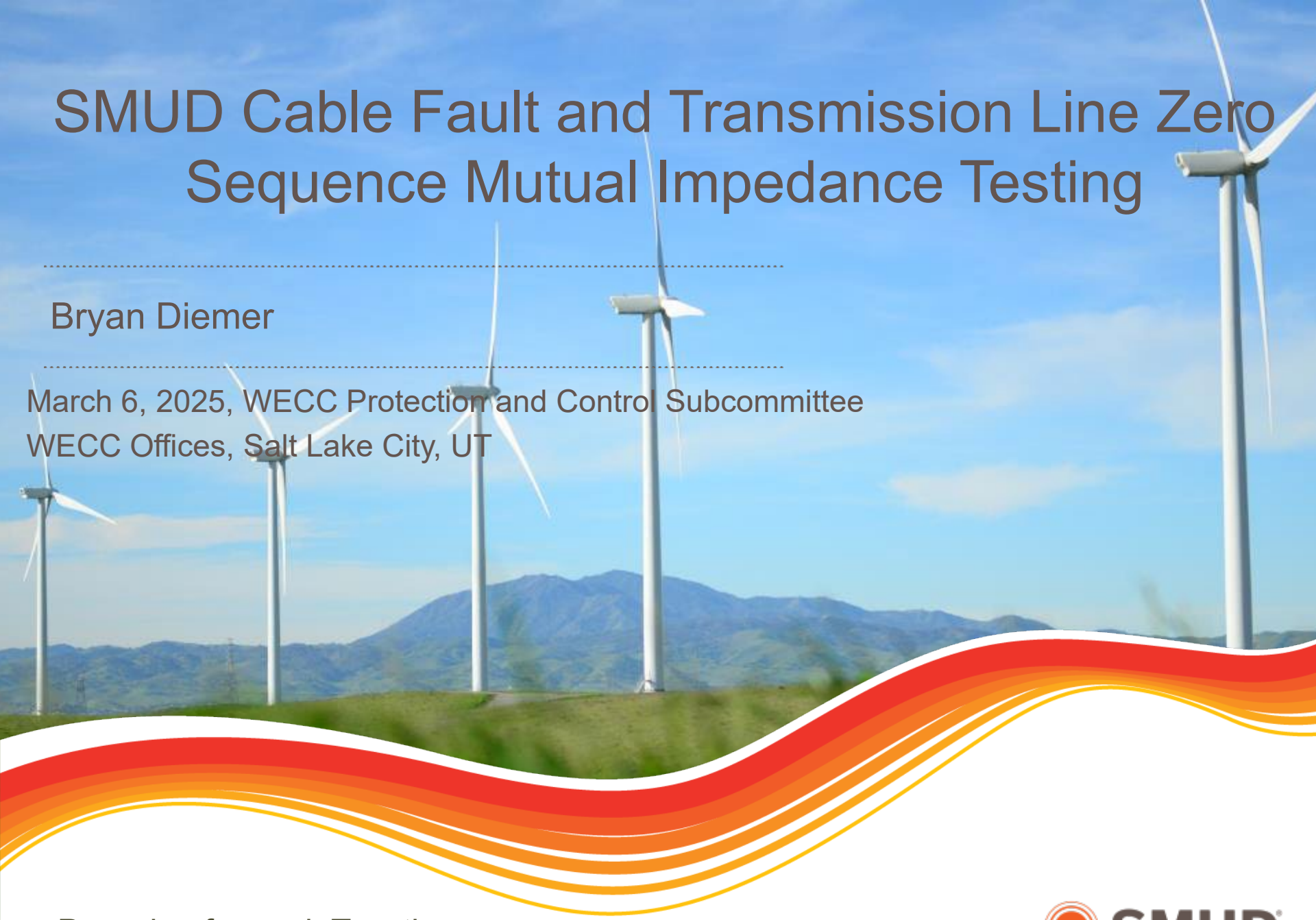
SMUD Cable Fault and Transmission Line Zero Sequence Mutual Impedance Testing

Bryan Diemer

March 6, 2025, WECC Protection and Control Subcommittee
WECC Offices, Salt Lake City, UT



Powering forward. Together.

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Agenda

- Quick review of impedance testing due to faulty cable models.
- 20kA 115kV cable fault occurred last week on February 25th.
- Overhead transmission line zero sequence mutual impedance testing results and analysis.

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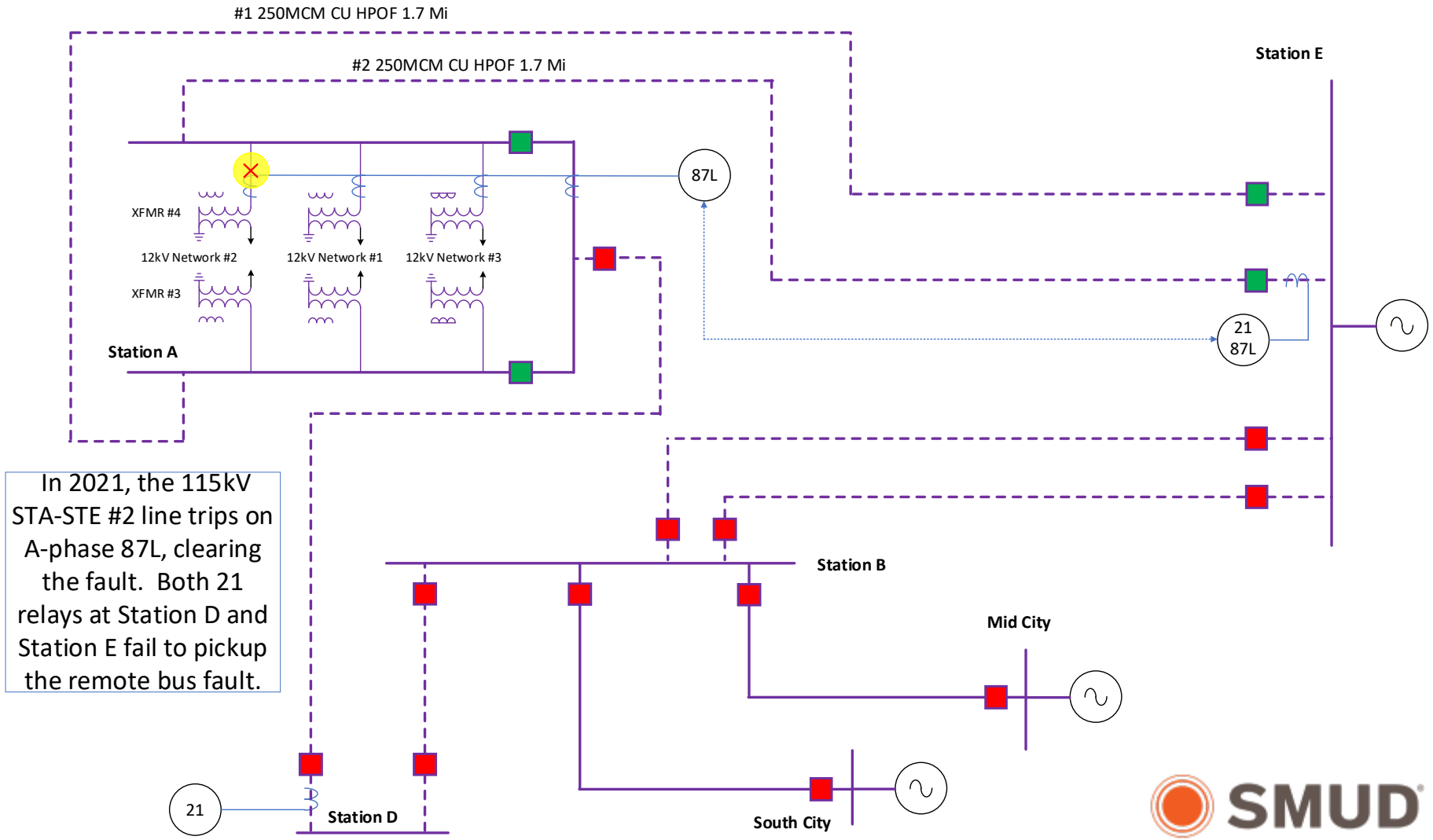
Downtown Sacramento 115kV Underground Cable System and 2021 Fault



In 2021, the 115kV STA-STE #2 line trips on A-phase 87L, clearing the fault. Both 21 relays at Station D and Station E fail to pickup the remote bus fault.

115kV Network Changes Between the 2021 and 2025 Events

- Station A was built in 1895 as the terminal fed from Folsom generation, then the longest 3-phase AC transmission line in the U.S. (11 miles at 22kV). It was replaced by Station G in 2023.
  - High Pressure Oil Filled (HPOF) cables were installed in 1954.
  - New short HPOF cable sections were spliced near the Station G and Station E terminals.
- Impedance testing of the HPOF cables revealed substantial cable impedance modeling errors.
- Some 21 distance relays were revised based on the test data; others were *still* not changed.

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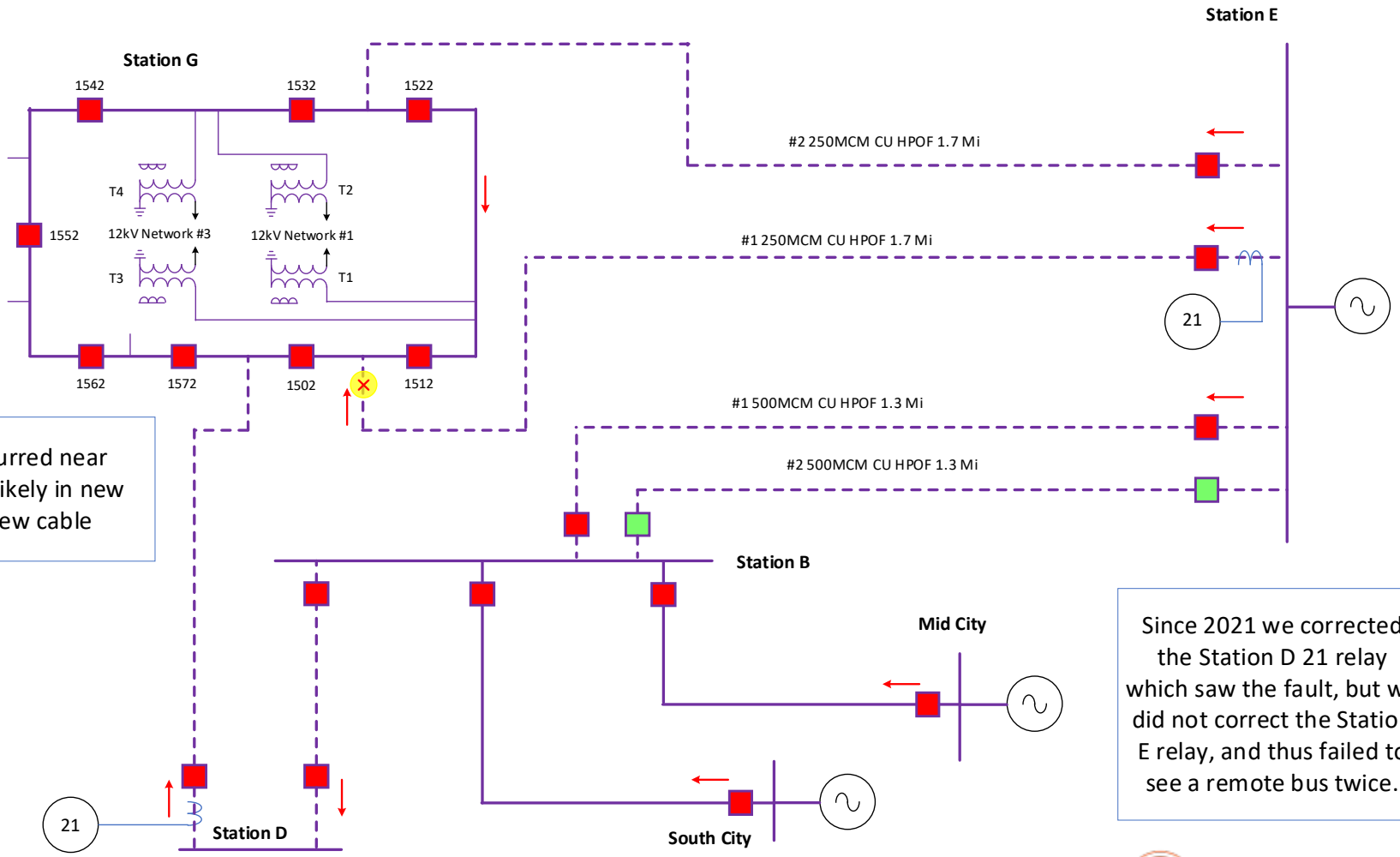
2025 Downtown Sacramento 115kV Underground Cable System and Cable Fault



Fault occurred near Station G, likely in new splice/new cable

Since 2021 we corrected the Station D 21 relay which saw the fault, but we did not correct the Station E relay, and thus failed to see a remote bus twice.

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Protective Relay Response

- 20kA fault was cleared in 2 cycles by Station G GIS breakers, 2.5 cycles by Station E SF6 breakers.
- Multi-ended fault location by the 411L relays matched at both ends.
  - The 311L relays did not provide good single-ended fault locations;
  - The 411L relays did not provide travelling wave fault locations, likely due to incorrect LPLVL settings (investigation continues).
- Relay/DFR data and our updated ASPEN OneLiner model – all match within 3%. The ASPEN model is accurate.
- The Station D zone I and II elements correctly picked up.

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Overhead Transmission Line Zero Sequence Mutual Coupling Impedance Testing

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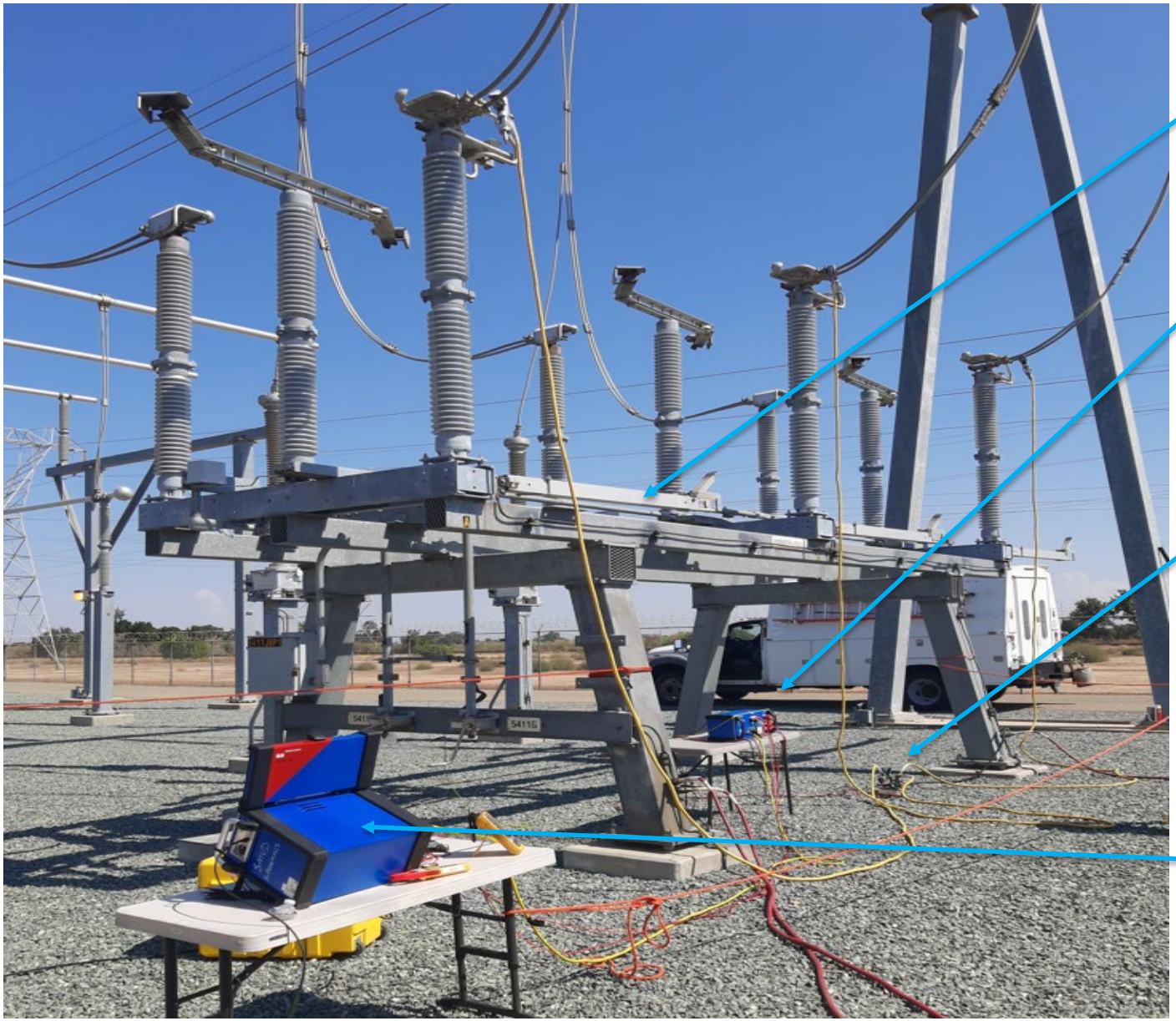
Omicron CPC-100 with CP CU1



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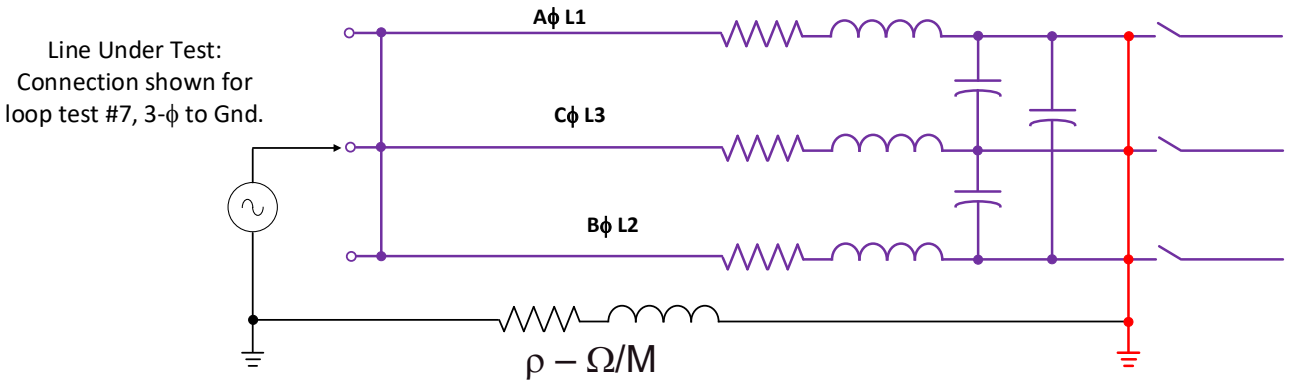
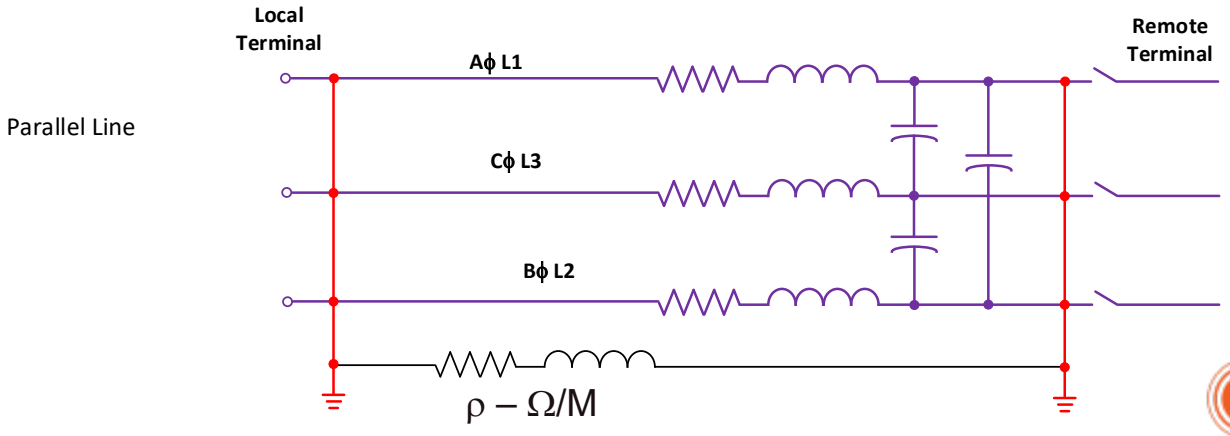
Zero Sequence Mutual Coupling

With line self tests, the parallel line is grounded only at one terminal. To test for zero sequence mutual coupling, run the same line under test, but ground ***both*** ends of the parallel line.





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Overhead Line Self-Impedance Test Results

- Positive sequence tested values match within 1-3% of calculated values, where zero sequence self-impedances are 20-35% *lower* than calculated, for two primary reasons:
  - OPGW incorrectly modeled;
  - Ground impedances (ρ, in Ω/mi) are either much lower (in the Sacramento Valley) or much higher (in the high Sierra) than assumed.

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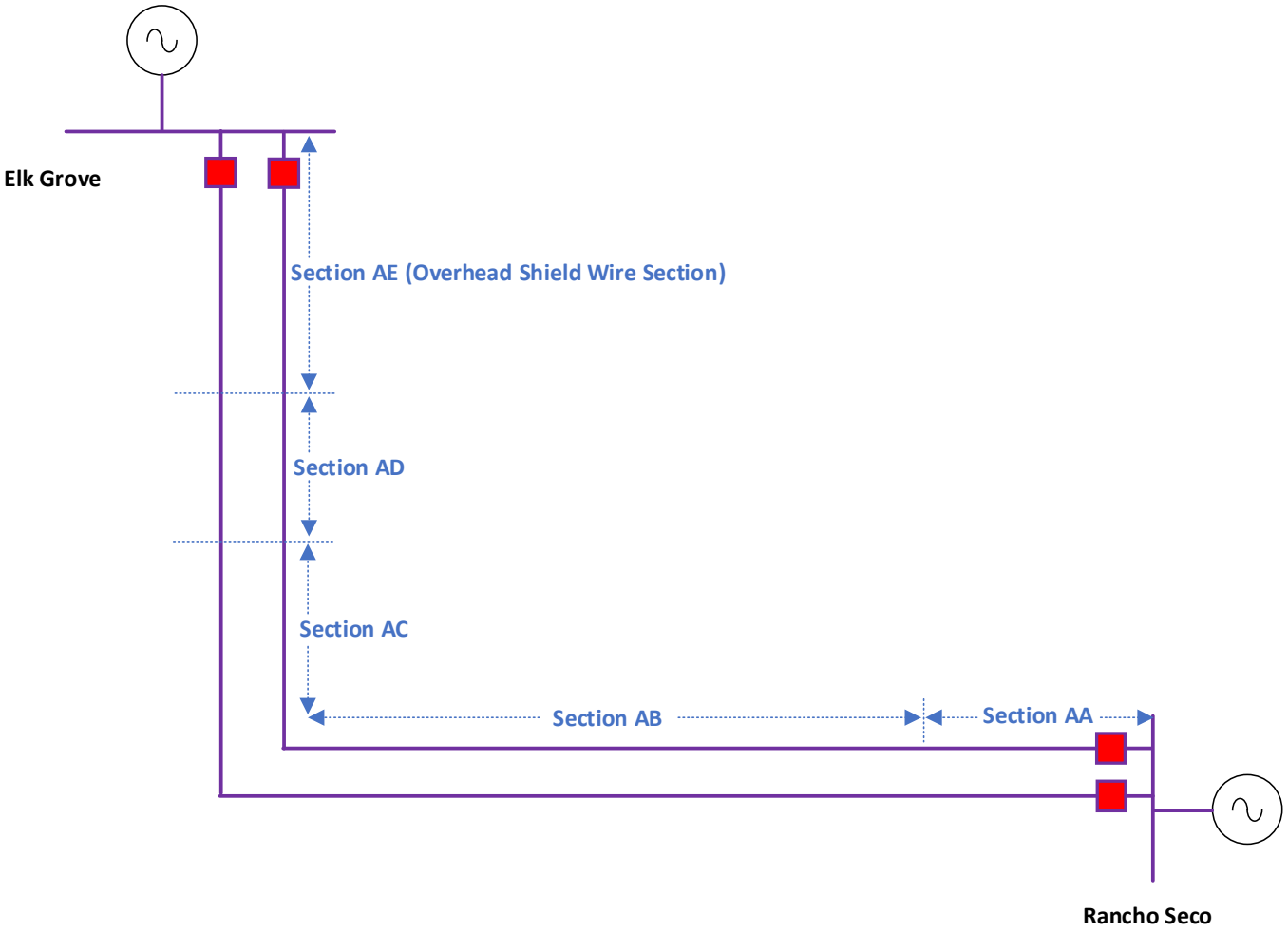
First Test: Lines terminated into the same substations



Comparison of Zero Sequence Mutual Impedance Test Results to Modeling Data

- The mutual tests were performed twice, once with line #1 under test and parallel line #2 grounded at both ends, then repeated vice versa. Results were identical, as expected.
- Good results between measured and calculated mutual coupling, after correcting for the following:
  - Ground impedance was originally 100 Ω/Meter everywhere; now using 15 Ω/Meter from substation ground testing results (in the Sacramento Valley).
  - Overhead shield wire sections leaving the station were originally modeled as ½" steel, now they are aluminum/steel OPGW;
  - Entirely new OPGW was installed over Section AB that was not previously accounted for.

Error Calculation:								
	Z_1		Z_0		Z_{0M}		Z_{0M}	
	R / Ω	X / Ω	R / Ω	X / Ω	R / Ω	X / Ω	Z / Ω	φ / °
Tested Value / Ω:	0.82	8.48	3.93	25.71	3.08	14.72	15.04	78.18
Calculated Value / Ω:	0.85	8.47	4.25	27.15	3.26	15.19	15.55	77.70
Error (ref. to tested value) / %:	-3.66	0.12	-8.14	-5.60	-5.84	-3.19		

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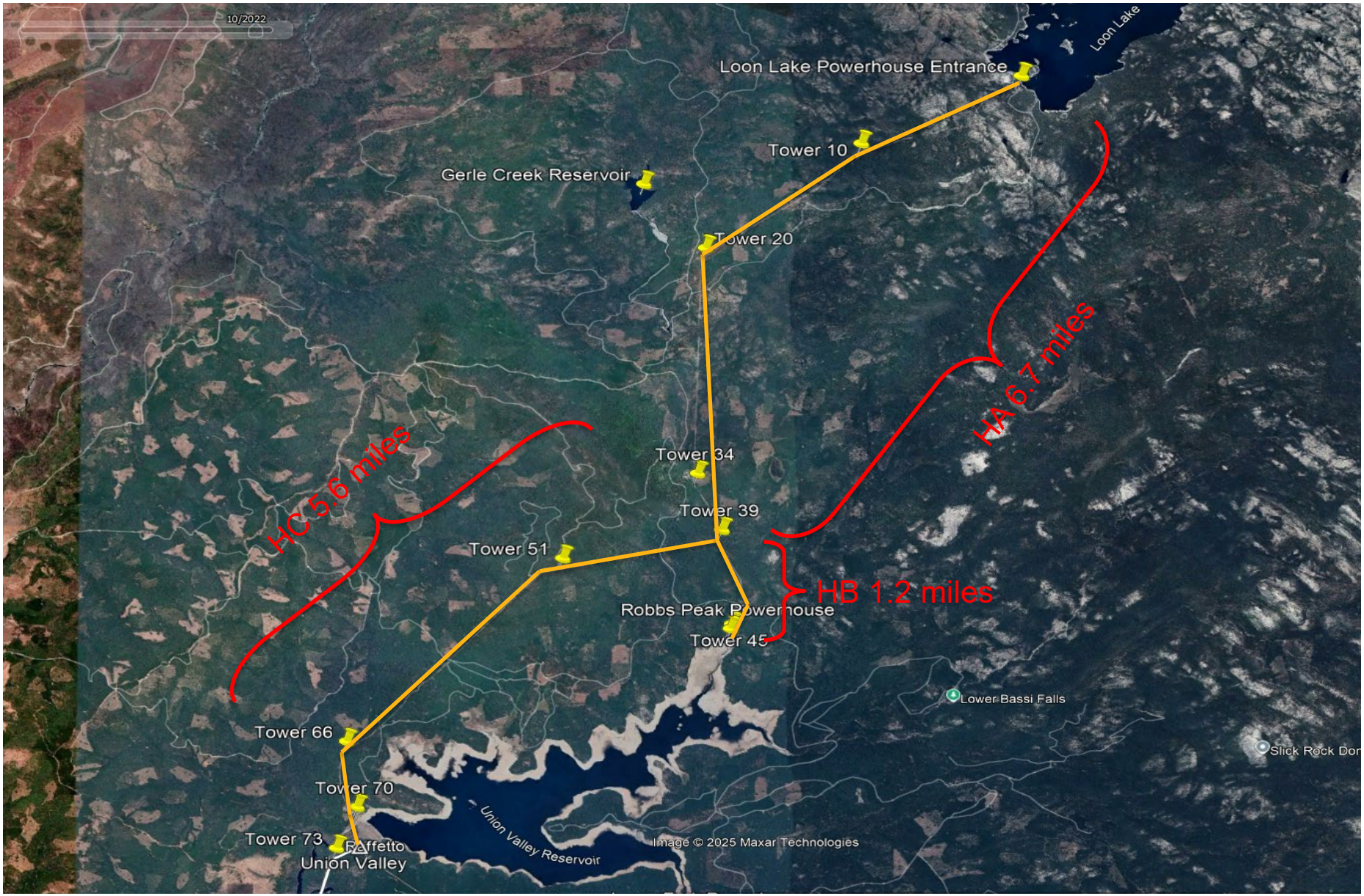
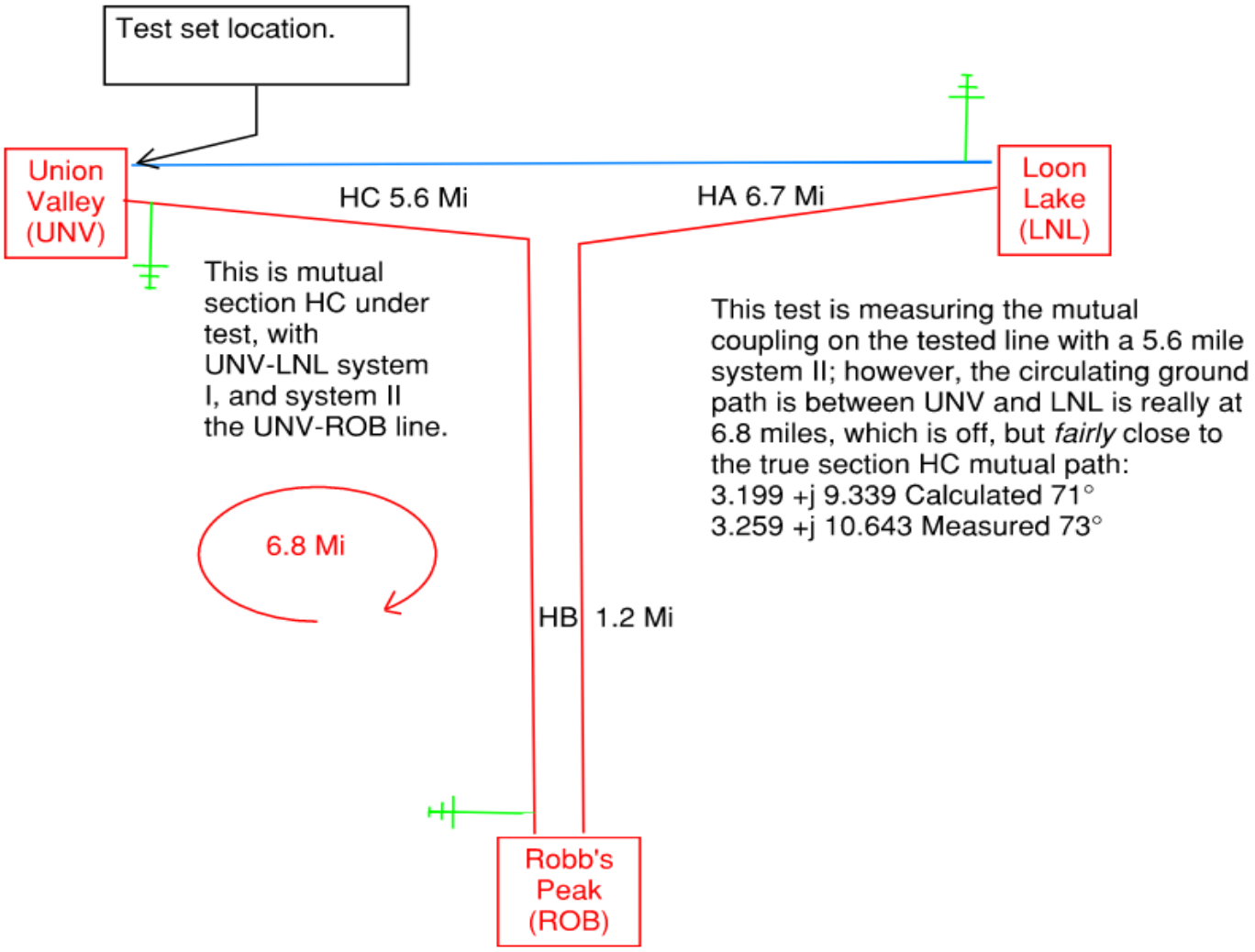
Second Test: Three 69kV Lines Under Test, All Double Circuit Vertical Towers



Union Valley shooting to Loon Lake. Line in blue is the line being tested from Union Valley, with Union Valley to Robb's Peak grounded at both ends.



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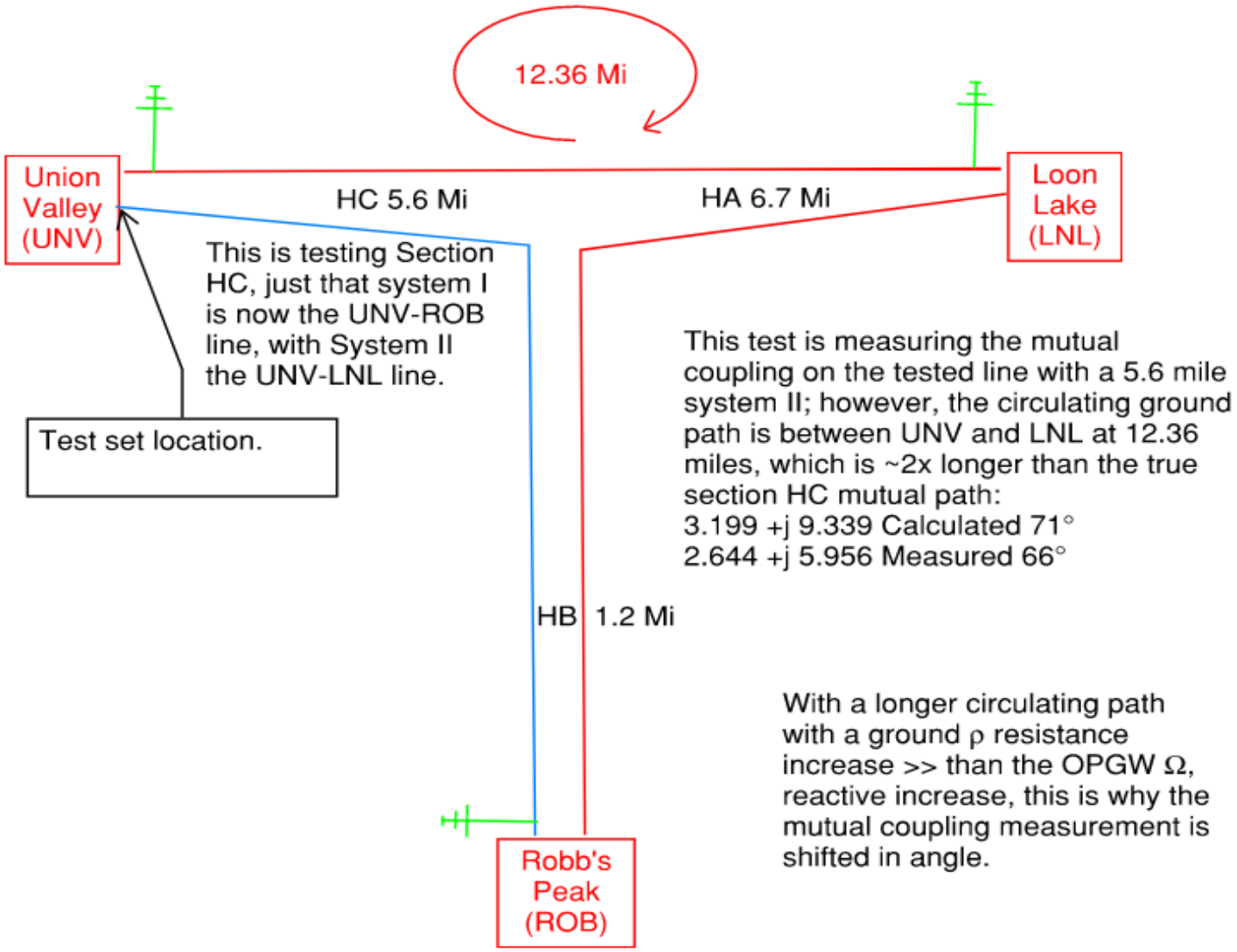
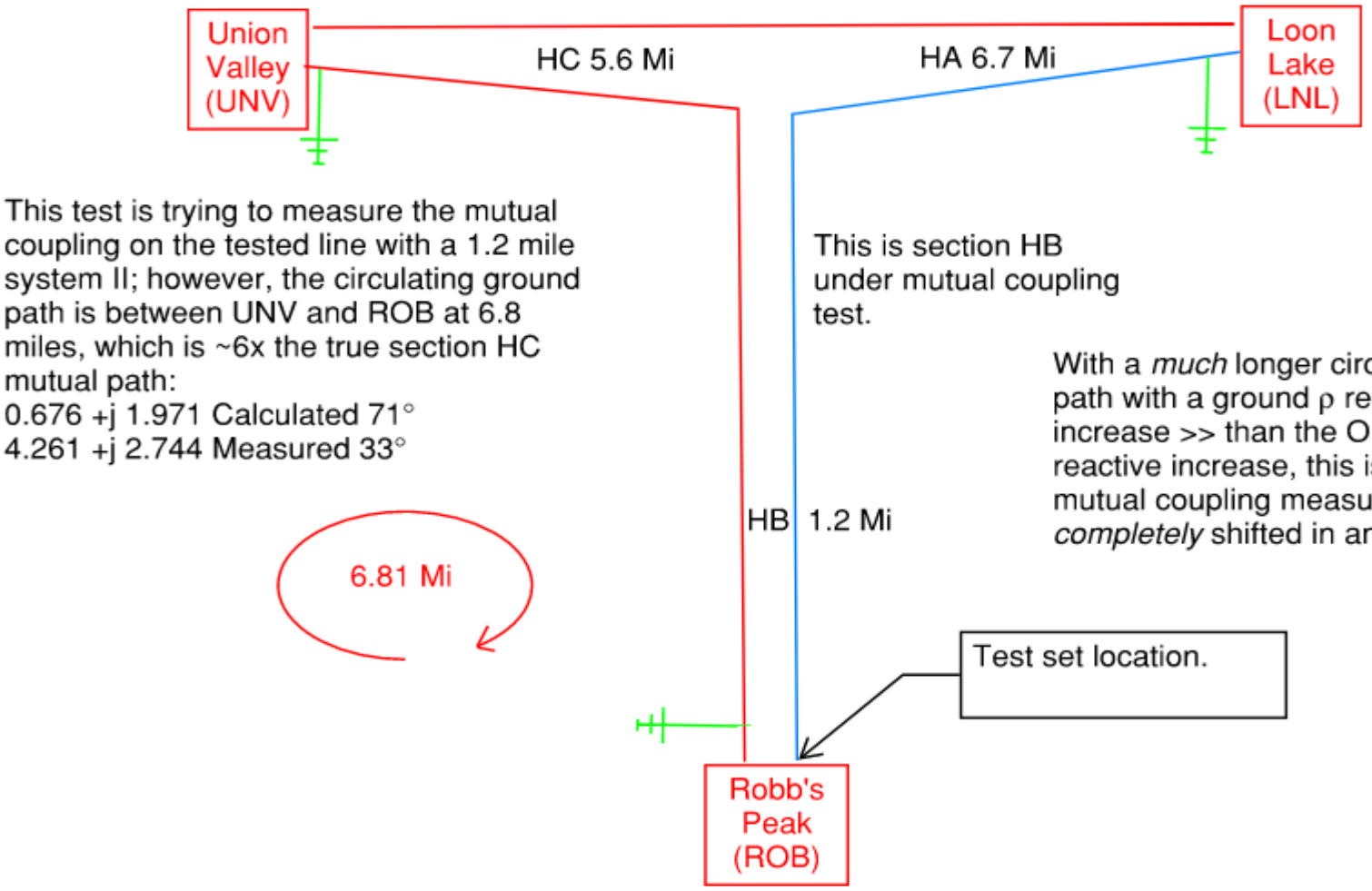
Union Valley shooting to Robb's Peak. Line in blue is the line being tested, with Union Valley -- Loon Lake line grounded at both ends.



Robb's Peak shooting to Loon Lake. Line in blue is the line being tested (system I) with the Union Valley - Robb's Peak line grounded at both ends.



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Conclusions and Next Steps

- The grounding of the parallel line needed to be at the TEE point (Tower 39), *not* at the remote station for mutual impedance testing:
  - This is the only true mutually coupled section;
  - We will correct this procedurally going forward;
- The testing errors backed me into trusting the mutual modeling.
- Late 2025 we will test this against a new set of partially parallel lines.

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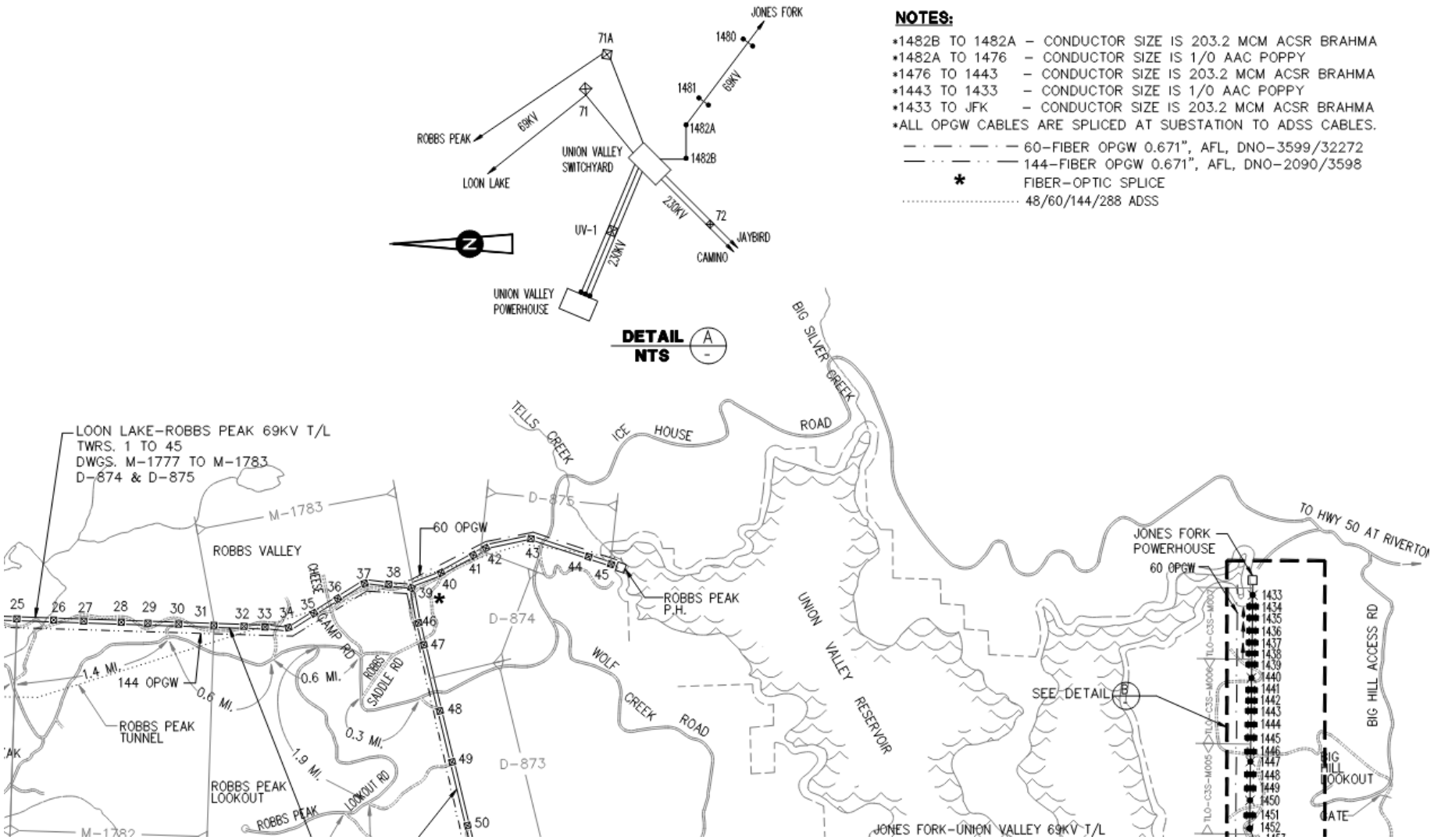
<Public>

Our Transmission Line Department's Maps Now Show ADSS/OPGW Installations



Questions?

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