each individual load (next slide)

TO ISIM LOADS

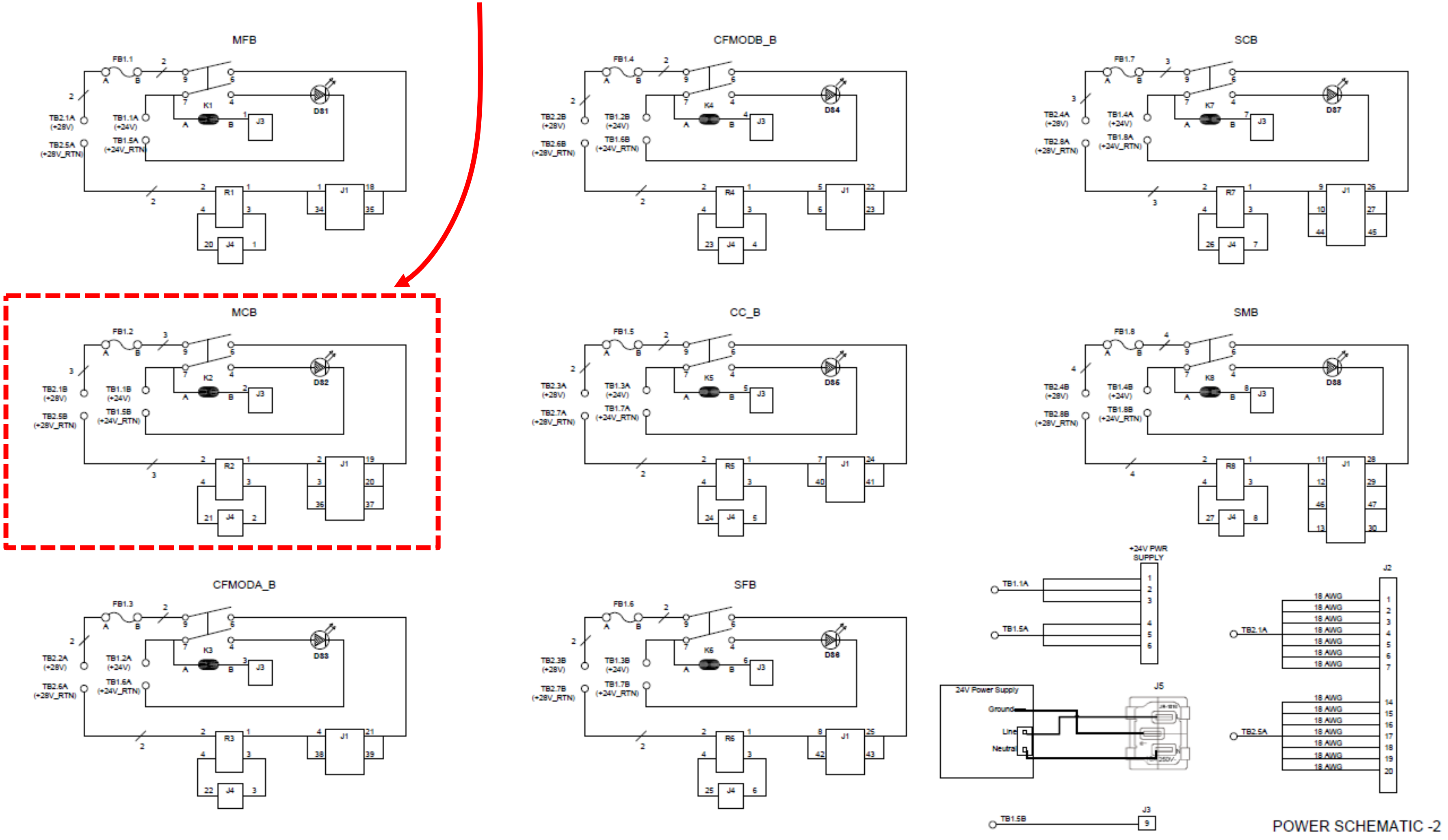
Relay driver card (~3 meters of cable away from relays)

SI Redundant Power Drawer Interior



SI Redundant Power Drawer Block Diagram

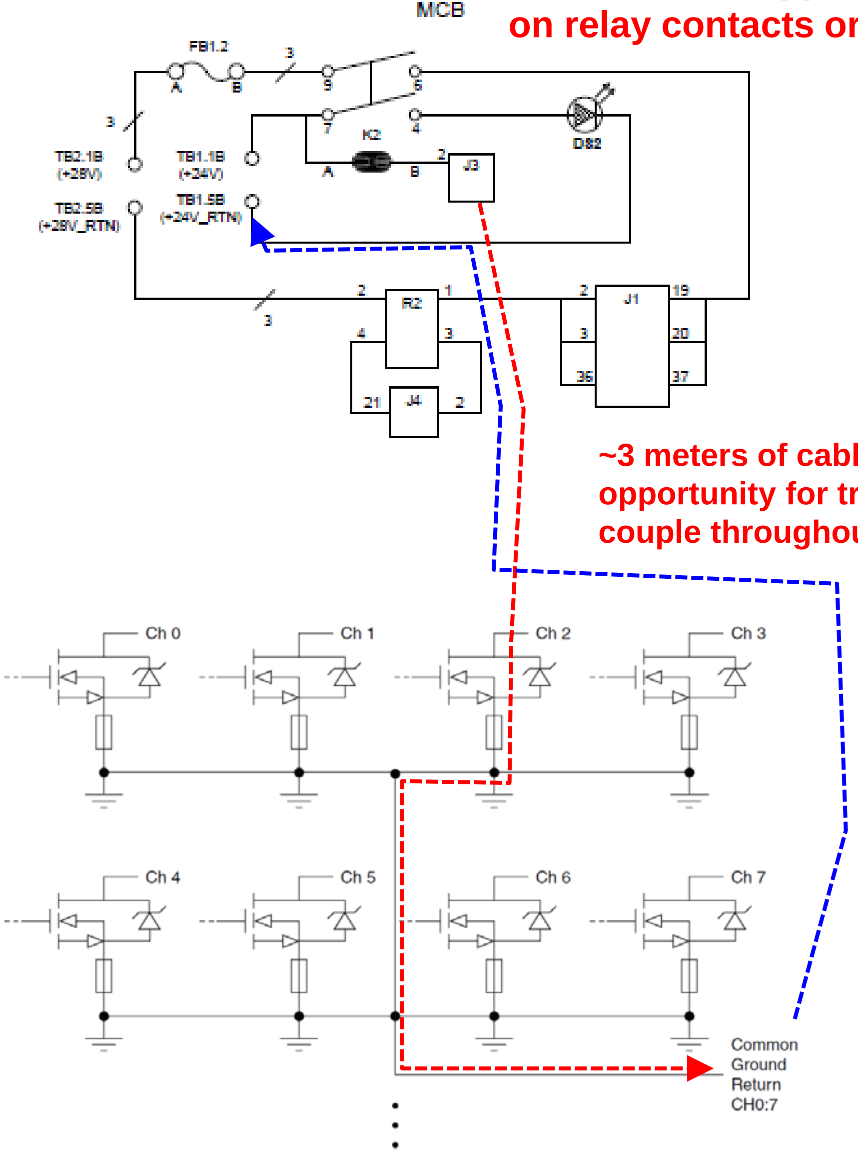
MIRI ICE B feed
(identical to all others)



SI Redundant Power Drawer Block Diagram

Power drawer

No transient suppression elements on relay contacts or coils



~3 meters of cable provides ample opportunity for transient energy to couple throughout SCSim rack

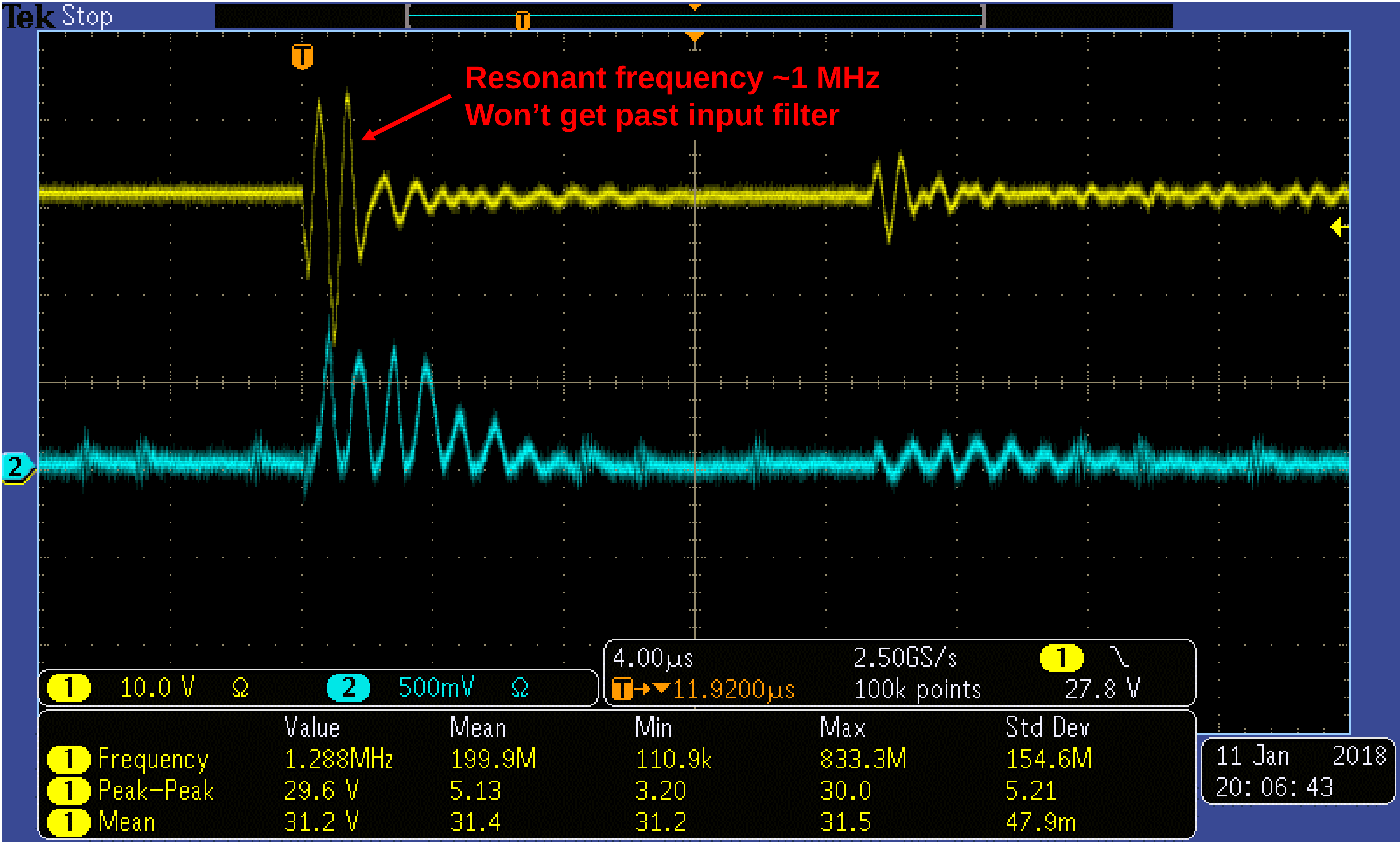
Relay driver card

Limited transient suppression (~3 meters of cable from relays)

SCSim Power Distribution Observations

- **Mechanical relays**
  - Inherently noisy (contact bouncing, etc.)
  - No transient suppression elements (transorbs, etc.)
- **Long cables and large current loops**
  - Increased risk of coupling
- **Measurements show significant noise generated by relay switching transients, but…**
  - These relays were not operating when 1553 events occurred (relays close to turn on box and stay closed)
  - Transient energy couples EVERYWHERE; no credible explanation for why only one side of one box would be affected
  - Ringing in switching transients has resonant frequency of ~1 MHz
  - MIRI ICE B has robust input filter with lots of attenuation at 1 MHz
  - **RELAY SWITCHING TRANSIENTS UNLIKELY ROOT CAUSE**

Typical Relay Coupling Transient

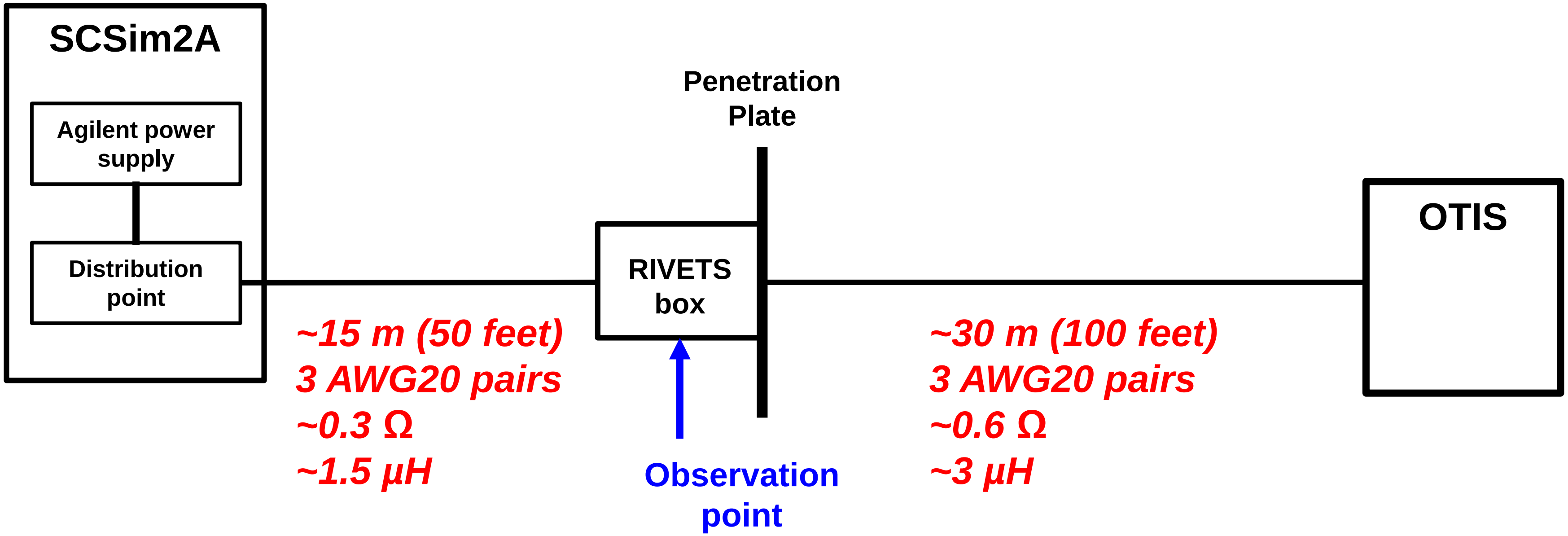


Resonant frequency ~1 MHz
Won't get past input filter

	Value	Mean	Min	Max	Std Dev
1 Frequency	1.288MHz	199.9M	110.9k	833.3M	154.6M
1 Peak-Peak	29.6 V	5.13	3.20	30.0	5.21
1 Mean	31.2 V	31.4	31.2	31.5	47.9m

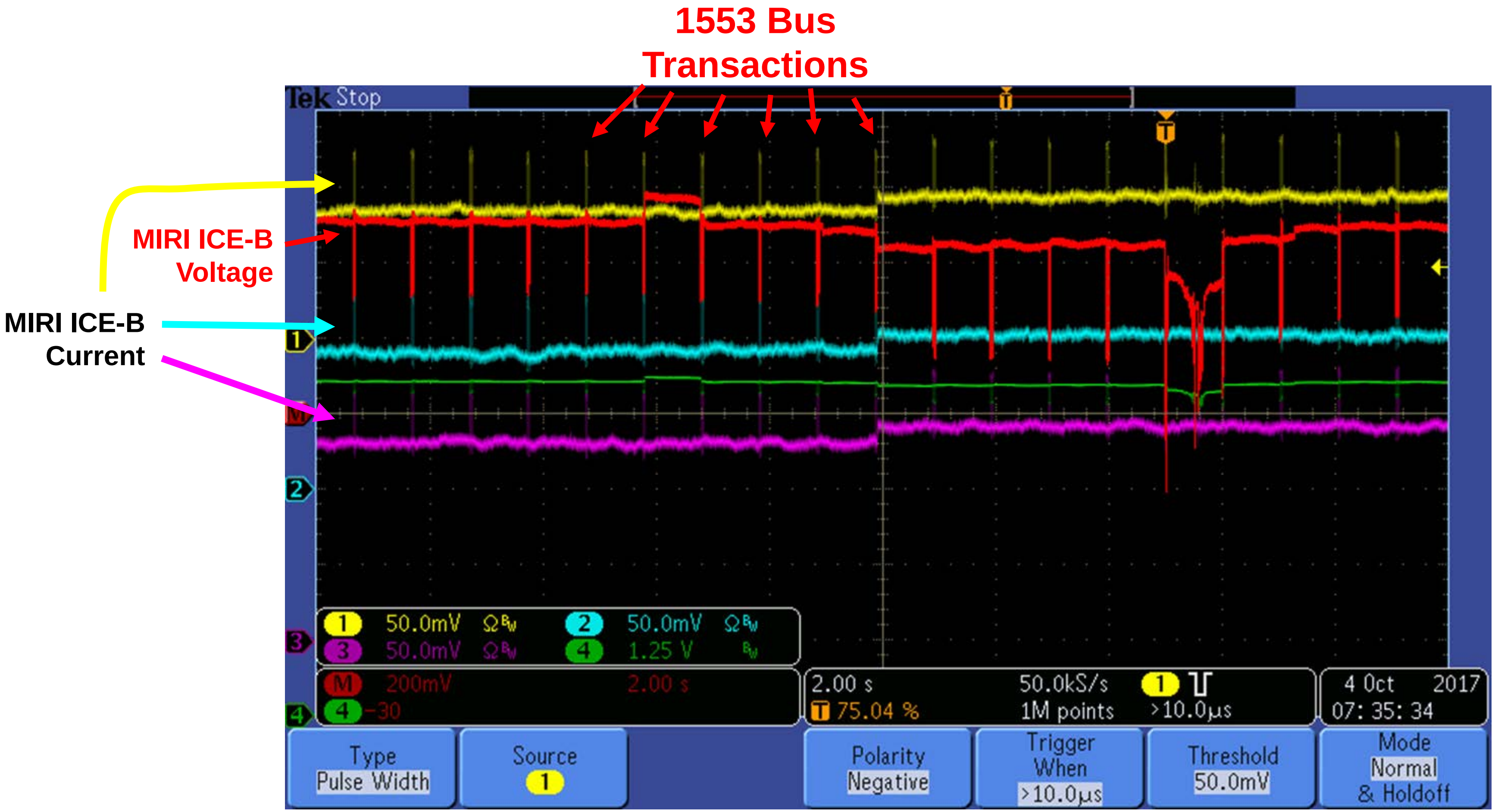
Where Did That Leave Us?

- **Using "RIVETS" box (Remote Interface Verification Electrical Test System) at penetration plate, observed voltage and current on power feed to MIRI ICE-B**



MIRI ICE B Power Feed (measured at RIVETS)

- ***During 1553 transactions:***
  - *ΔI ≈ 120 mA, ΔV ≈ 200 - 300 mV*
- ***Effective Z ≈ 1.7 – 2.5 Ω***



1553 Bus Transactions

MIRI ICE-B Voltage

MIRI ICE-B Current

Tek Stop

1 50.0mV Ω B_W
2 50.0mV Ω B_W
3 50.0mV Ω B_W
4 1.25 V B_W
M 200mV 2.00 s
4 -30

2.00 s
T 75.04 %
50.0kS/s
1M points
1 >10.0μs
4 Oct 2017
07: 35: 34

Type: Pulse Width
Source: 1
Polarity: Negative
Trigger When: >10.0μs
Threshold: 50.0mV
Mode: Normal & Holdoff

Power Harness Resistance

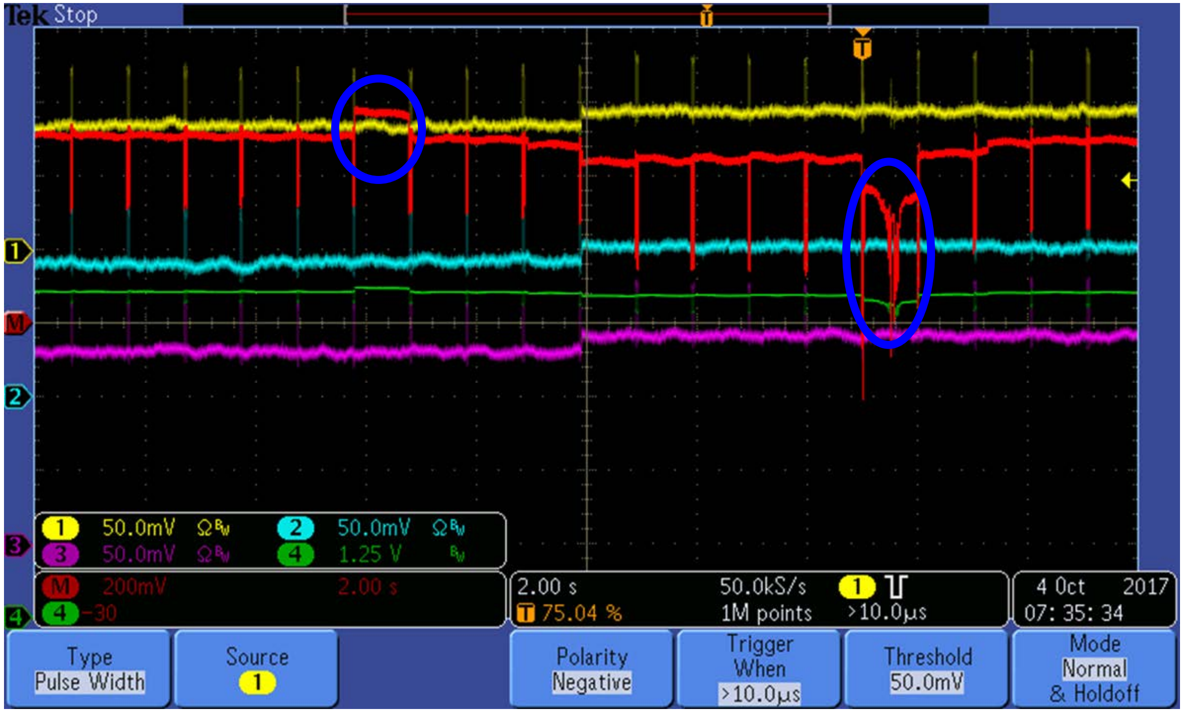
- **Resistance**
  - AWG20 wire, 30 mΩ/m
  - MIRI ICE feed
    - 3 AWG20 pairs in parallel
    - ~50 feet (15 m) between SCSim and feedthrough plate
  - Total resistance on MIRI ICE power feed
    - (0.03 Ω/m) x (15 m) x (2) / 3 = 0.3 Ω

- **HARNESS RESISTANCE DOES NOT FULLY ACCOUNT FOR OBSERVED VOLTAGE DROPS**

- **LED TO CLOSER LOOK AT POWER INTERFACES…**

Unexplained Voltage Shifts

- **Occasional shifts in voltage with no corresponding change in MIRI ICE-B current**
  - Did not coincide with 1553 events, but indicated erratic behavior on power bus
- **IEC heaters only equipment switching on/off power bus**
  - Voltage shifts did not coincide with switching events
  - Most switching events produce no such transients
  - NOT CREDIBLE CAUSE OF VOLTAGE SHIFTS

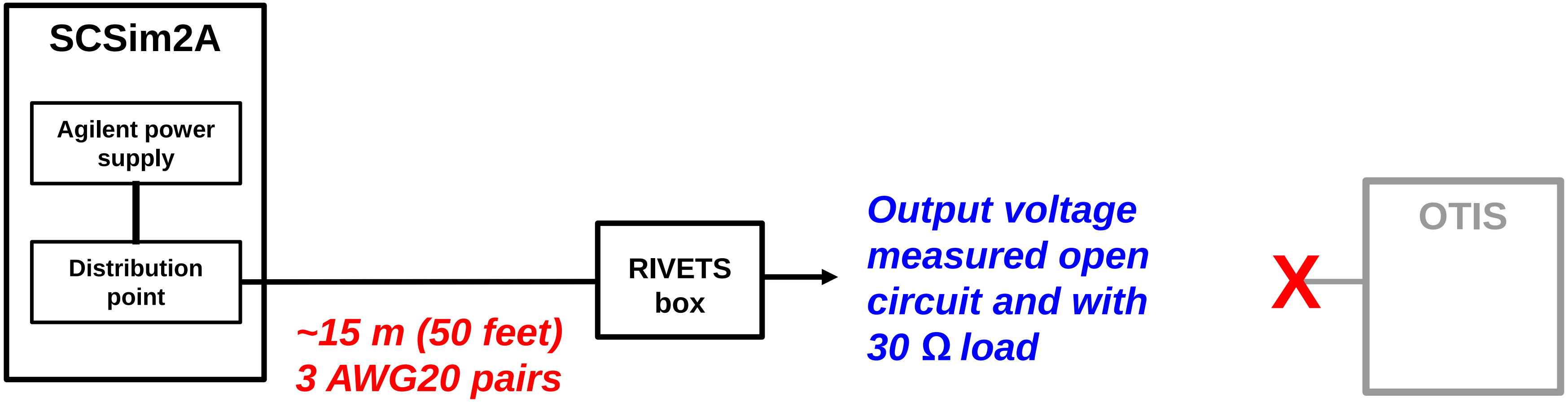


1 50.0mV Ω B_W
2 50.0mV Ω B_W
3 50.0mV Ω B_W
4 1.25 V B_W
M 200mV 2.00 s
4 -30
2.00 s
T 75.04 %
50.0kS/s
1M points
1 >10.0µs
4 Oct 2017
07:35:34

Type: Pulse Width
Source: 1
Polarity: Negative
Trigger When: >10.0µs
Threshold: 50.0mV
Mode: Normal & Holdoff

Power Feed Voltage Drop

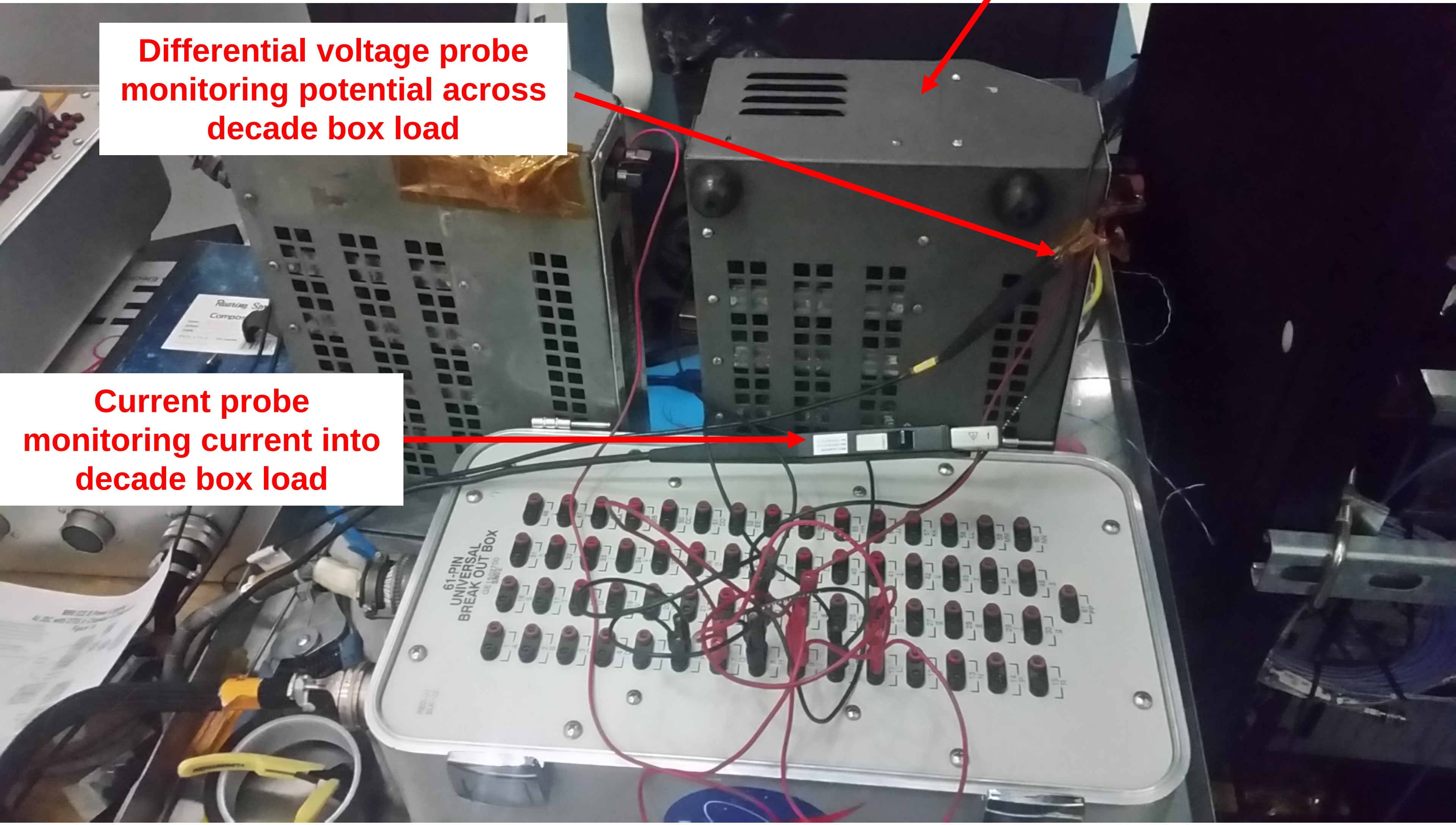
- **After completion of OTIS cryovac test, measured output voltage at RIVETS:**
  - Open circuit
  - With 30 ohm load (1 A at 30 V)
  - Set scope offset to open circuit voltage and expanded vertical scale
- **ΔV divided by ΔI of 1 A gives source impedance**
  - Should be nice, stable voltage, right?



~15 m (50 feet)
3 AWG20 pairs
~0.3 Ω
~1.5 µH

Output voltage measured open circuit and with 30 Ω load

Setup

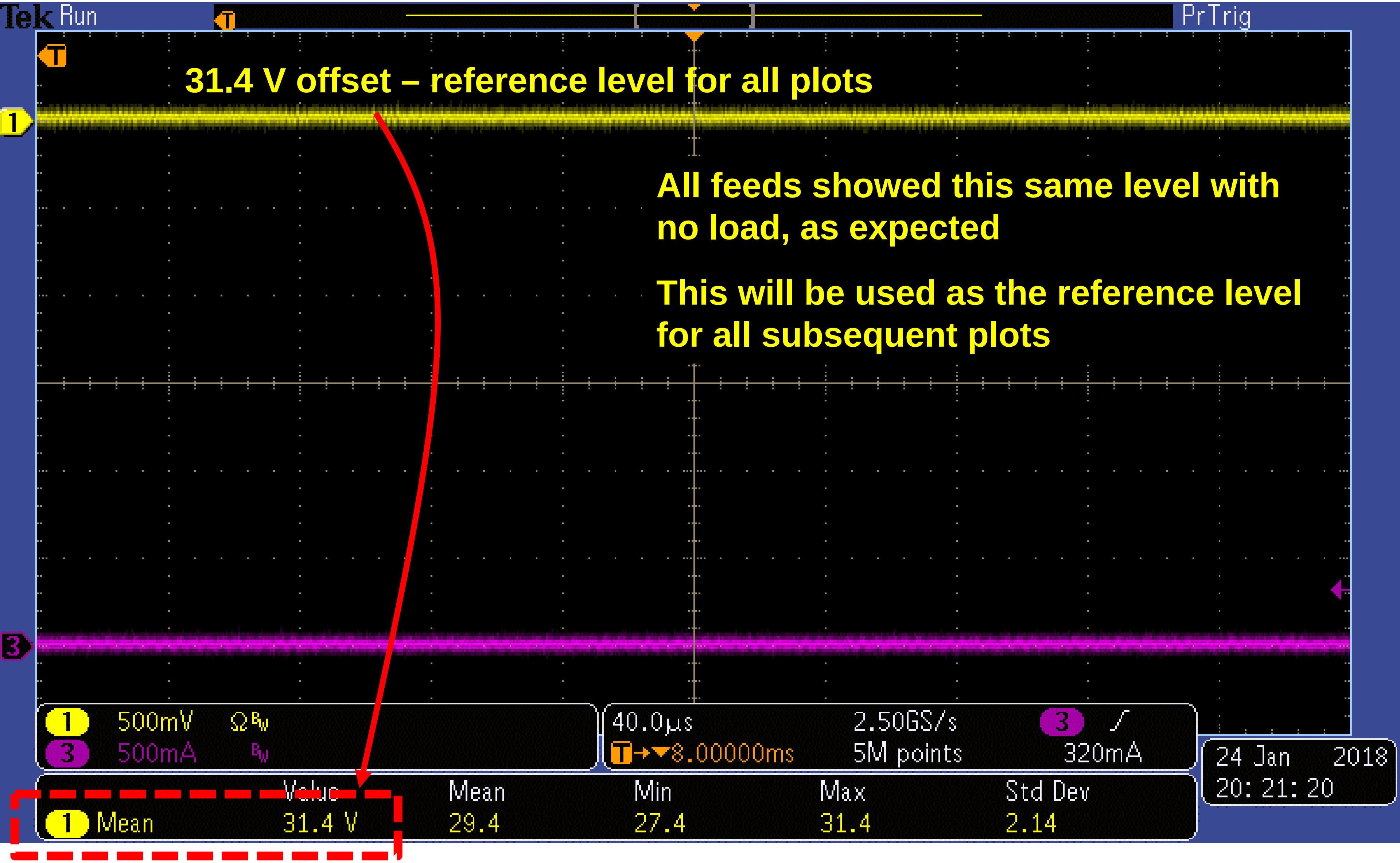


Decade box
Set to 30 Ω for 1 A load

Differential voltage probe monitoring potential across decade box load

Current probe monitoring current into decade box load

Reference Level – no load



31.4 V offset – reference level for all plots

All feeds showed this same level with no load, as expected

This will be used as the reference level for all subsequent plots

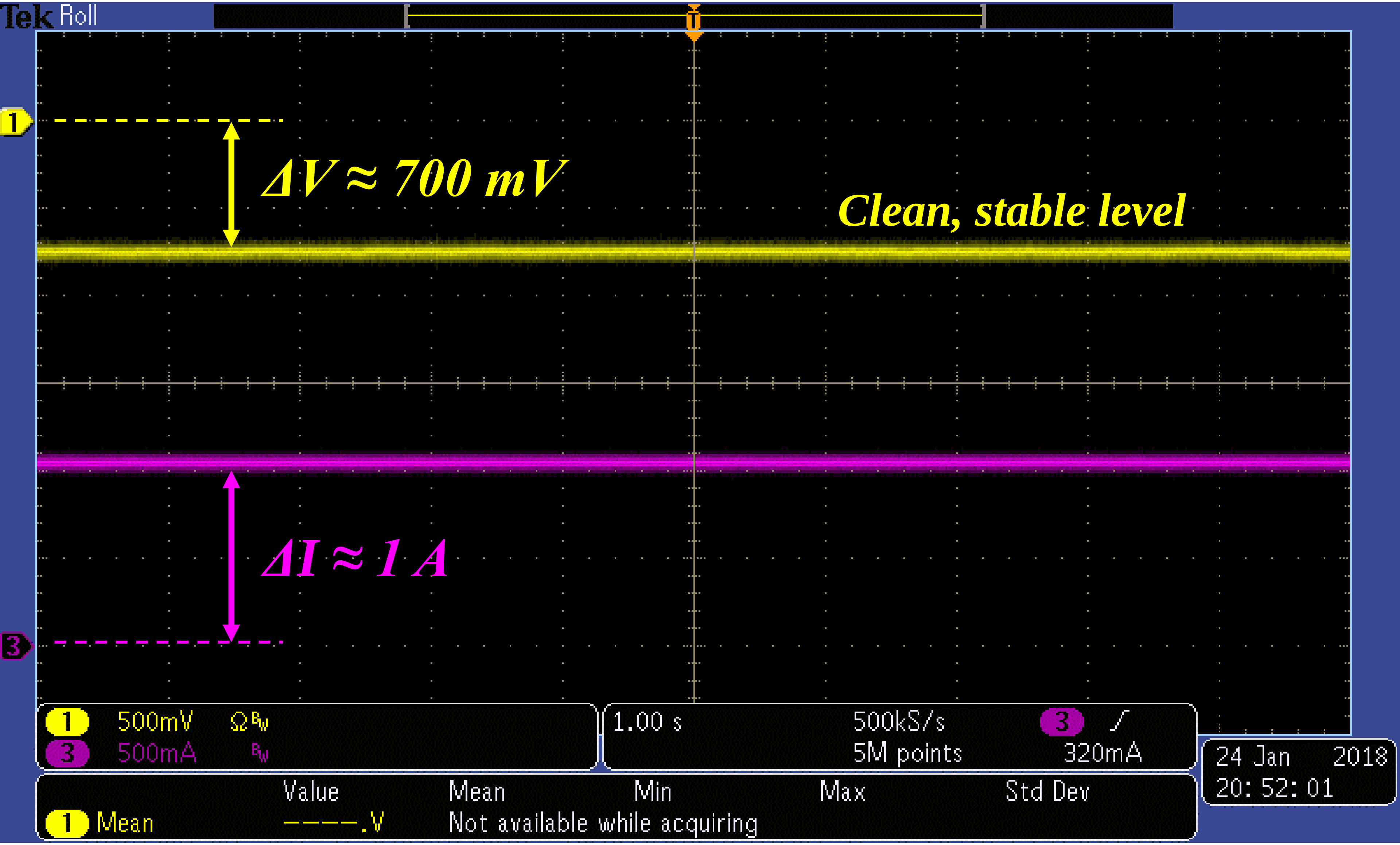
1 500mV Ω BW
3 500mA BW

40.0µs 2.50GS/s 3 ∫
T→▼8.00000ms 5M points 320mA

	Value	Mean	Min	Max	Std Dev
1 Mean	31.4 V	29.4	27.4	31.4	2.14

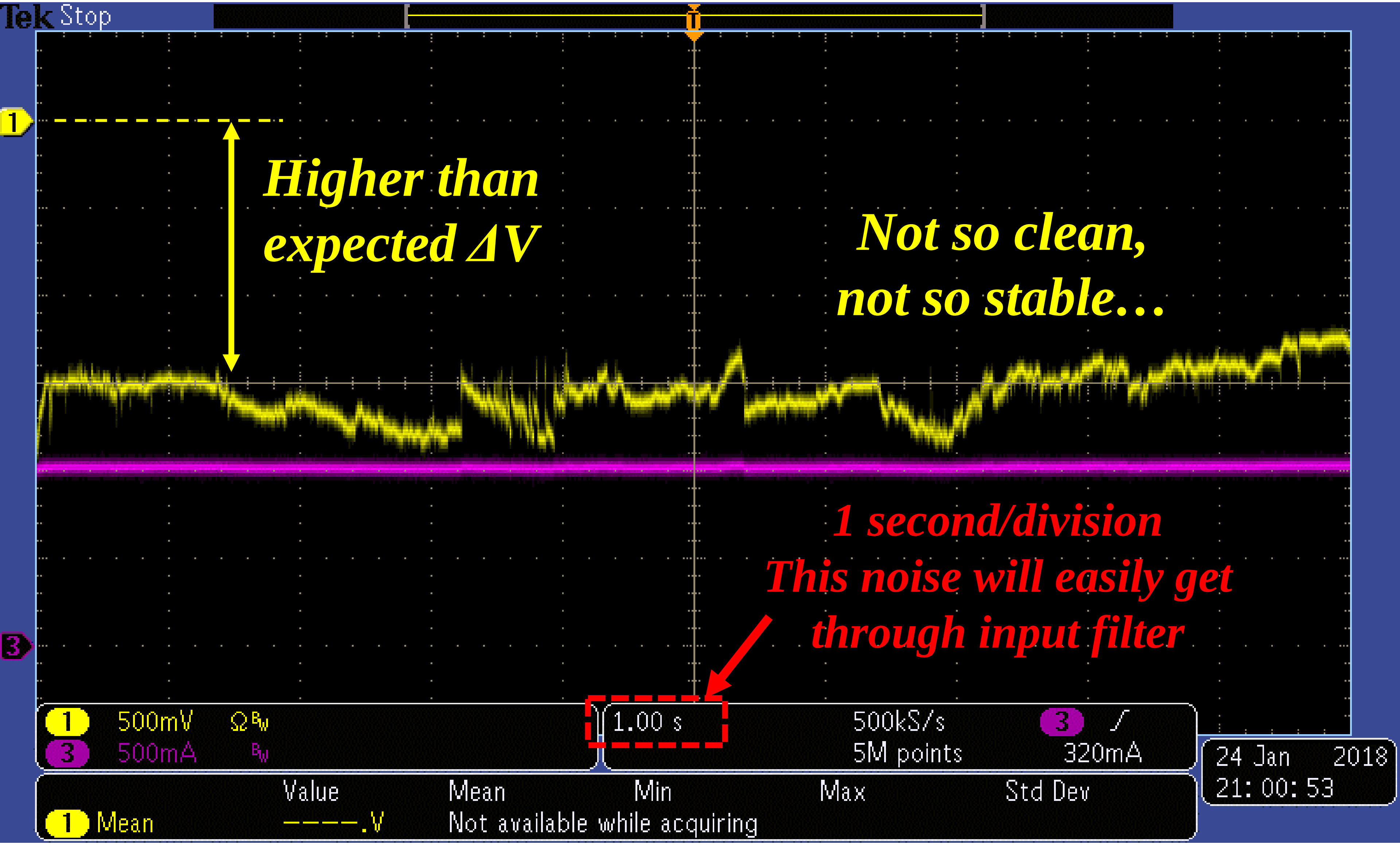
24 Jan 2018
20: 21: 20

MIRI ICE A



```
1  500mV  Ω Bw          1.00 s    500kS/s     3  ∫
3  500mA    Bw                    5M points   320mA
                                                       24 Jan  2018
          Value    Mean      Min    Max    Std Dev     20: 52: 01
1 Mean    -----.V  Not available while acquiring
```

MIRI ICE B – 30 Ω load



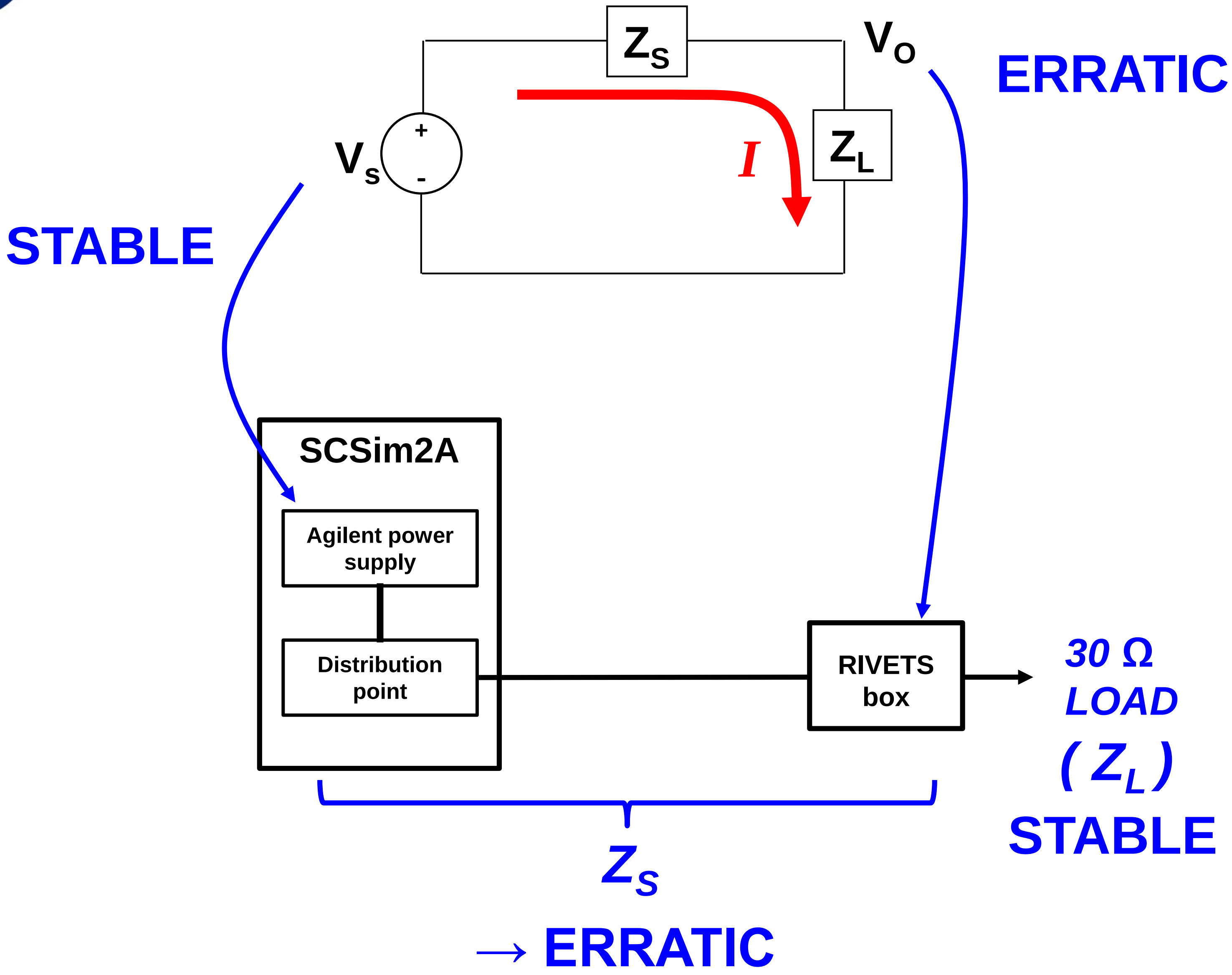
Higher than expected ΔV

Not so clean, not so stable…

1 second/division

This noise will easily get through input filter

Power Feed Voltage Drop



ERRATIC

STABLE

SCSim2A

Agilent power supply

Distribution point

RIVETS box

30 Ω LOAD

(Z_L)

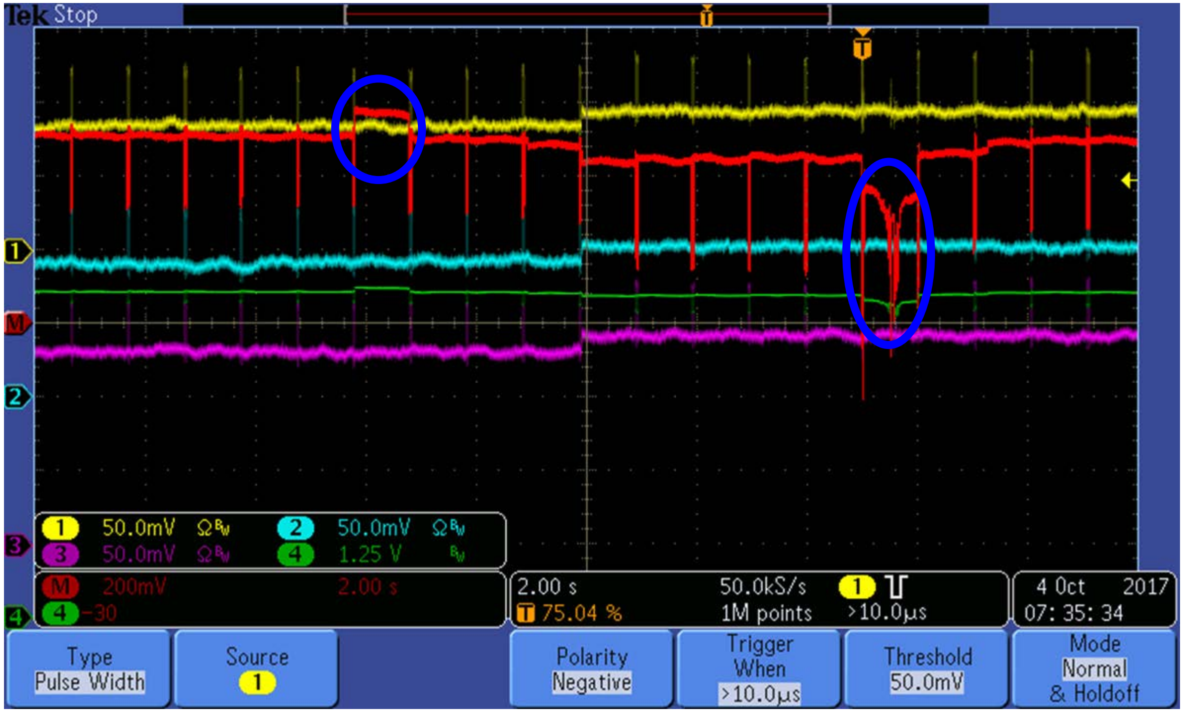
STABLE

Z_S

→ ERRATIC

Possible Relay Corrosion

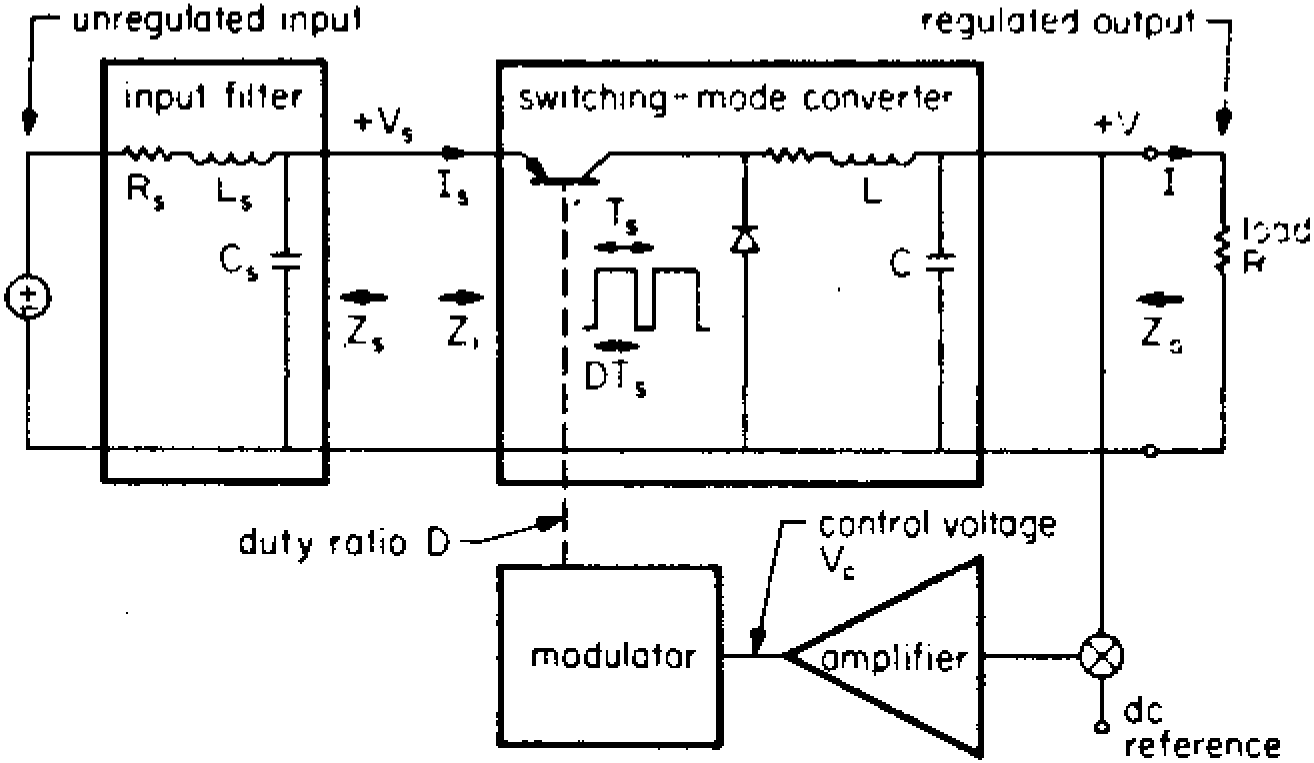
- Per GSFC Parts Branch (Code 562), erratic behavior is consistent with previously observed behavior of corroded relay contacts (SCSim has been in near continuous use for > 5 years)
- May contribute to instability in power interface
- May correlate to previously observed events



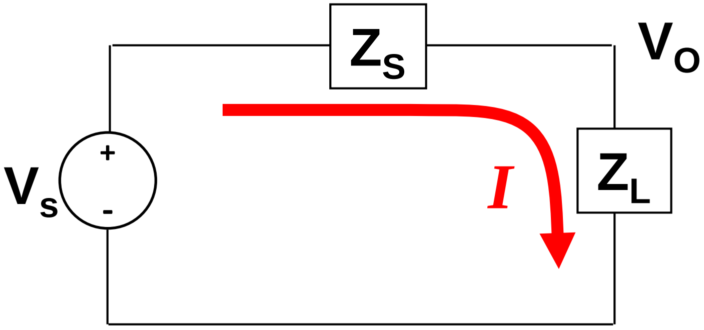
Type Pulse Width
Source 1
Polarity Negative
Trigger When >10.0μs
Threshold 50.0mV
Mode Normal & Holdoff

Load Stability - Power Converter Interface Model

- **From R.D. Middlebrook, “Input Filter Considerations In Design and Application of Switching Regulators” (1976)**
  - https://spaces.gsfc.nasa.gov/display/EMCWG/Power



Load Stability - Simplified Network Model



$$\frac{V_O}{V_S} = \frac{Z_L}{Z_L + Z_S} = \frac{1}{1 + \left(\frac{Z_S}{Z_L}\right)}$$

If Z_S and Z_L are complex: $Z_S = |Z_S|\angle\theta_S \quad Z_L = |Z_L|\angle\theta_L$

$$\frac{V_O}{V_S} = \frac{Z_L}{Z_L + Z_S} = \frac{1}{1 + \left|\frac{Z_S}{Z_L}\right| \angle(\theta_S - \theta_L)}$$

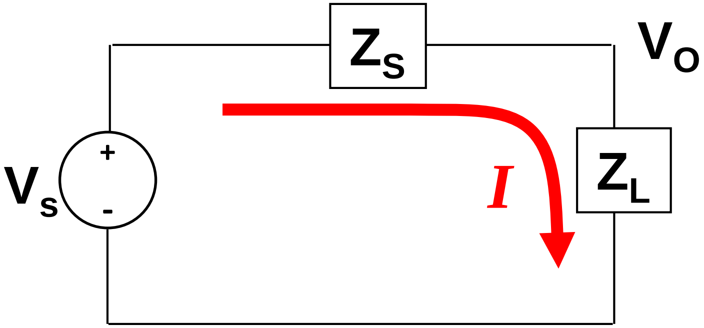
If $|Z_S| = |Z_L|$ and $(\theta_S - \theta_L) = +/- 180^o$:

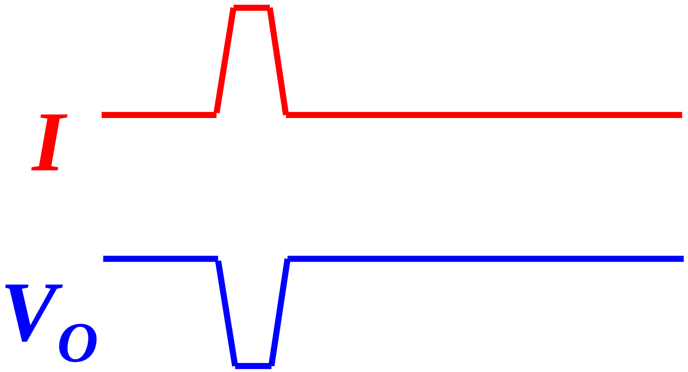
$$\frac{V_O}{V_S} = \frac{1}{1-1} = \frac{1}{0}$$

INSTABILITY, OSCILLATIONS, etc.

Instability Implications

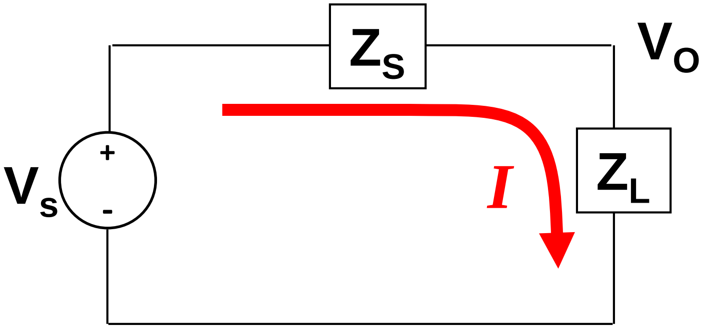
- ***$\theta_S - \theta_L \approx 0$***
  - Source and load are in phase and behave as a resistive divider
  - Magnitude ratio irrelevant; stable for any combination of Z_S and Z_L
  - Current transients ΔI at load induce temporary $\Delta V_O = \Delta I^* Z_S$ at load input; input voltage recovers in controlled, stable manner

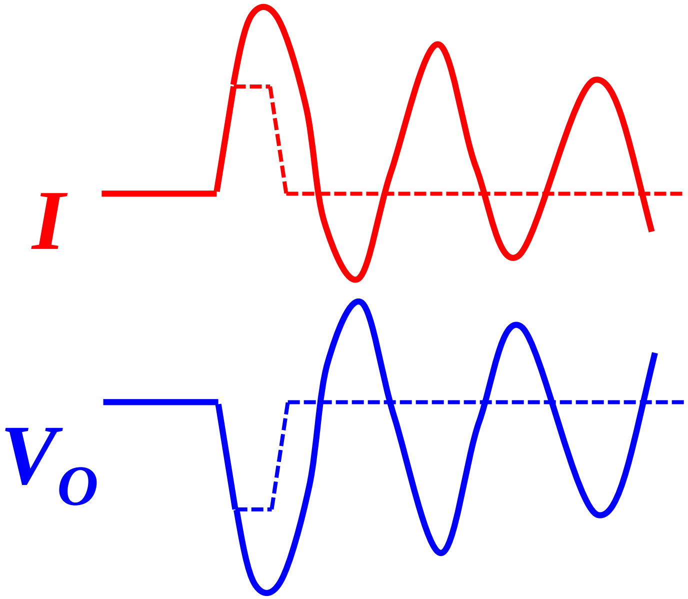




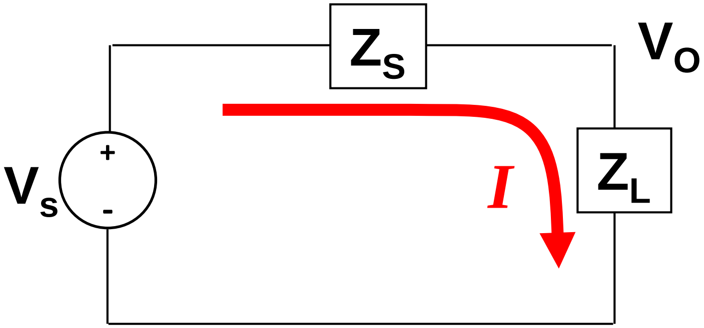
Instability Implications (cont.)

- ***$\theta_S - \theta_L \approx 180^o$***
  - Source looks like resistance, load looks like negative resistance
    - Simplified model for power converter
    - For constant power load, current increases when voltage drops and vice versa
  - When magnitudes are (nearly) equal, current from any transient increases uncontrollably
    - larger than expected ΔV_O, oscillations, etc.





Middlebrook Stability Criteria



$$\frac{V_O}{V_S} = \frac{Z_L}{Z_L + Z_S} = \frac{1}{1 + \left(\frac{Z_S}{Z_L}\right)}$$

To ensure system stability:

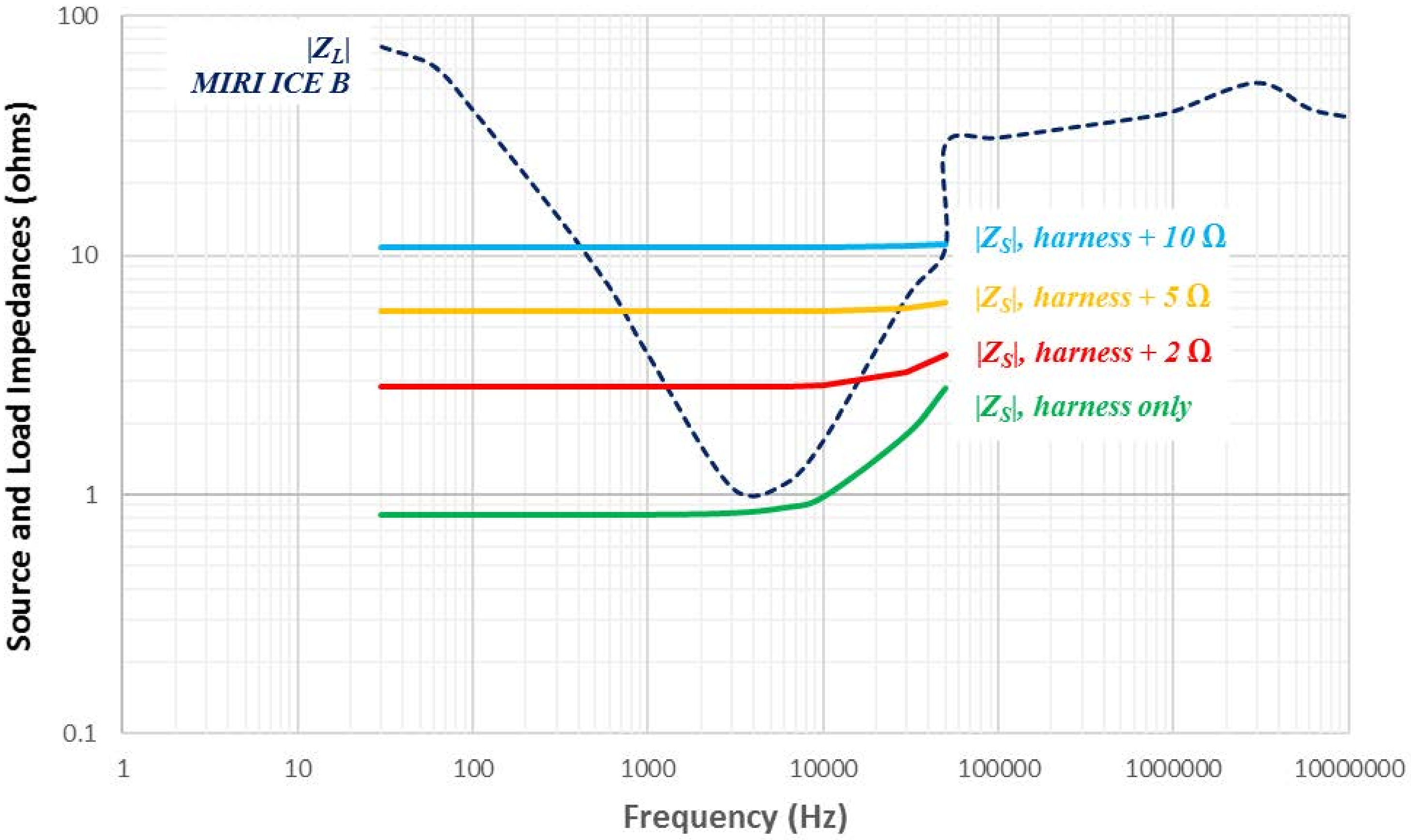
$$|Z_S| << |Z_L|$$

AT ALL FREQUENCIES

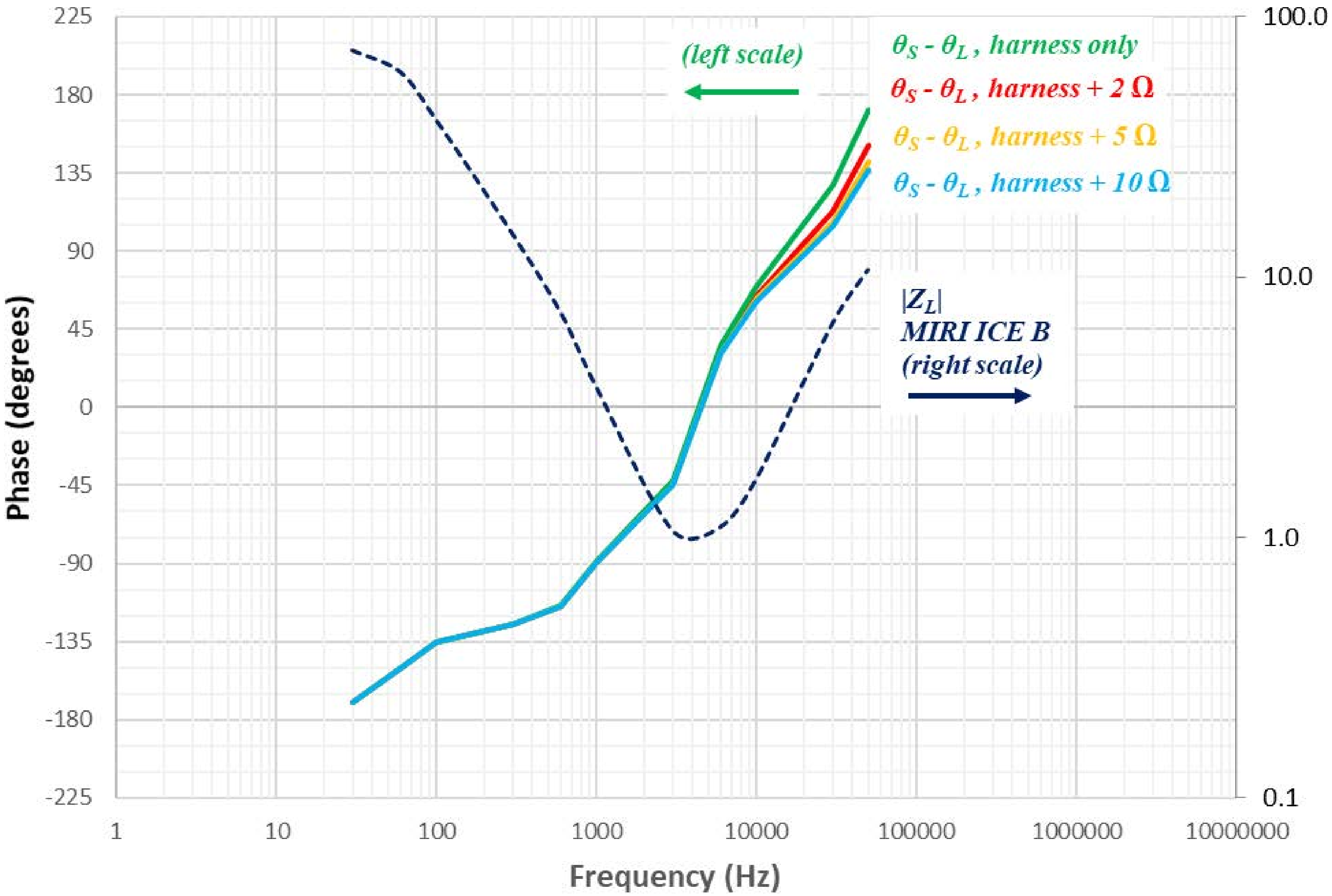
If this criterion is not met, need to look at phase margin at frequencies at which it is not

$|Z_S|$ vs. $|Z_L|$

- **Middlebrook magnitude criterion met when $|Z_S|$ curve is under $|Z_L|$ curve at all frequencies (curves never cross each other)**
  - Met for harness only with not much margin
- **Violated for increasing values of relay contact resistance – need to look at phase at frequencies where violated (next slide)**



θ_S - θ_L



Summary

- **Though not proven, instability is leading theory for root cause**
  - Middlebrook magnitude criteria violated from ~500 Hz to ~50 kHz for increasing values of relay contact series resistance
  - Decent phase margin (difference between $\theta_S - \theta_L$ and 180°) for most of frequency range where magnitude criteria violated
  - Could violate magnitude and phase criteria with temporary large increase in resistance
  - Narrow frequency range of potential instability is consistent with intermittent nature of original problem under investigation
- **If true, places problem squarely on SCSim2A and exonerates MIRI ICE-B**
- **All relays and sockets replaced in SCSim2A**
  - All power feeds now “clean”; show no trace of erratic behavior
  - Relays provided to GSFC parts branch for evaluation; could not reproduce erratic behavior 🤢
- **Follow-up tests during OTIS post-shipment functional test at NG to verified that MIRI ICE-B is still functioning properly**