Troubleshooting Challenges on the James Webb Space Telescope (JWST)

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John McCloskey

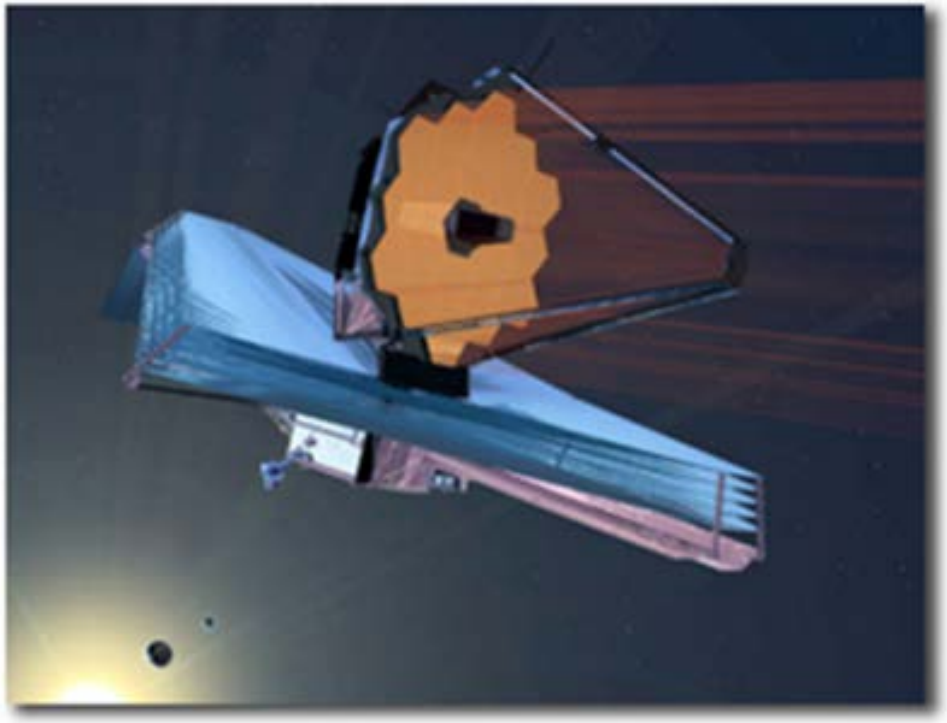
NASA/GSFC Chief EMC Engineer
301-286-5498
John.C.McCloskey@nasa.gov

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

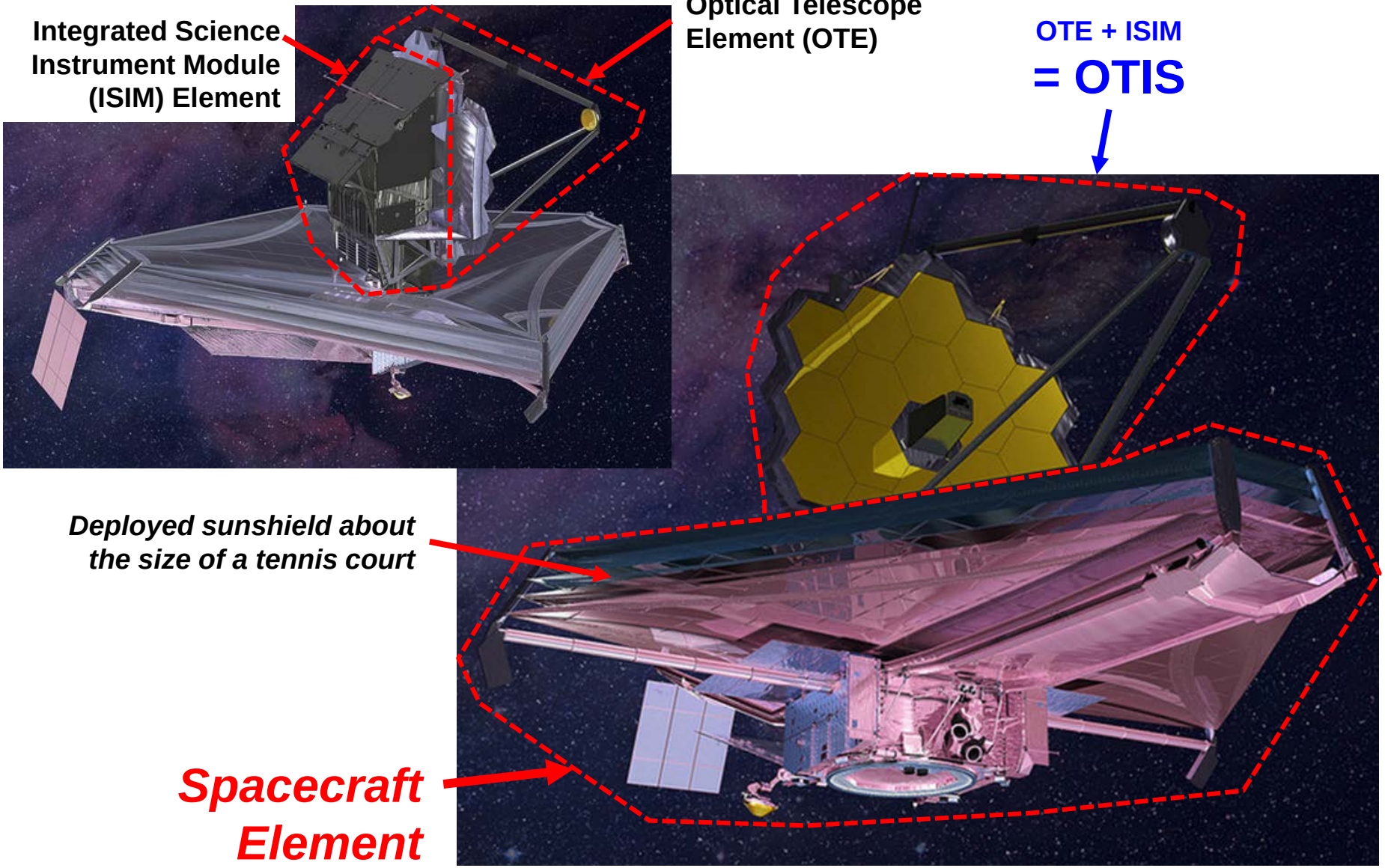


“Elements” of JWST

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

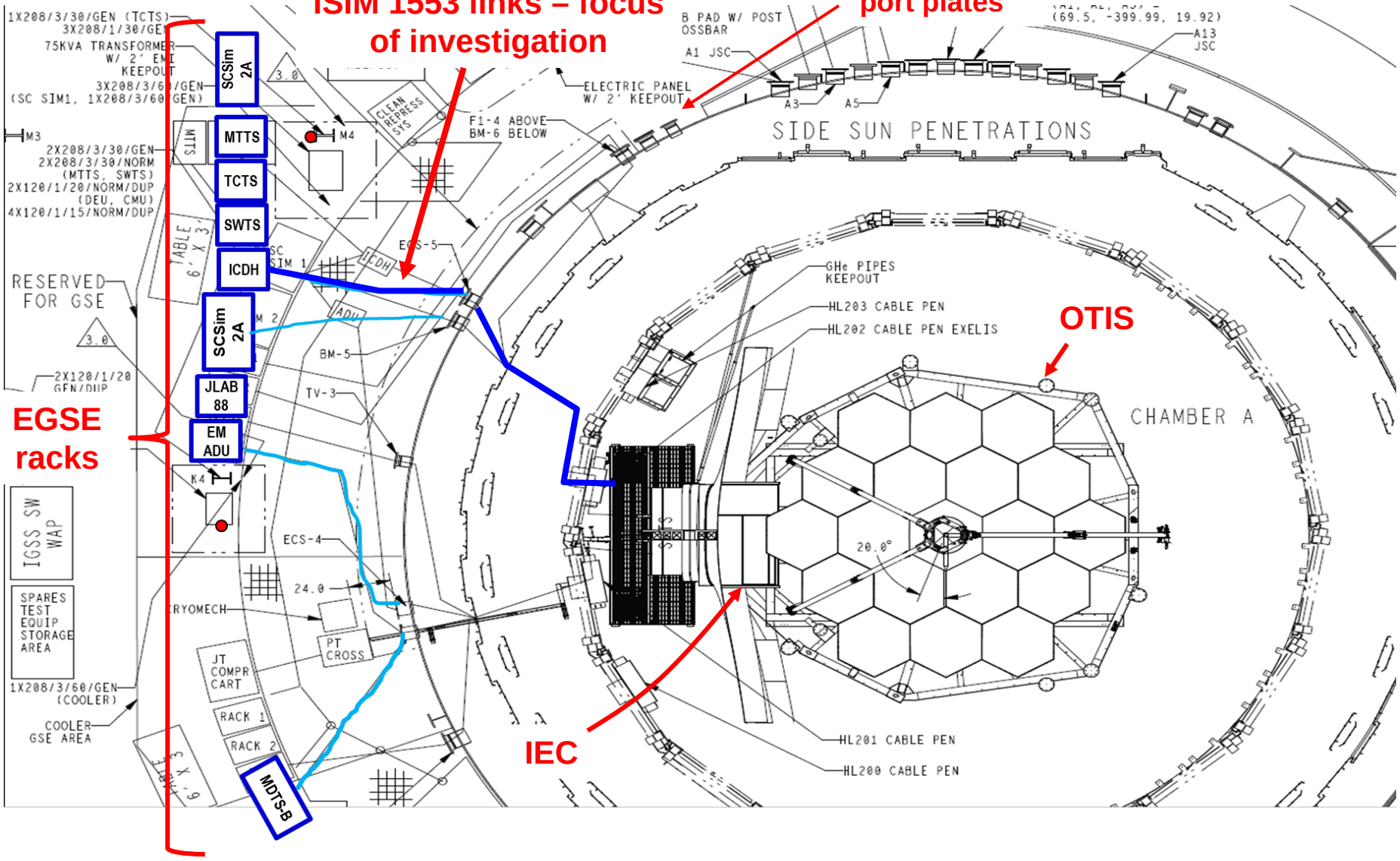
- **OTIS**
  - Completed cryo vacuum test campaign in large chamber at Johnson Space Center (JSC), May – Dec. 2017
  - Shipped to Northrop Grumman's (NG's) Space Park facility, Redondo Beach, CA, Feb. 2018
- **Spacecraft**
  - Being integrated at NG's Space Park facility, Redondo Beach, CA
  - Final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

Focus of Presentation

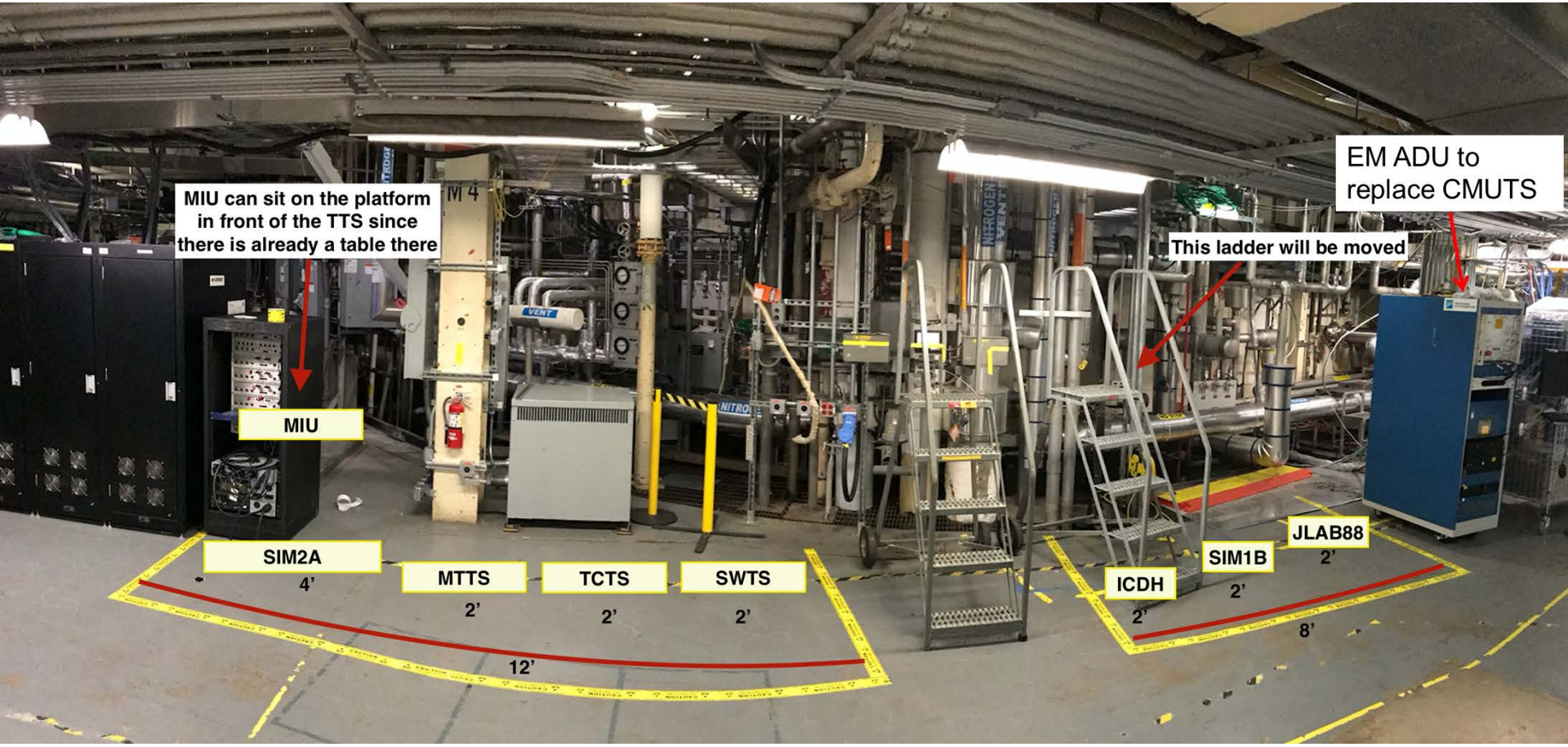
- **This presentation summarizes recent troubleshooting on OTIS at JSC**
  - My services were requested to address any possible EMC/noise issues
  - In a previous life, I was the ISIM Electrical Systems Lead Engineer
  - Both “hats” were necessary
  - This turned out to be an investigation of power quality
- **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



General Test Layout (cont.)



General Test Layout (cont.)

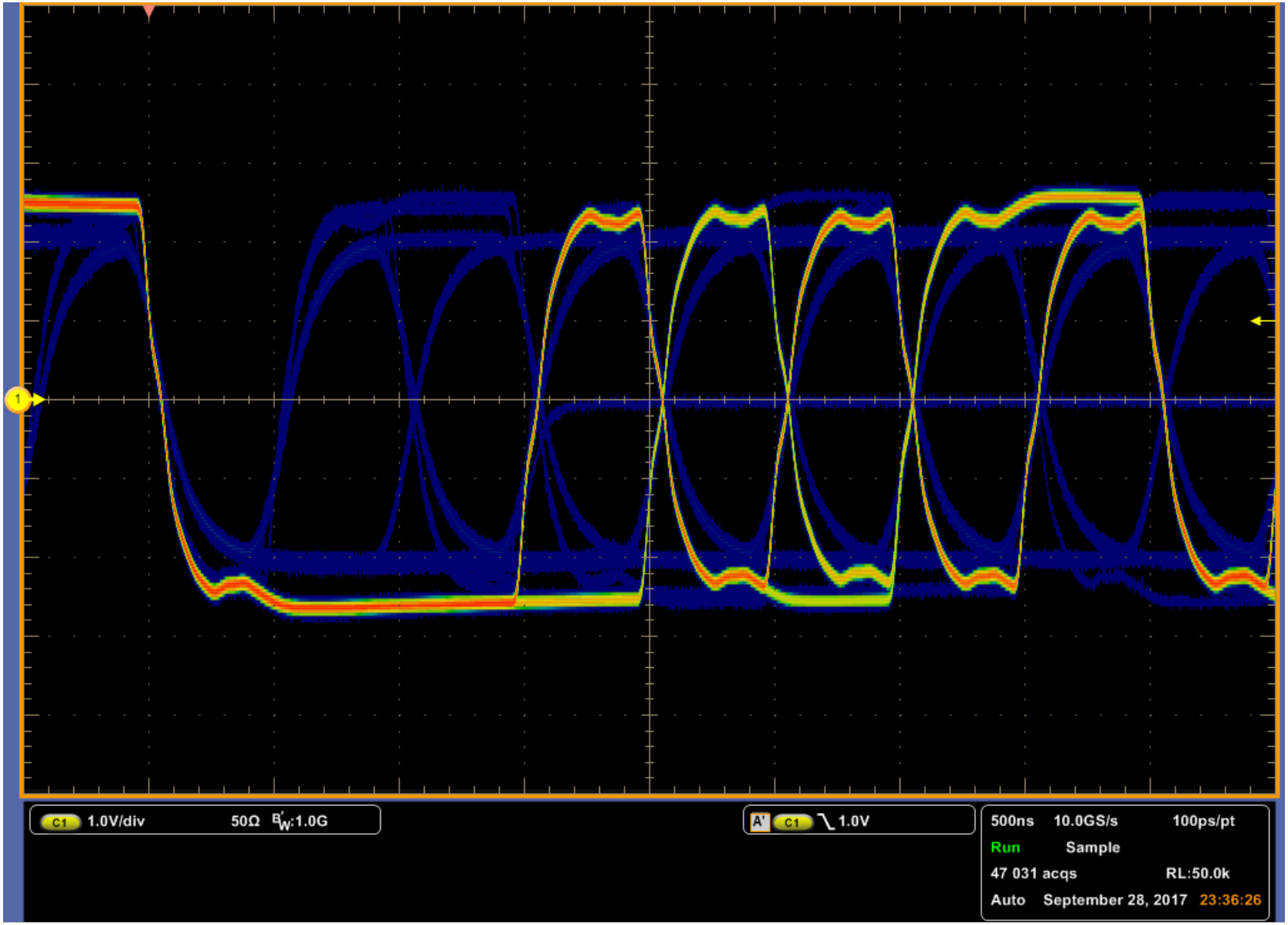
Troubleshooting Challenges

- **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**

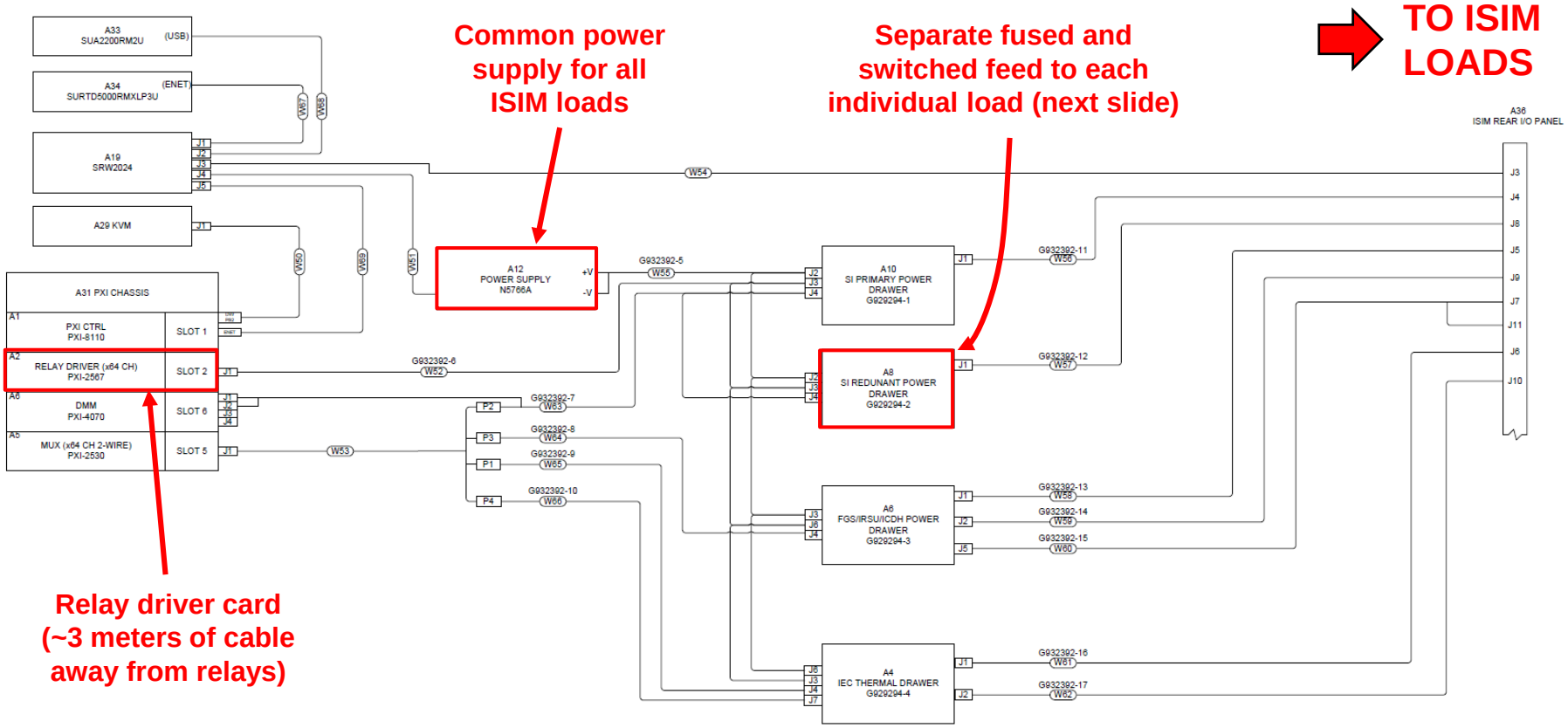
Investigation Overview

- **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

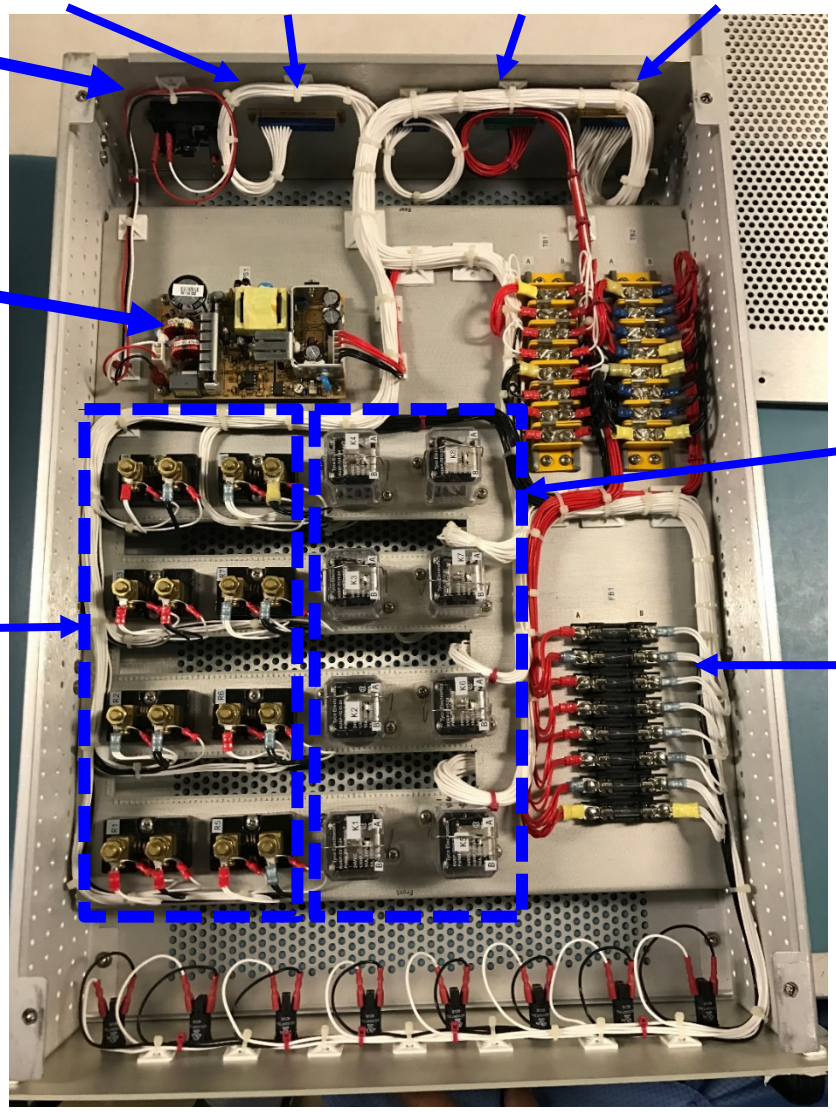
1553 Bus Signals



SCSim2A Power Distribution Overview

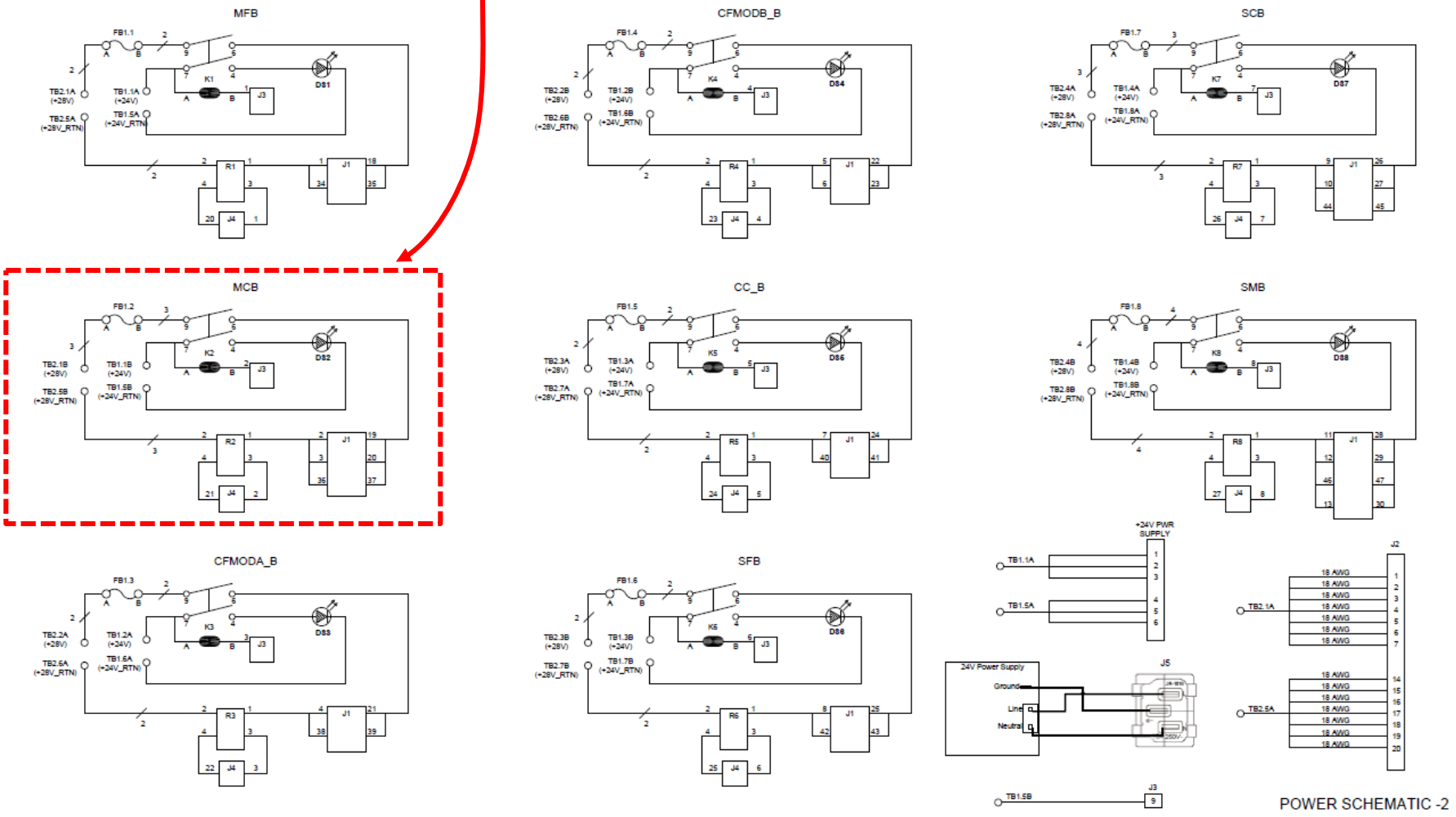


SI Redundant Power Drawer Interior



SI Redundant Power Drawer Block Diagram

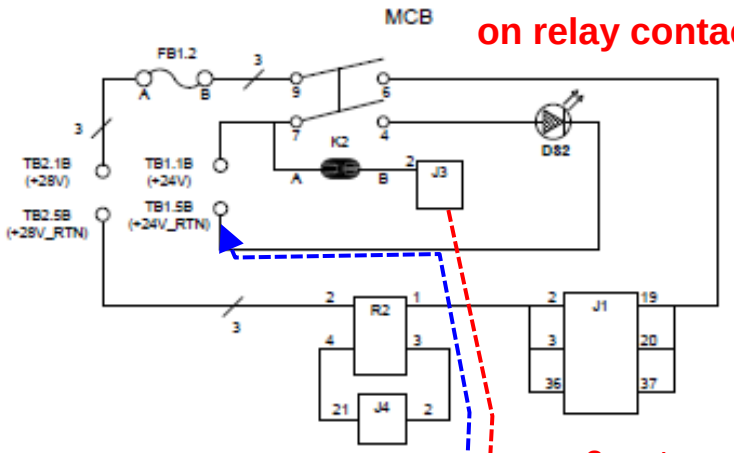
MIRI ICE B feed
(identical to all others)



SI Redundant Power Drawer Block Diagram

No transient suppression elements on relay contacts or coils

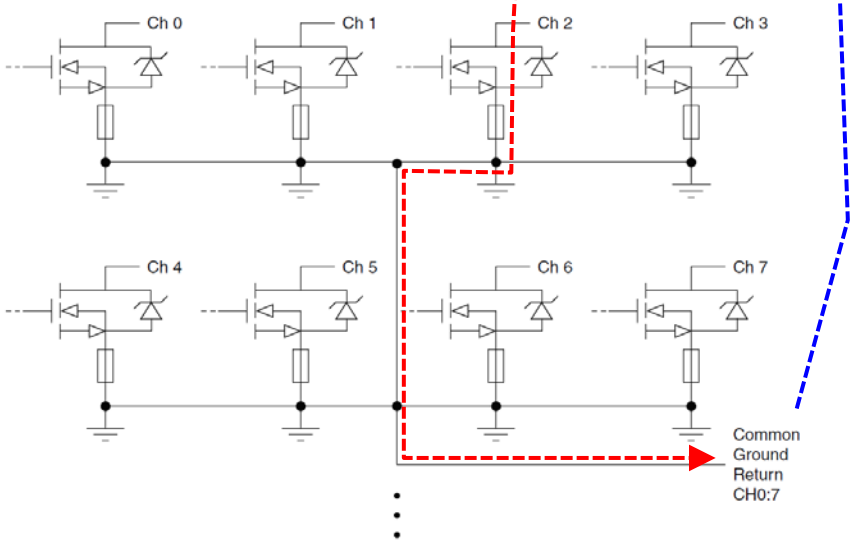
Power drawer



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

Relay driver card

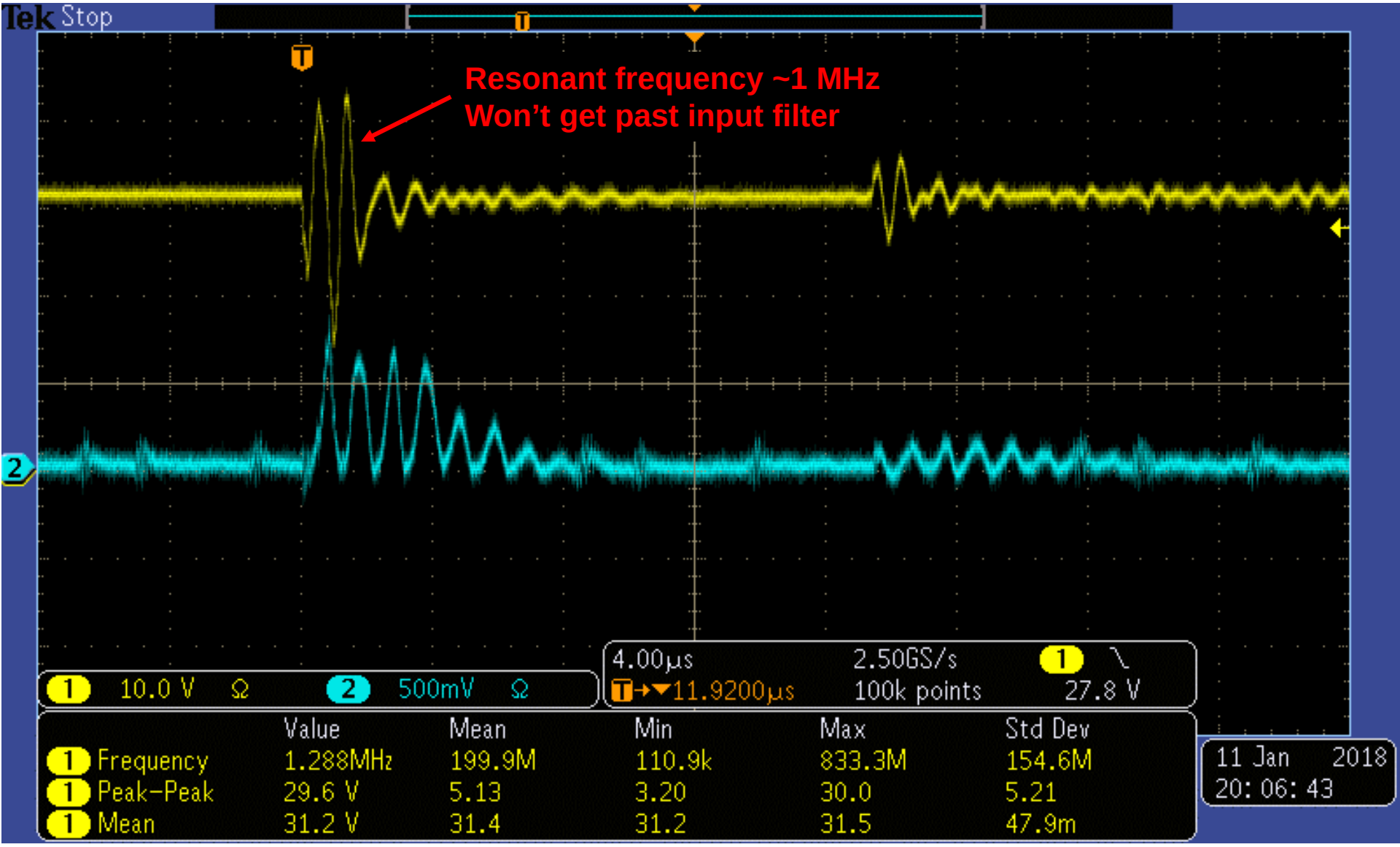
Limited transient suppression (~3 meters of cable from relays)



SCSim Power Distribution Observations

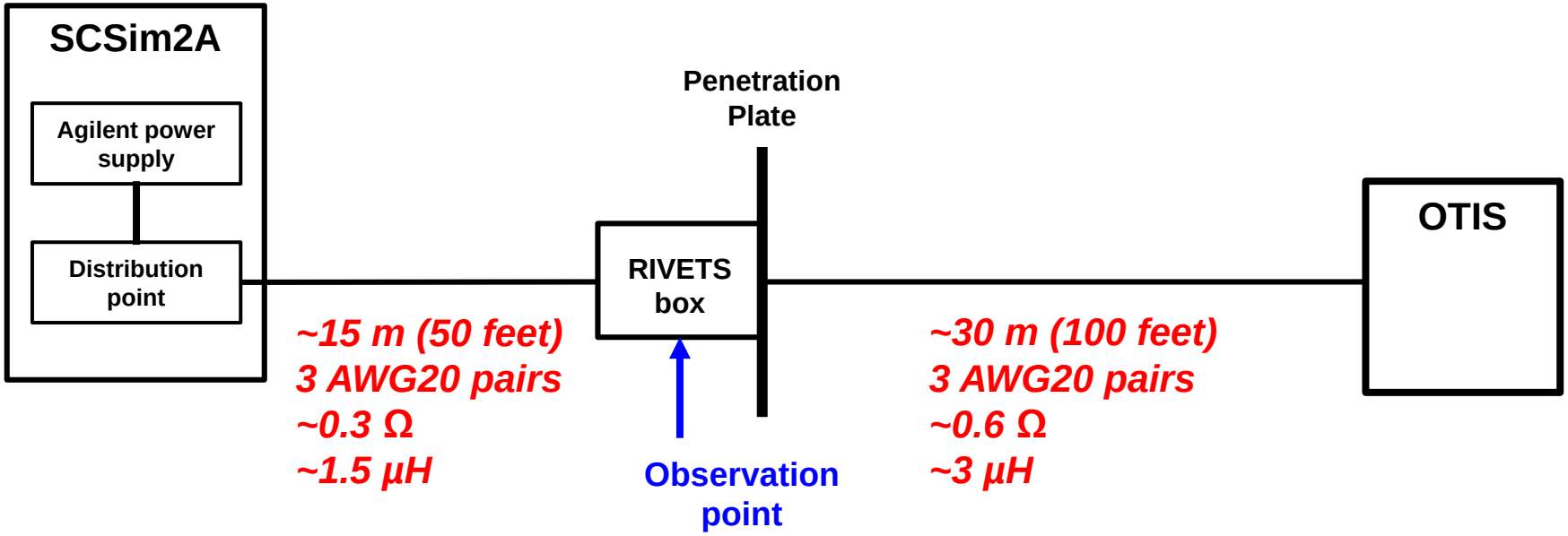
- **Mechanical relays**
  - Inherently noisy (contact bouncing, etc.)
  - No transient suppression elements (transorbs, etc.)
- **Long cables and large current loops**
  - Increased risk of coupling
- **Measurements show significant noise generated by relay switching transients, but…**
  - These relays 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



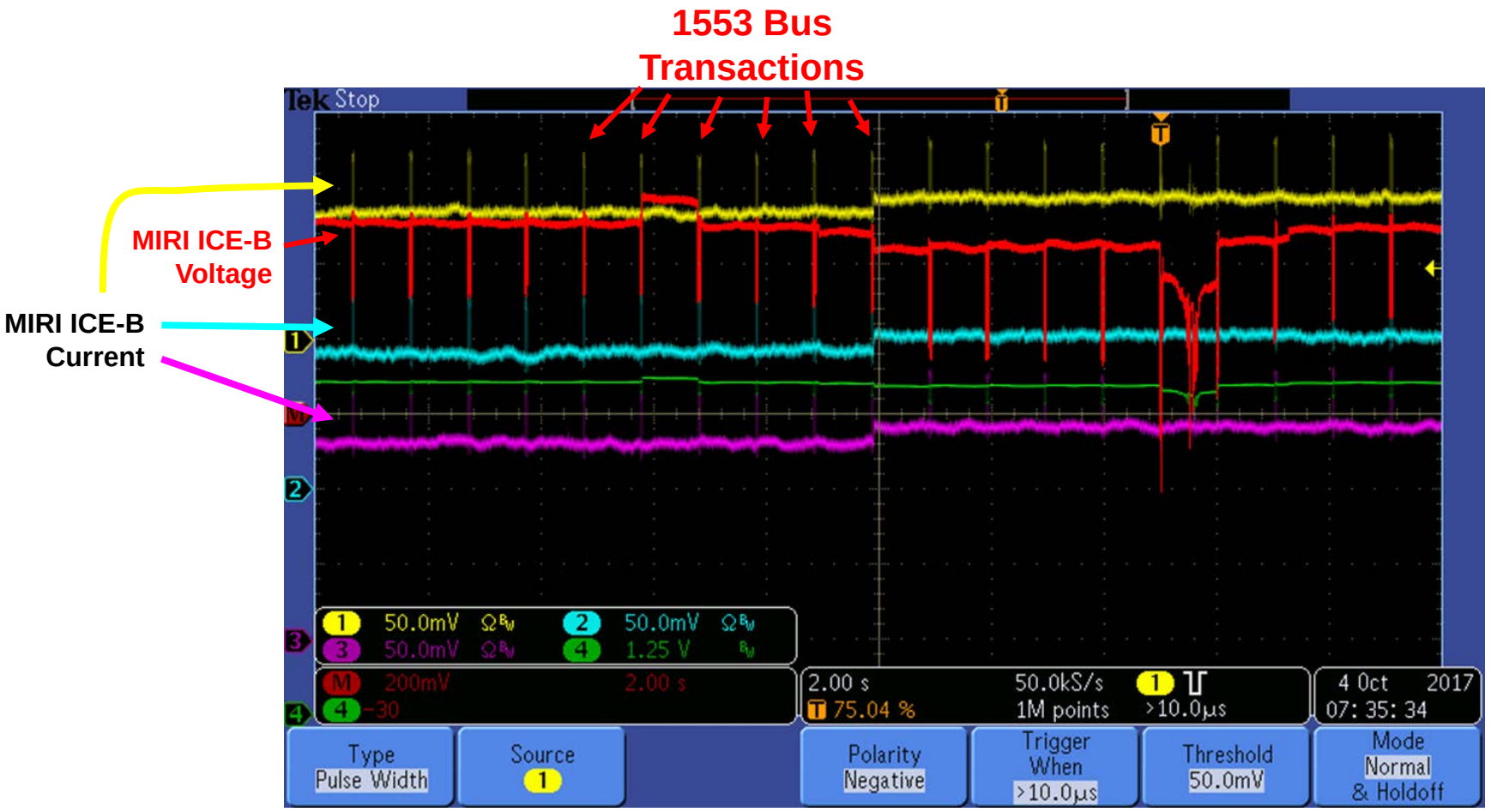
Where Did That Leave Us?

- 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***



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**

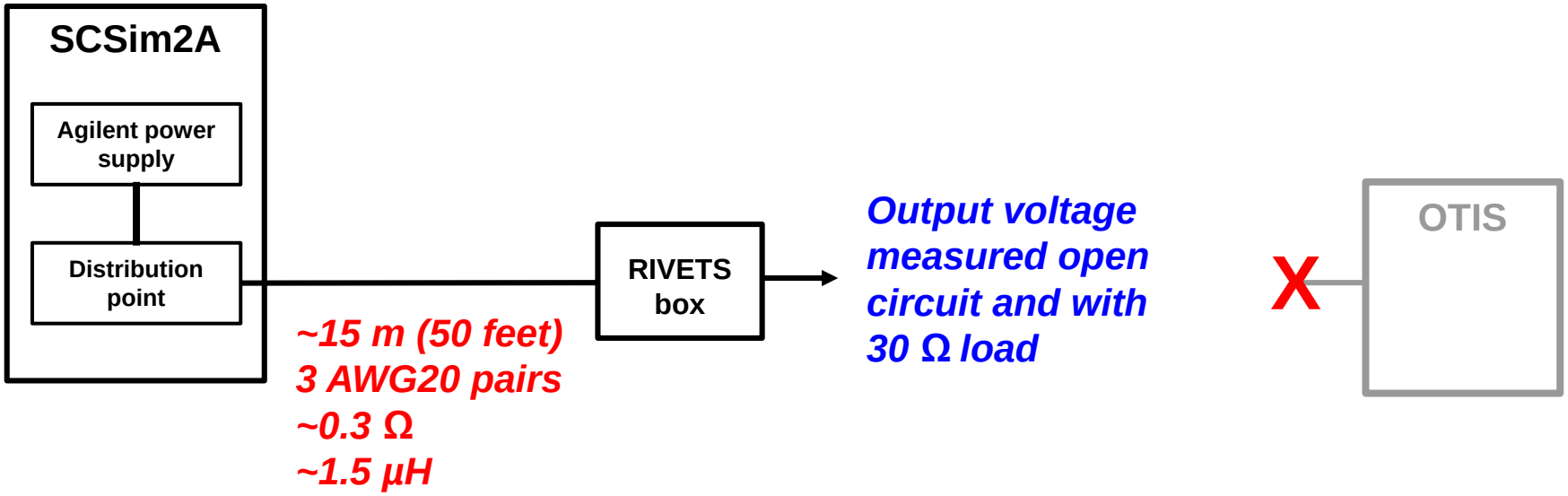
- **LED TO CLOSER LOOK AT POWER INTERFACES…**

Unexplained Voltage Shifts

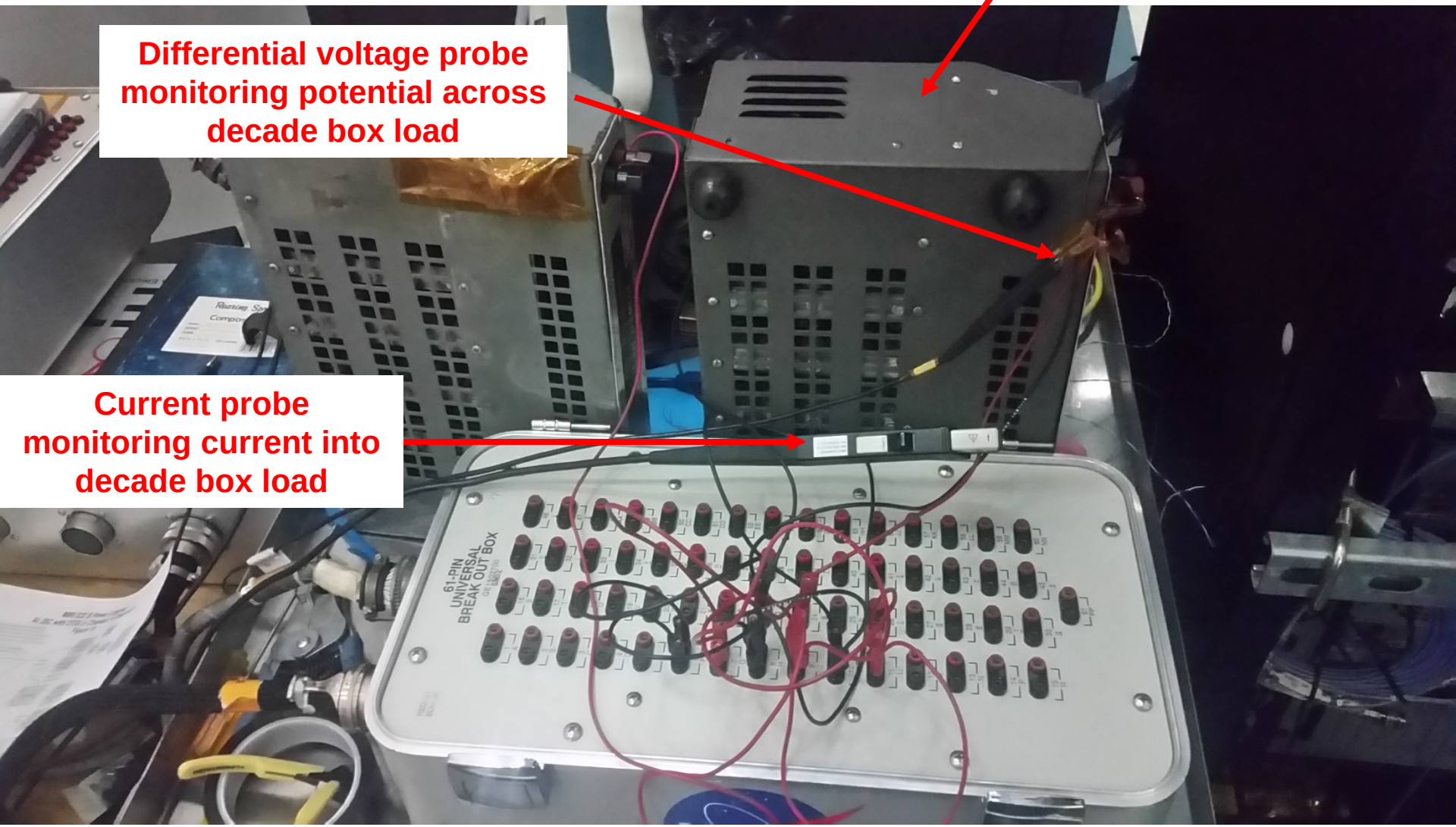
- **Occasional shifts in voltage with no corresponding change in MIRI ICE-B current**
  - Did not coincide with 1553 events, but indicated erratic behavior on power bus
- **IEC heaters only equipment switching on/off power bus**
  - Voltage shifts did not coincide with switching events
  - Most switching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

Power Feed Voltage Drop

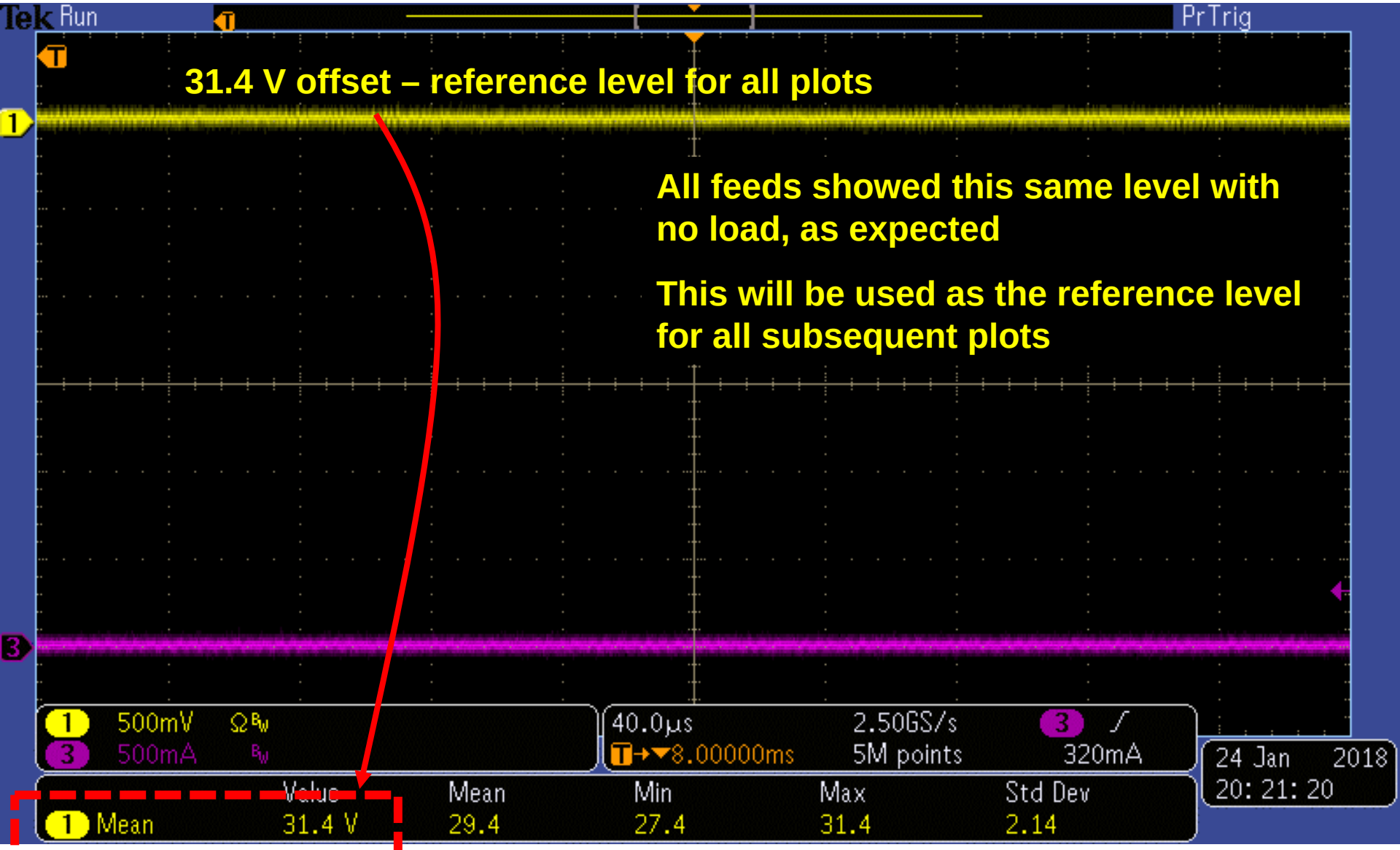
- **After completion of OTIS cryovac test, measured output voltage at RIVETS:**
  - Open circuit
  - With 30 ohm load (1 A at 30 V)
  - Set scope offset to open circuit voltage and expanded vertical scale
- **ΔV divided by ΔI of 1 A gives source impedance**
  - Should be nice, stable voltage, right?



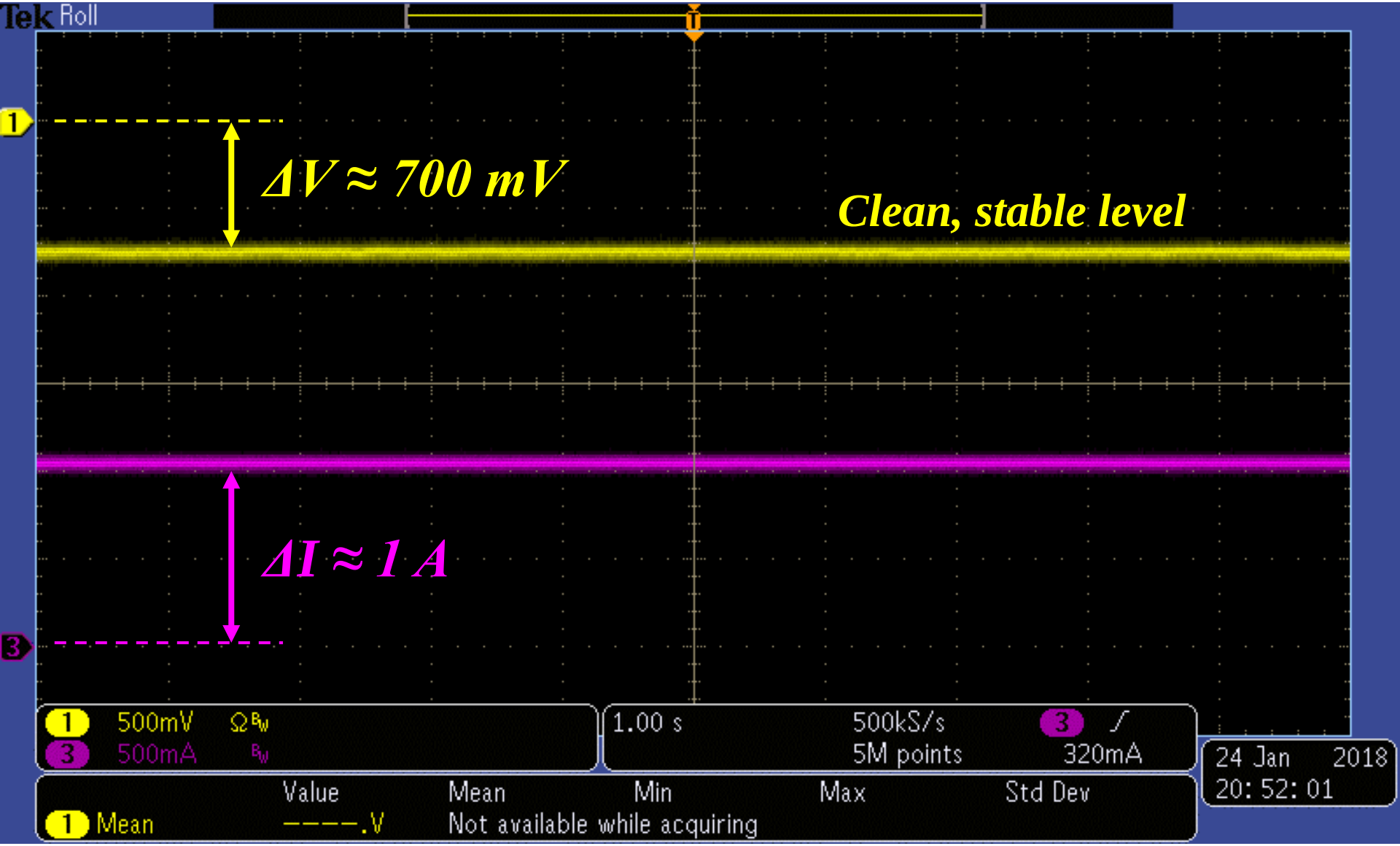
Setup


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
61-PIN UNIVERSAL BREAK OUT BOX

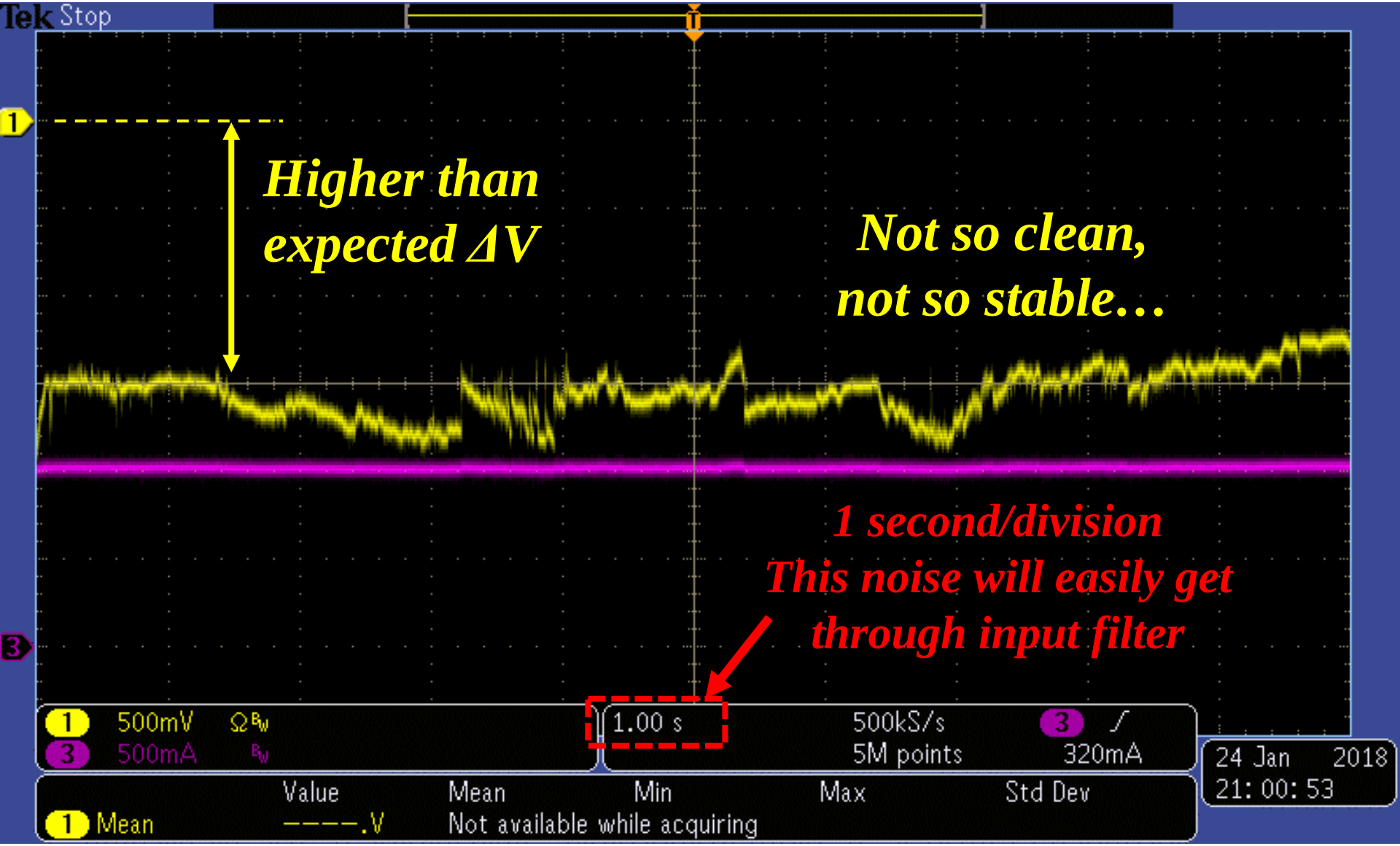
Reference Level – no load



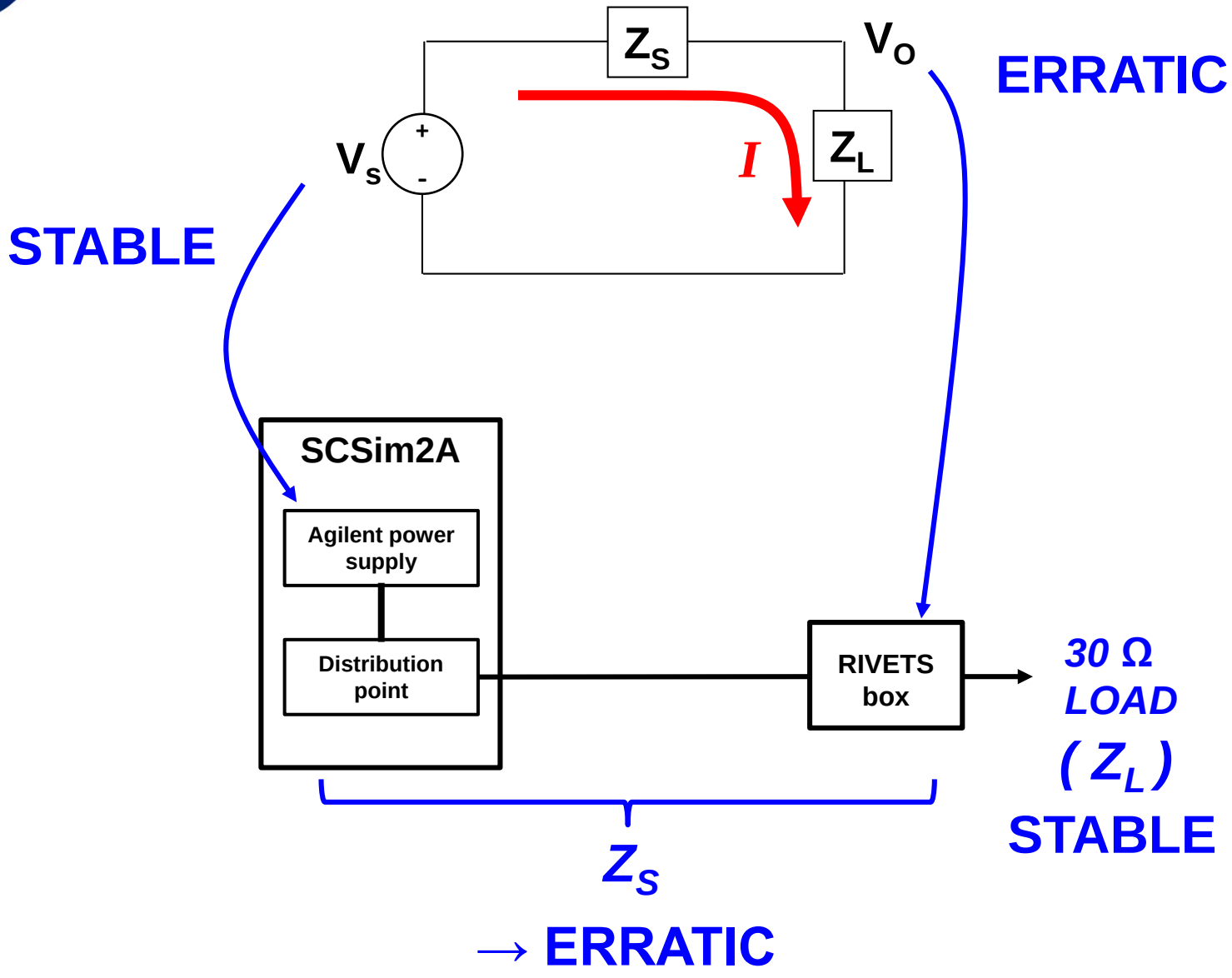
MIRI ICE A


Tek Roll
ΔV ≈ 700 mV
Clean, stable level
ΔI ≈ 1 A
1 500mV
3 500mA
1.00 s
500kS/s
5M points
3 320mA
24 Jan 2018
20: 52: 01
Value Mean Min Max Std Dev
1 Mean ----.V Not available while acquiring

MIRI ICE B – 30 Ω load

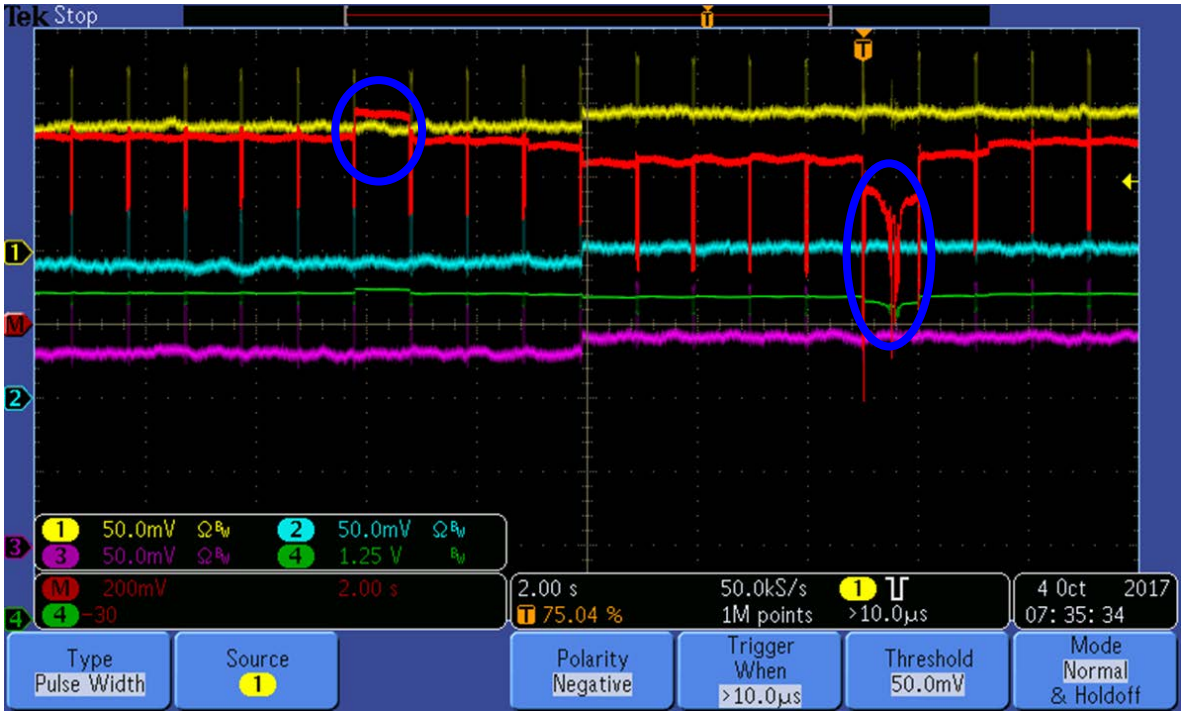


Power Feed Voltage Drop



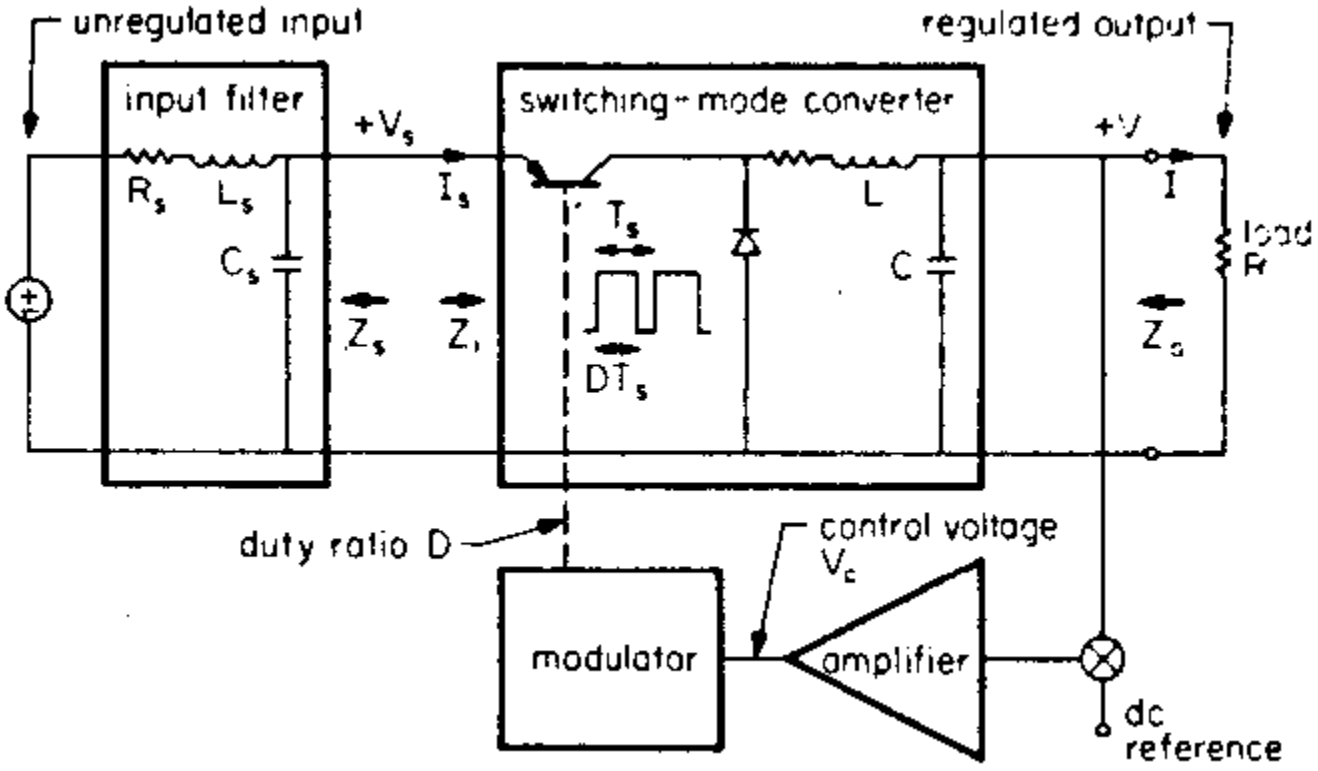
Possible Relay Corrosion

- 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

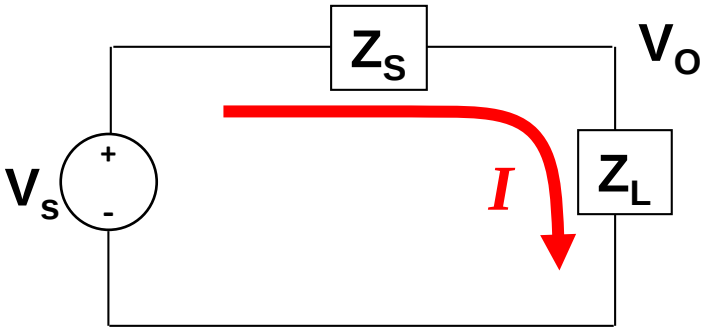


Load Stability - Power Converter Interface Model

- **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: $Z_S = |Z_S|\angle\theta_S \quad Z_L = |Z_L|\angle\theta_L$

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

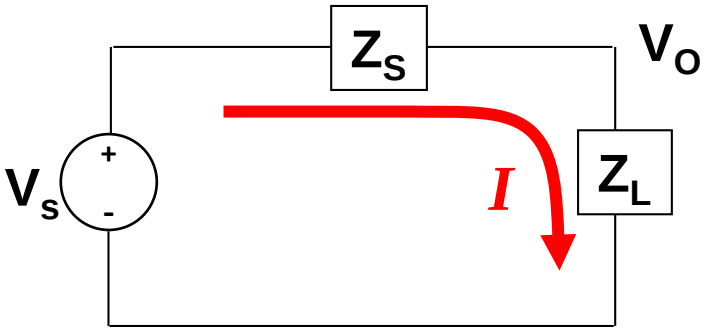
If $|Z_S| = |Z_L|$ and $(\theta_S - \theta_L) = +/- 180^o$:

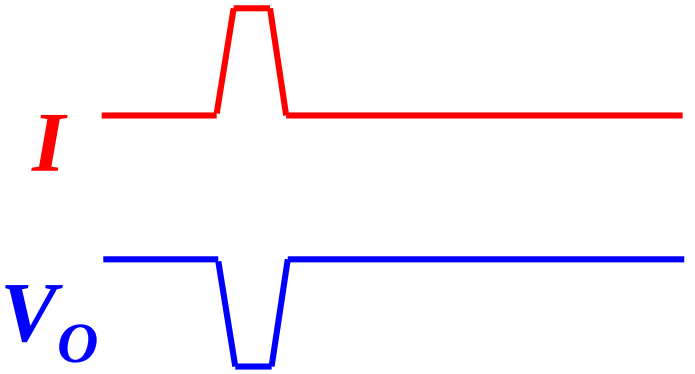
$$\frac{V_O}{V_S} = \frac{1}{1 - 1} = \frac{1}{0}$$

INSTABILITY, OSCILLATIONS, etc.

Instability Implications

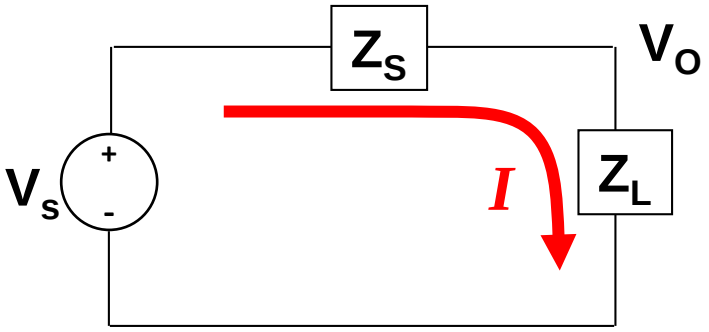
- $\theta_S - \theta_L \approx 0$
  - Source and load are in phase and behave as a resistive divider
  - Magnitude ratio irrelevant; stable for any combination of Z_S and Z_L
  - Current transients ΔI at load induce temporary $\Delta V_O = \Delta I * Z_S$ at load input; input voltage recovers in controlled,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

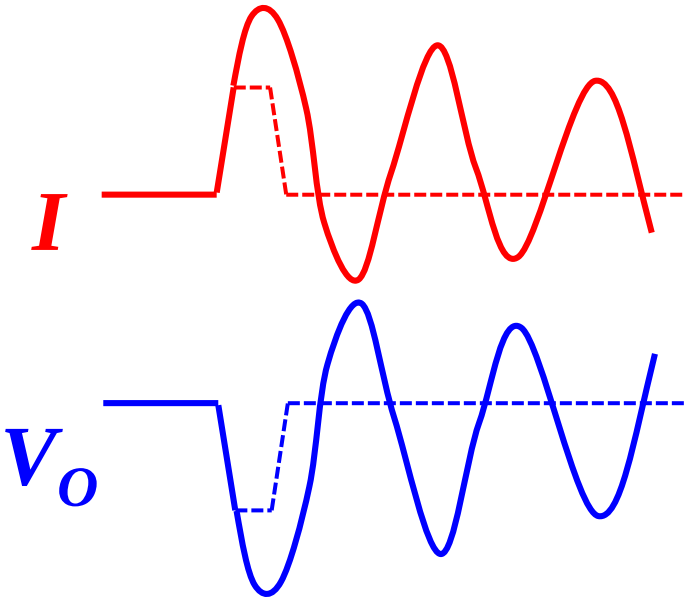




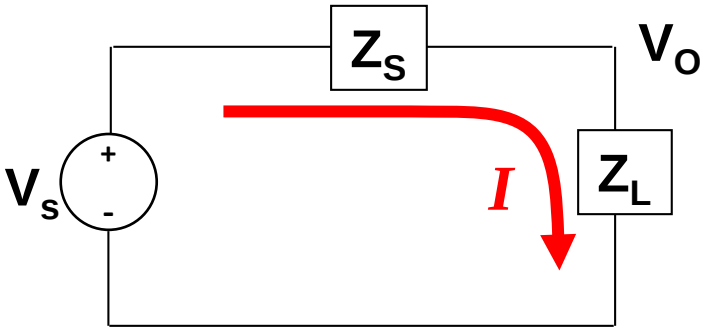
Instability Implications (cont.)

- $\theta_S - \theta_L \approx 180^o$
  - 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:

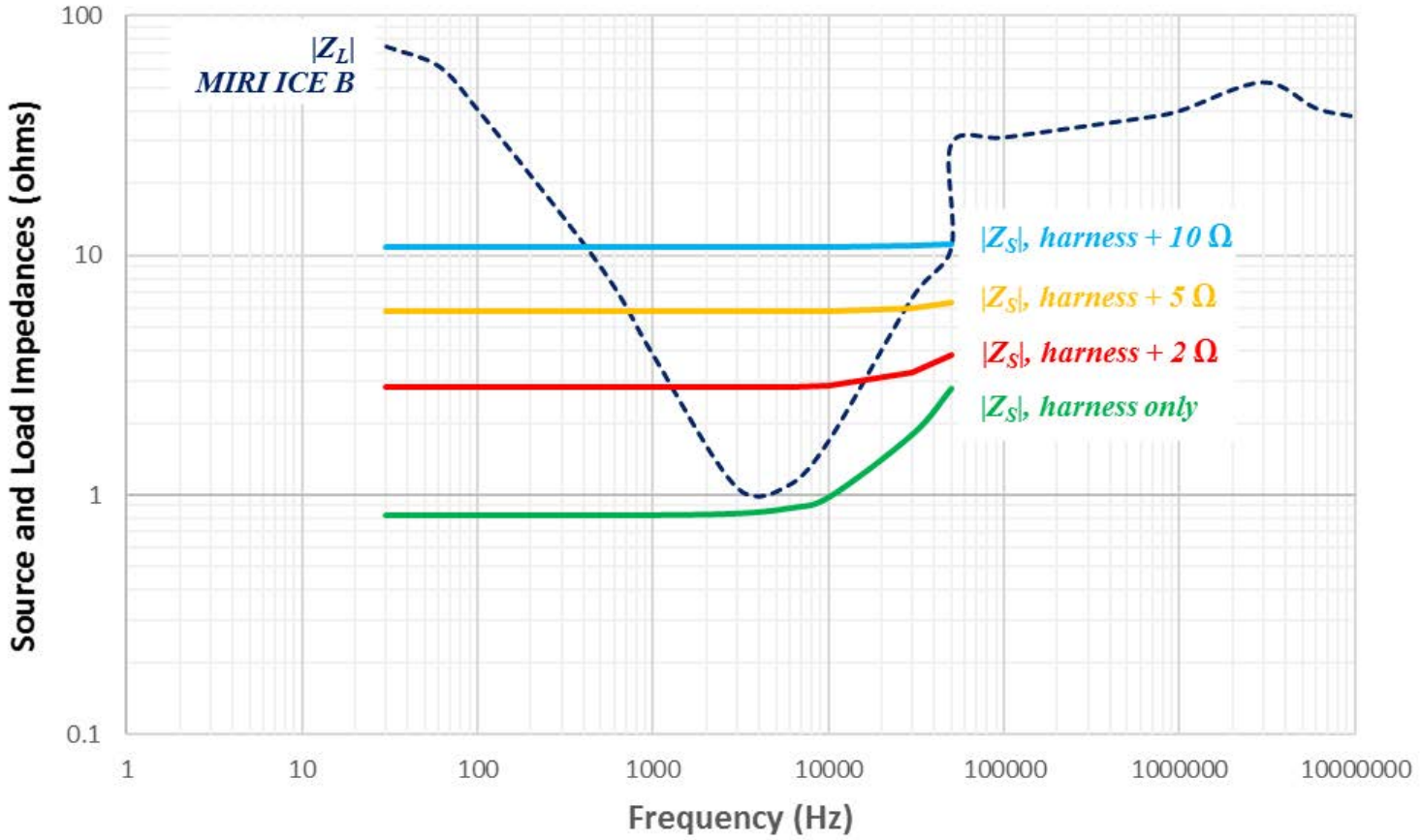
$$|Z_S| << |Z_L|$$

AT ALL FREQUENCIES

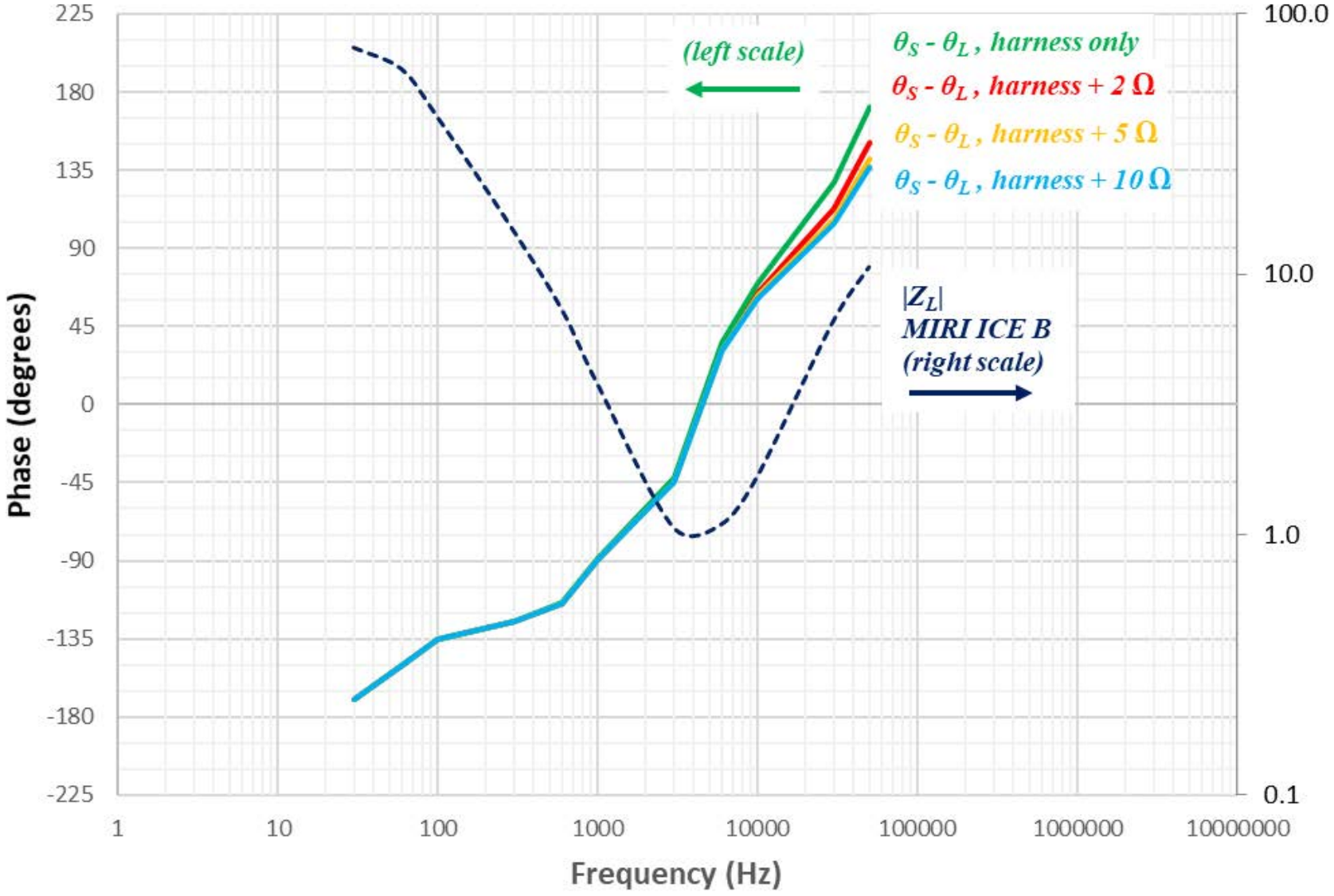
If this criterion is not met, need to look at phase margin at frequencies at which it is not

$|Z_S|$ 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)**



$\theta_S - \theta_L$



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^o) 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**