Evolvable Cryogenics (eCryo) Project
Technology Workshop with Industry

Engineering Development Unit (EDU) Workshop

Mass Gauging Test Results

Greg Zimmerli

Mass Gauging

Mass gauging sensors on the EDU

- DT-670 diode temperature/wet-dry rake
- RF Mass Gauge
- Reduced Gravity CryoTracker (Sierra Lobo)
- Capacitance Probe (American Magnetics)

LH2 Test Objectives met or addressed:

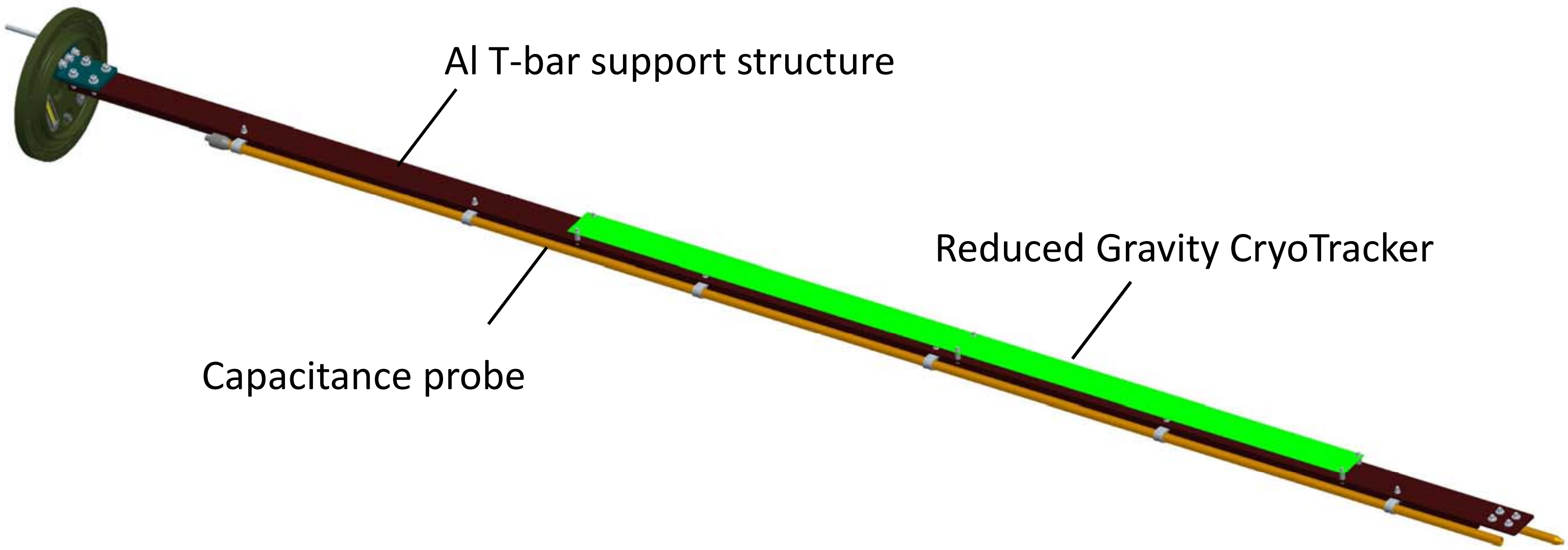
- Ground loading: Mass gauging checkouts & heat load measurement
- Gather data for model validation

LH2 Test Success Criteria met or addressed:

- Load the EDU to 90% full with Liquid Hydrogen
- Conduct mass gauging measurements with RFMG and compare to liquid level information provided by temperature rake
- Measure EDU Boil off for simulated on-orbit heat load
- Data collection from above objectives
- Gauging data was also critical for LAD outflow testing

Mass Gauging

EDU mass gauging probe

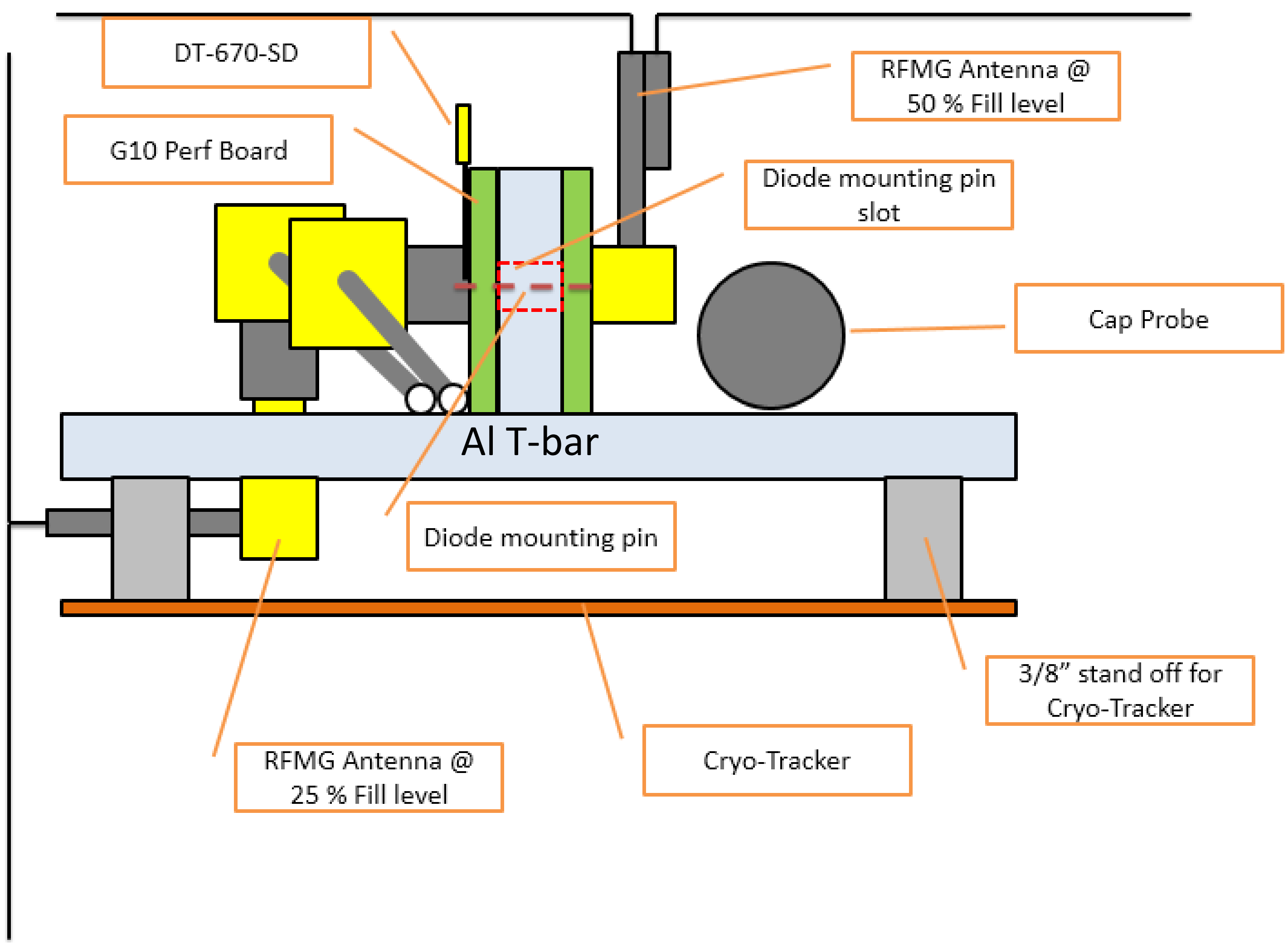


Not shown: RFMG antennas, diode rake

Mass Gauging

Not to Scale

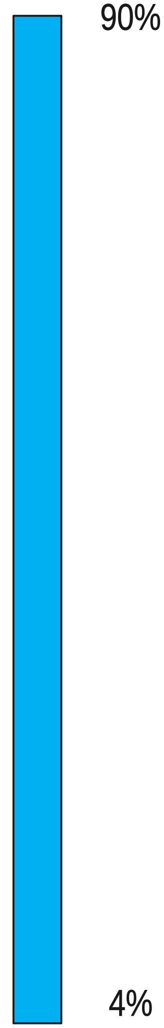
Top View



Mass Gauging

Fill Level (%)	Tank Station (in)	Instrumentation ID		
		Temperature Rake	Cryo Tracker	RFMG
98	85.2	D2401		
94	80.2	D2402		
91	77.3	D2428		
90	76.4	D2403	D2432	
89	75.6	D2429		
86	73.1	D2404		
82	70.0	D2405	D2433	
78	67.0	D2406		
74	64.0	D2407		
73	63.3		D2434	
70	61.0	D2408		
66	58.0	D2409		
63	55.7		D2435	
62	55.0	D2410		
58	52.0	D2411		
55	49.7		D2436	
54	49.0	D2412		
50	46.0			RF1440
48	51.3	D2413		
46	43.0	D2414	D2437	
42	40.0	D2415		
38	37.0	D2416	D2438	
34	34.0	D2417		
30	30.9	D2418	D2439	
26	27.9	D2419		
25	27.1			RF1448
22	24.9	D2420		
18	21.9	D2421		
14	18.8	D2422		
10	15.5	D2423		
6	11.7	D2424		
5	10.6	D2425		
	10.2	D2426		
	9.8	D2430		

Capacitance probe CP2440

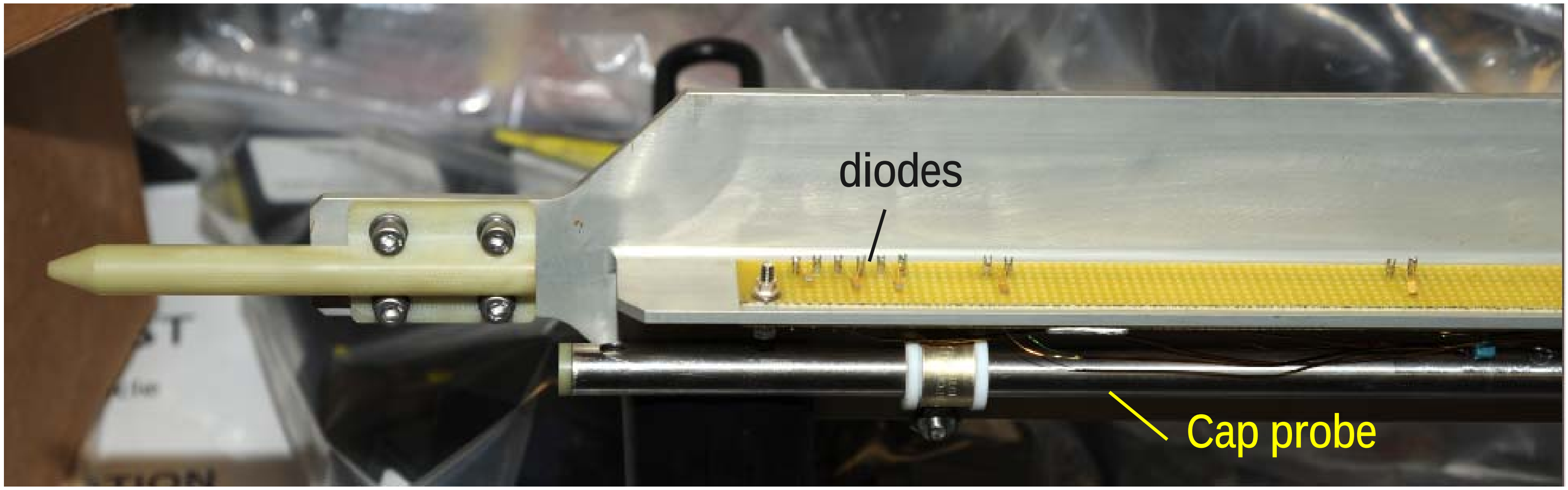


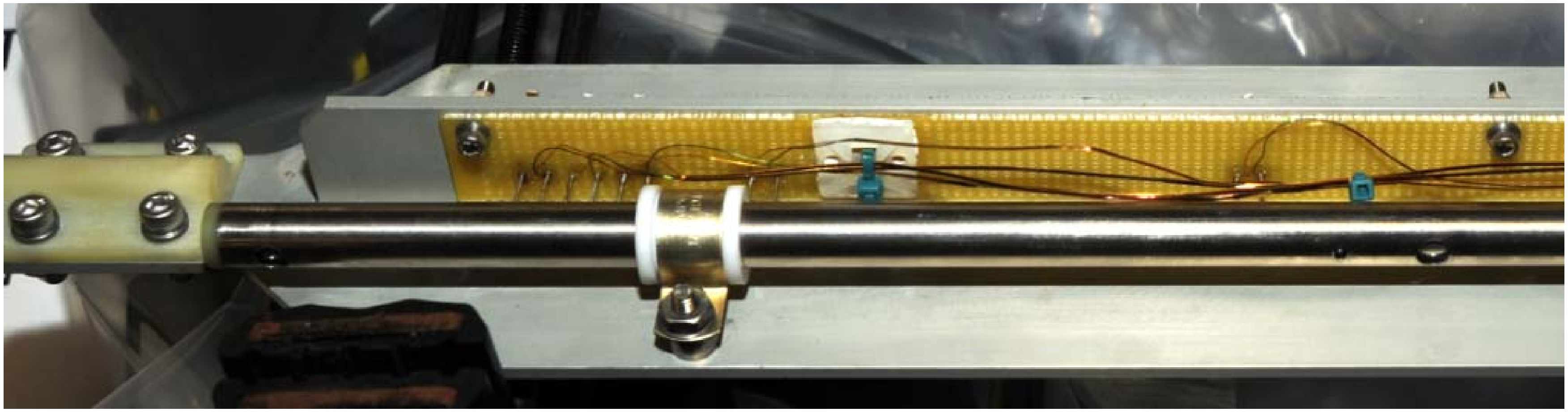
- Temperature rake (wet-dry sensors) and cap probe data is stored with facility CSV data files.
- RFMG and CryoTracker data were both stored on separate systems.
- RFMG and CryoTracker clocks were synchronized to the facility data computer clock to within a few seconds

NOTE: The diode tank station values are from the EDU CAD model, not the as-built configuration

Mass Gauging

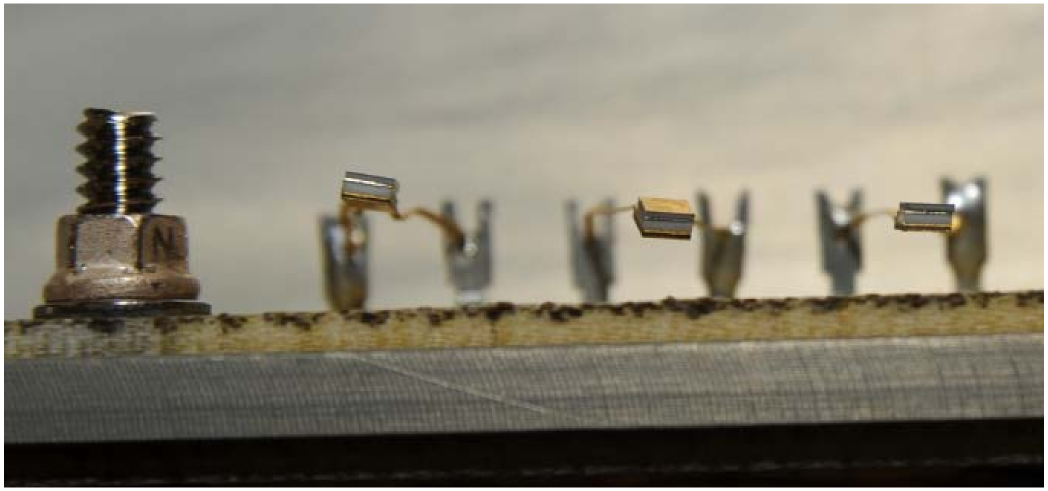
Photos of the mass gauging sensors, mounted to aluminum T-bar





Mass Gauging

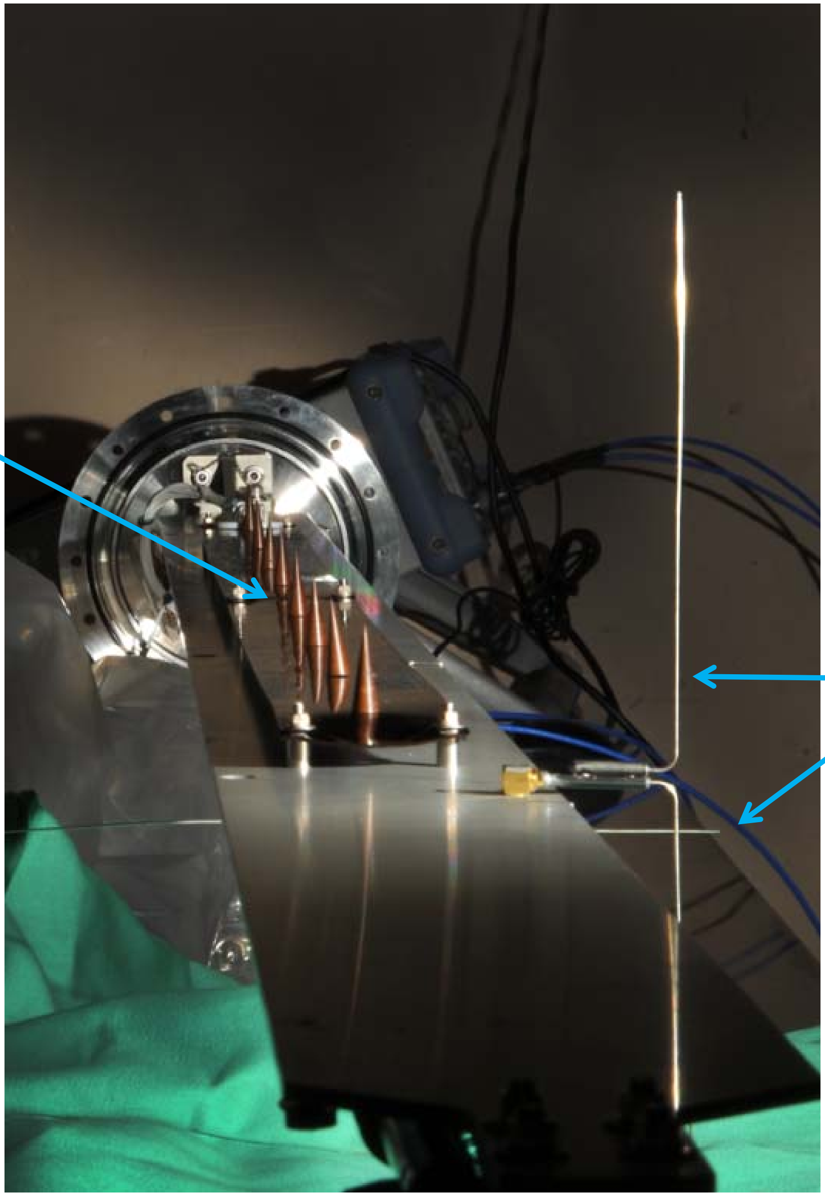
The wet-dry rake diodes are mounted above the perf board.



Silicon diodes at 5% location

Mass Gauging

- Reduced Gravity CryoTracker (RGCT) probe; contains 8 sensors mounted on backside of T-bar
- RF Mass Gauge antennas mounted on edges of T-bar, about 20 inches apart
- All mass gauging sensors are attached to the T-bar assembly

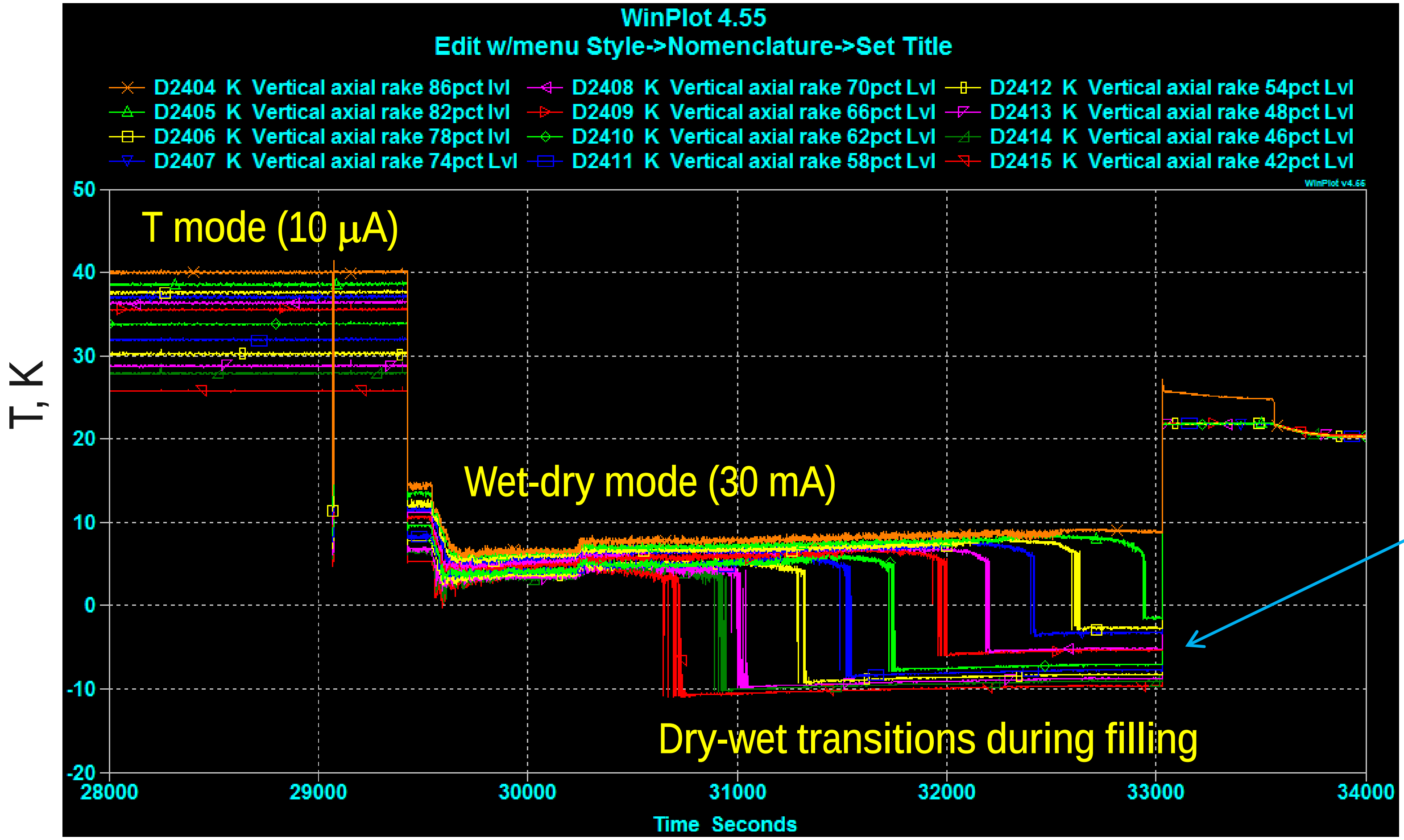


RFMG antennas

Mass Gauging – Wet/dry rake

Silicon diodes are run "hot" (30 mA) when in wet-dry mode.

- The T reading during wet-dry mode is obviously not accurate. It is based on an DT- 670 voltage vs T table (valid for 10 μA) extrapolated to negative temperatures



- Different offsets in the transition value are due to lead resistance
- This did not affect the analysis, which was done manually

Mass Gauging – Wet/dry rake

To analyze the wet-dry sensor data, CSV data files were used to find the transition times from dry-to-wet, and wet-to-dry. Winplot was used to visually narrow the search.

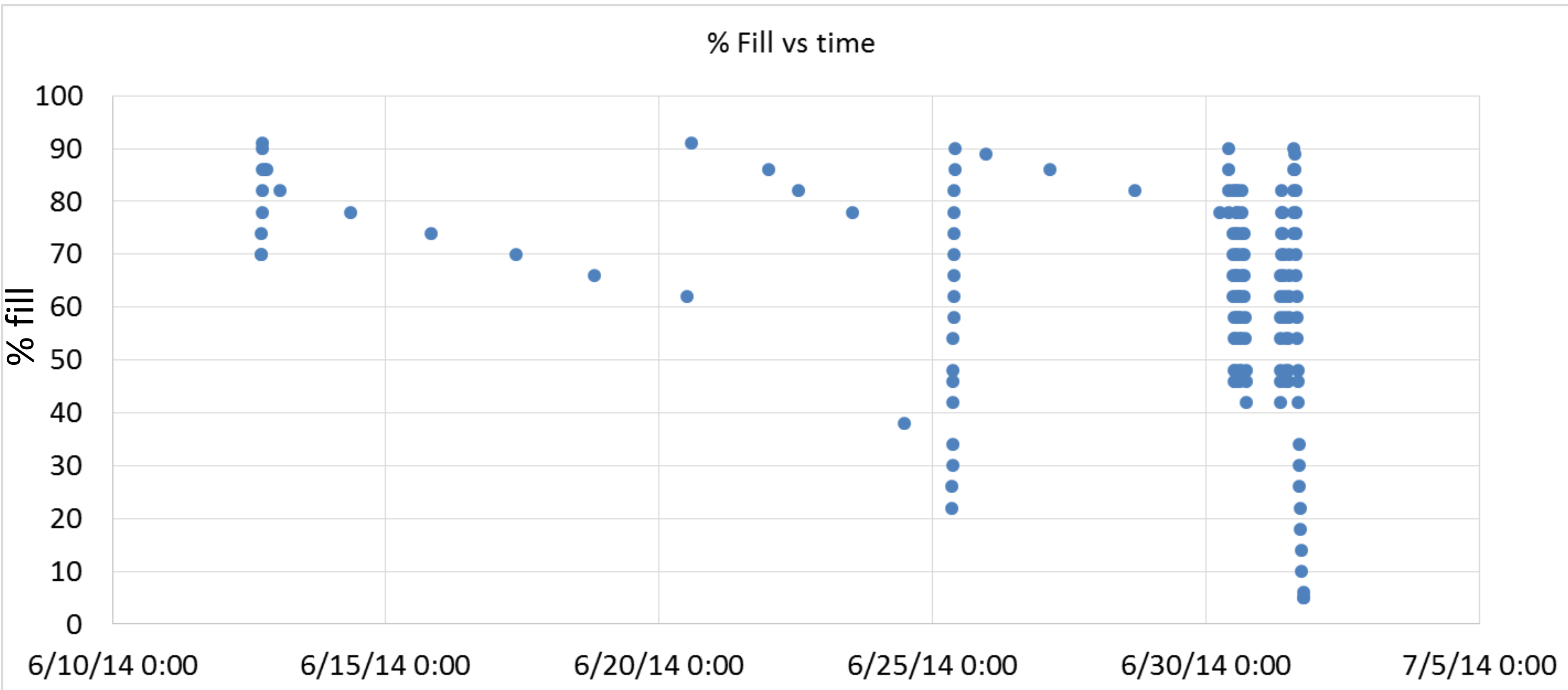
The data were recorded in an Excel spreadsheet.

F	G	H
CST date/time		wet-dry rake
6/12/14 17:17	163/17:17:2.187	70%
6/12/14 17:29	163/17:29:41.192	70%
6/12/14 17:33	163/17:33:49.194	74%
6/12/14 17:37	163/17:37:37.195	78%
6/12/14 17:41	163/17:41:8.197	82%
6/12/14 17:44	163/17:44:59.198	86%
6/12/14 17:48	163/17:48:51.200	90%
6/12/14 17:50	163/17:50:35.201	91%
6/12/14 18:45	163/18:45:33.223	86%
6/12/14 19:30	163/19:30:56.242	86%
6/13/14 1:31	164/01:31:4.884	82%
6/14/14 8:33	165/08:33:8.557	78%
6/15/14 20:02	166/20:02:40.512	74%
6/17/14 9:00	168/09:00:00	70%
6/18/14 19:46	169/19:46:00	66%
6/20/14 12:15	171/12:15:00	62%
6/20/14 14:00	171/14:00:00	91%
6/21/14 23:50	172/23:50:00	86%

- The T rake was periodically set to wet-dry mode during quiescent conditions, and sometimes left in wet-dry mode continuously during fill/drain.
- 150 transition points have been identified
- The wet-dry sensor data are used as the reference gauging data
- The data are considered accurate to within ± 1% of full-scale

Mass Gauging – Wet/dry rake

Wet-dry transition points during EDU LH2 testing:

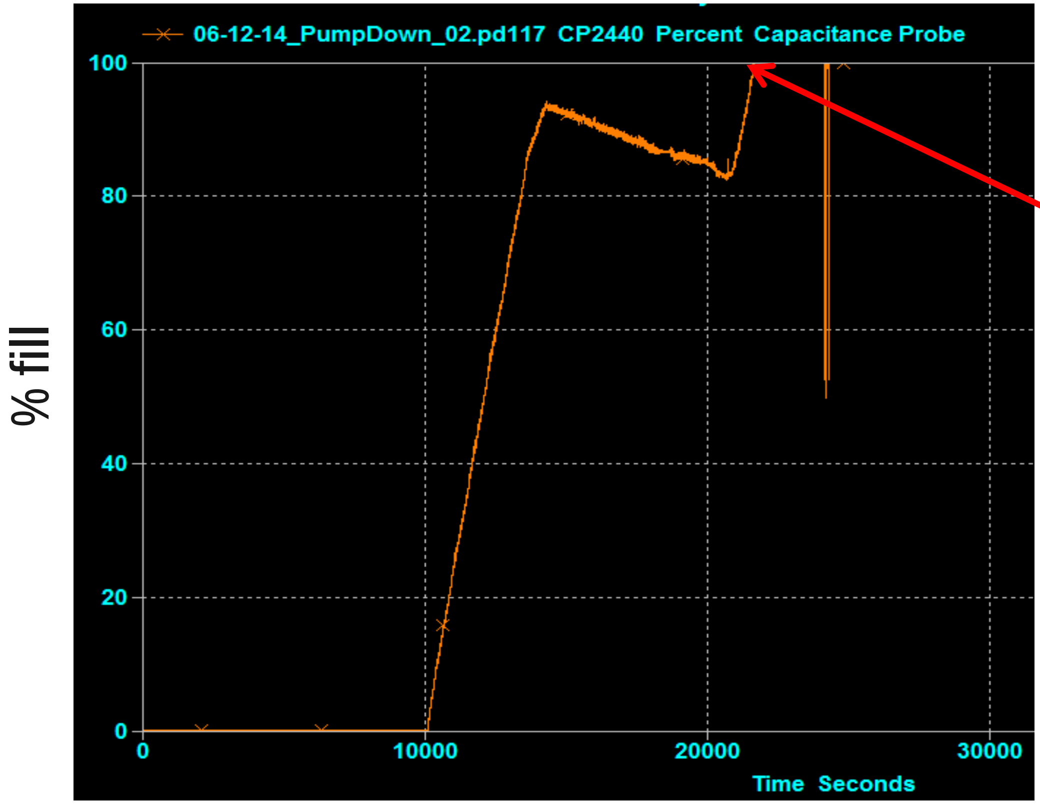


Discrete wet-dry data points are augmented by the continuous cap-probe data

Mass Gauging – Capacitance probe

Capacitance probe:

- American Magnetics, Model 185 controller
- Output was zeroed at LN2 temperature, He gas
- Output was calibrated to "100%" at two different fill levels:
  - An initial cal to "100%" was done with a partially filled tank
  - Wet-dry/RFMG data was used to find the cal-point, which was at 83% fill



- Cap probe output saturates at 100% reading at 163/17:39
- Actual fill level is 83%
- Reported cal fill level was 77% (not consistent with the data)

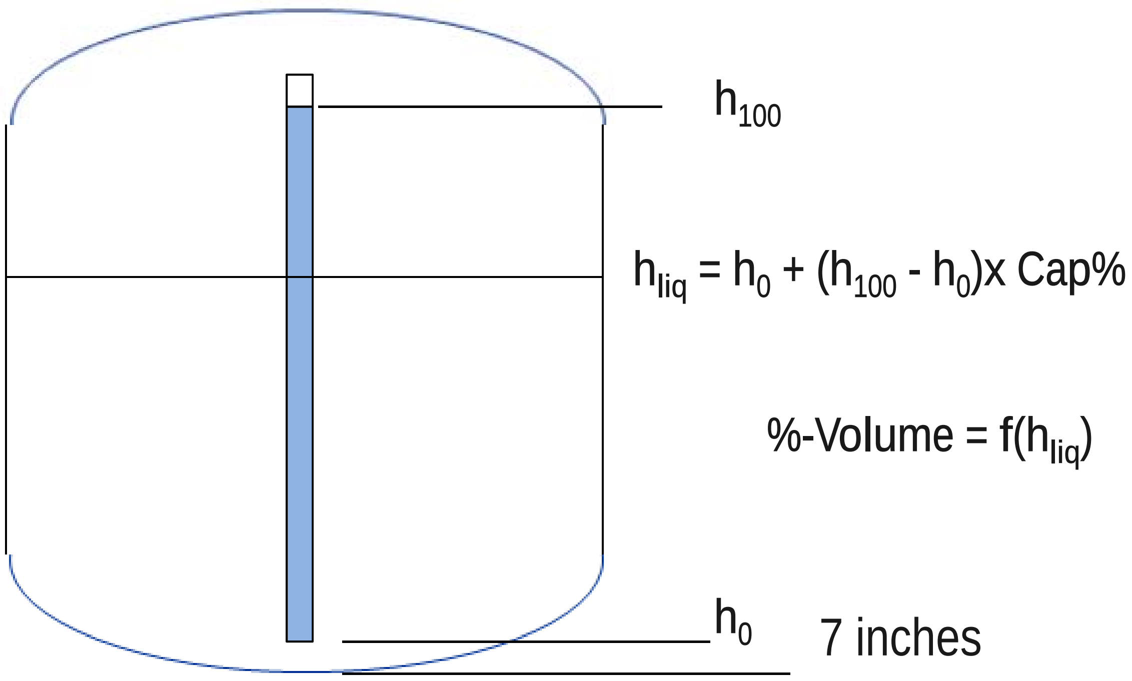
Mass Gauging – Capacitance probe

Capacitance probe:

- Cap probe 100% value was re-calibrated on June 20, around 2:17 pm
  - Fill level was between 90%-91%
- For a good approximation to the actual %volume fill level, the cap probe data should be multiplied by:
  0.83 for times before June 20, 2:17 pm (only good up to 83% fill)
  0.90 for times after June 20, 2:17 pm
- Note that the cap probe is a level sensor, and there is some error when converting % -level to %-volume. For EDU this is only important at fill levels below ~40%.
- A model of the cap probe and tank was used to refine the cap probe data
  - The correction is only significant below 30%

Mass Gauging – Capacitance probe

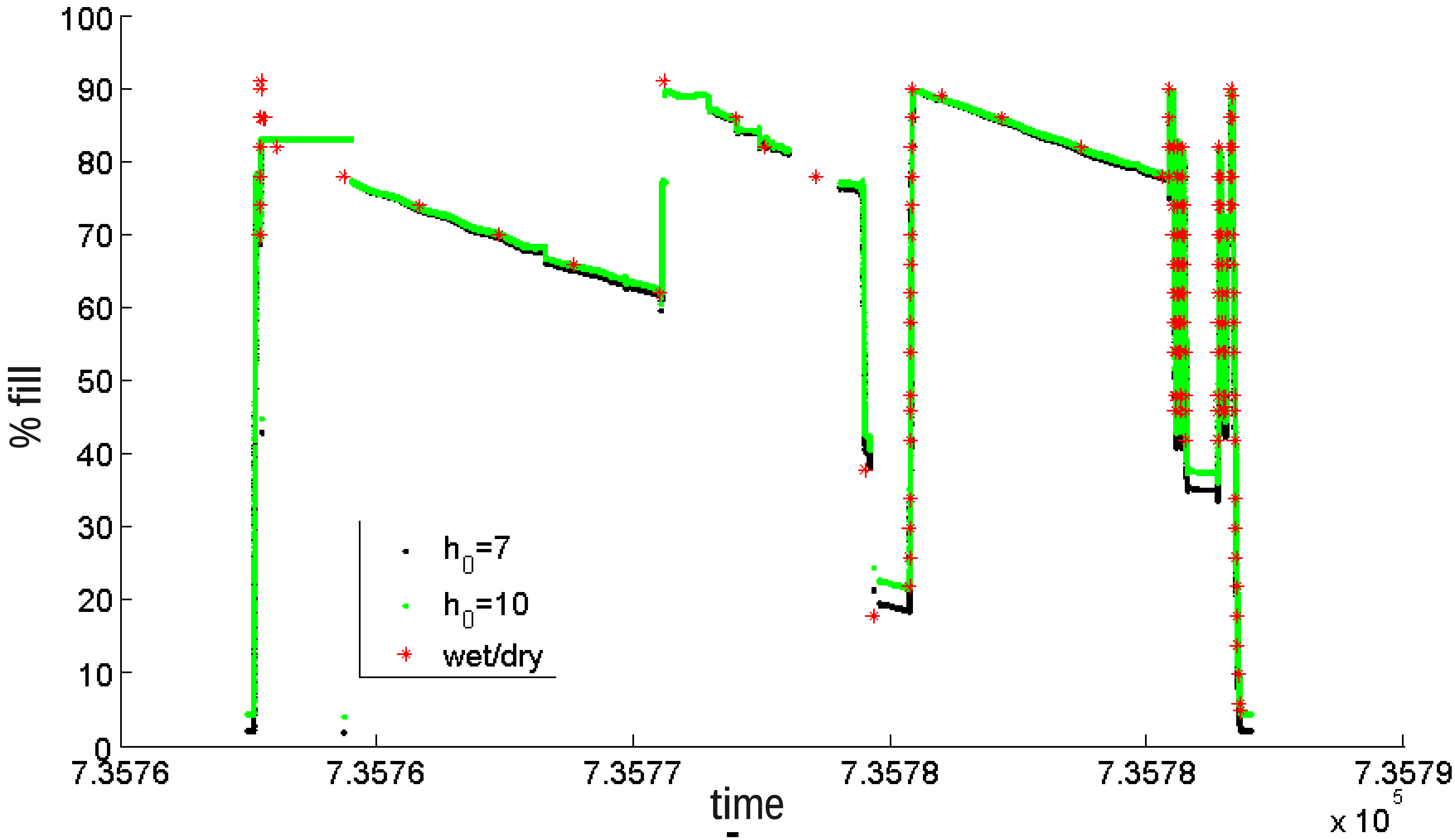
Refined cap probe output model



- COMSOL RF tank model was used to convert liquid height to %Vol

Mass Gauging – Capacitance probe

Cap probe correlation with wet-dry data

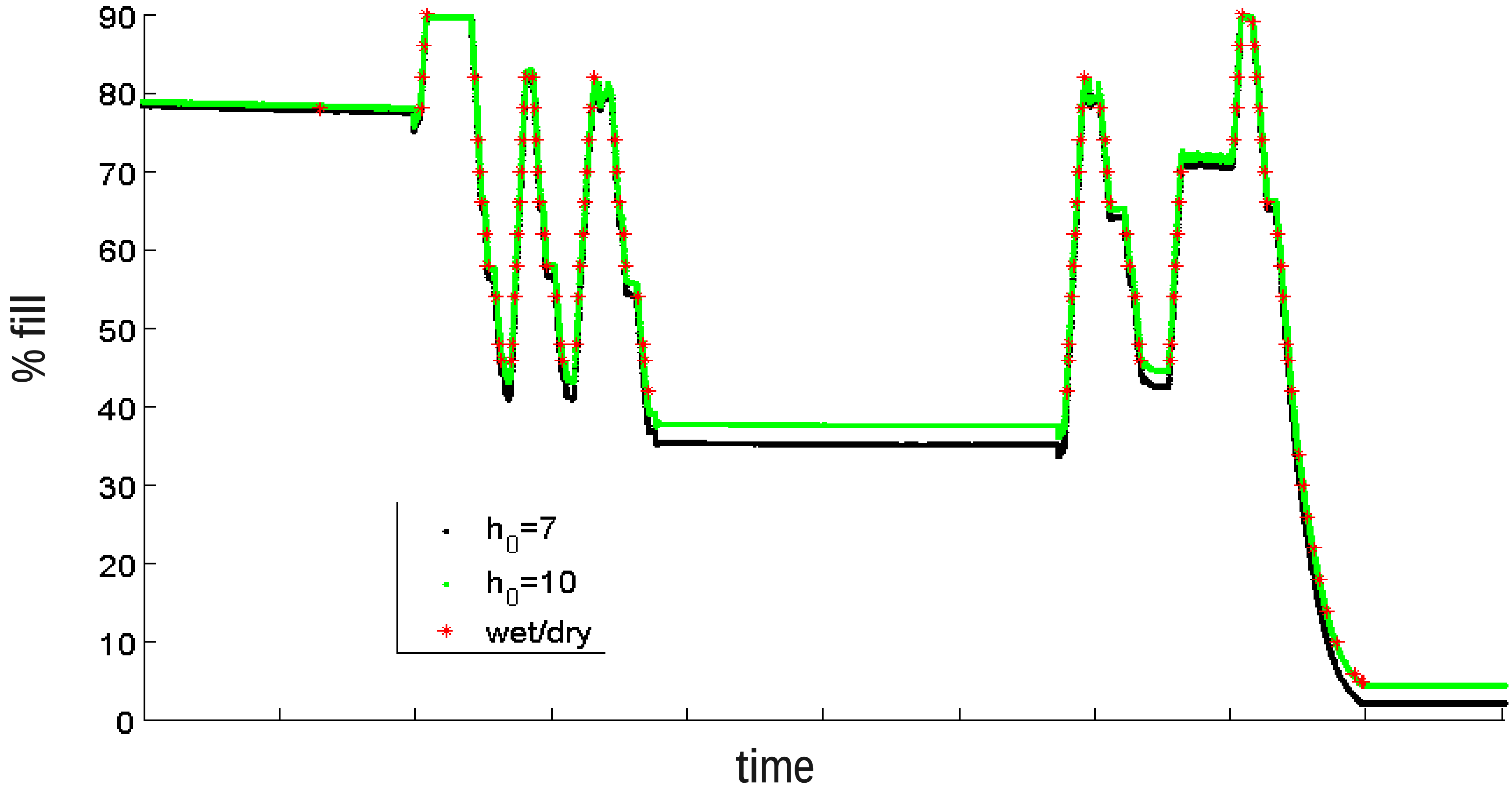


Actual value of h0 is 7 inches. Using 10 inches provides an additional offset that provides better agreement, especially below 40% fill during final drain.

Mass Gauging – Capacitance probe

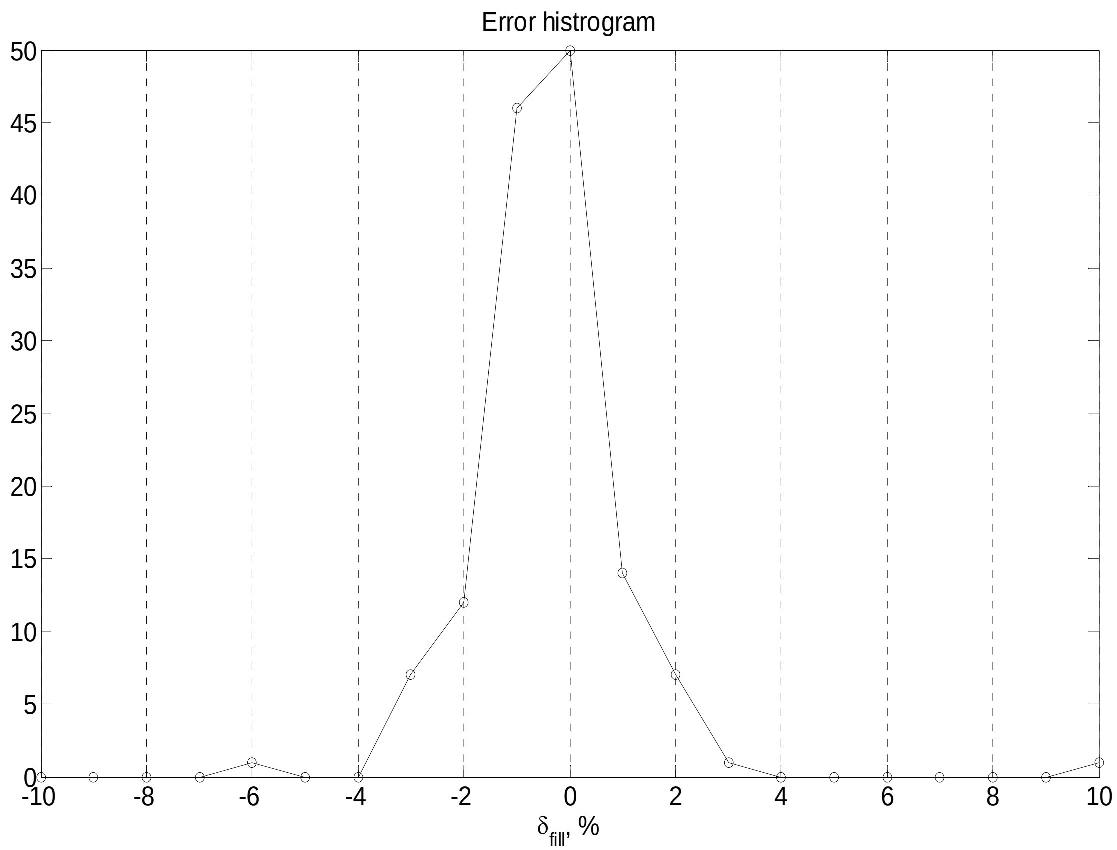
Cap probe correlation with wet-dry data

Detail during LAD testing



Mass Gauging – Capacitance probe

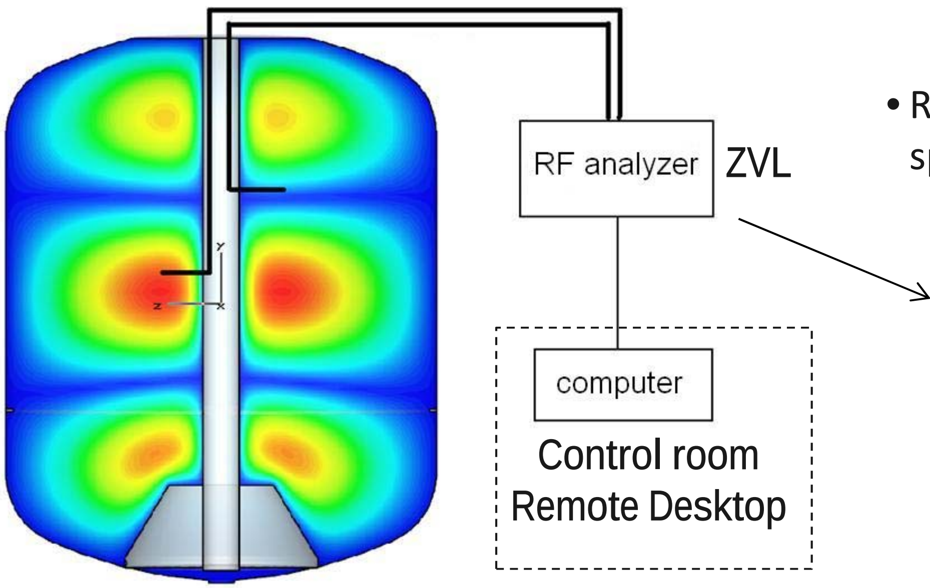
Comparison of adjusted cap-probe data (h_0 = 10”) with wet-dry rake



Mean difference: -0.3%
STDEV = 1.3%

Mass Gauging – RF Mass Gauge

RFMG: Principle of operation



- Metal tank has natural RF modes

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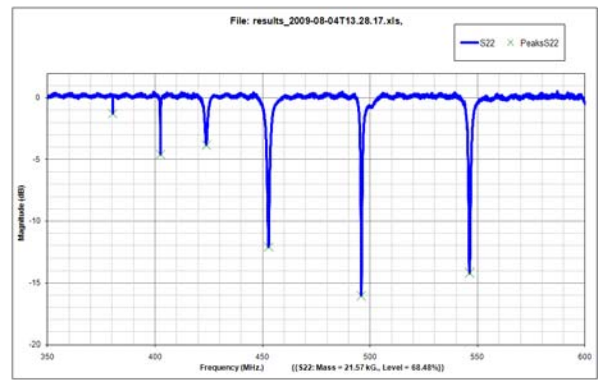
- RF network analyzer measures the tank spectrum (< 1 mW RF power)



- The tank RF spectrum changes with fill level, since the dielectric fluid slows the speed of light

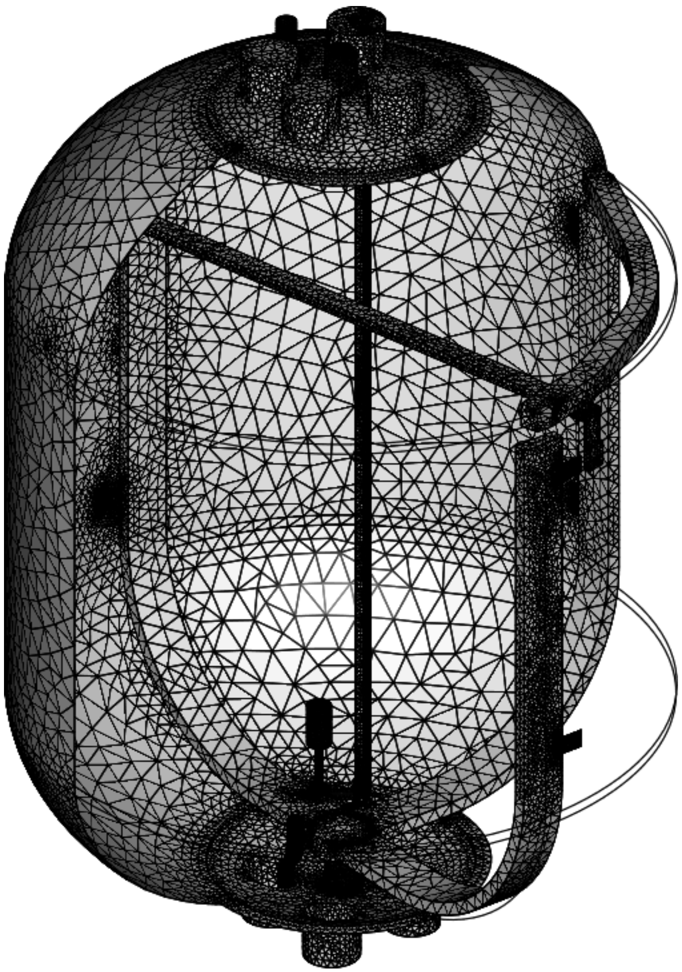
- The basis of the RFMG is that these changes can be accurately predicted

- RFMG software finds the peaks, compares the frequencies to a database of simulations, and returns the best match %fill-level information

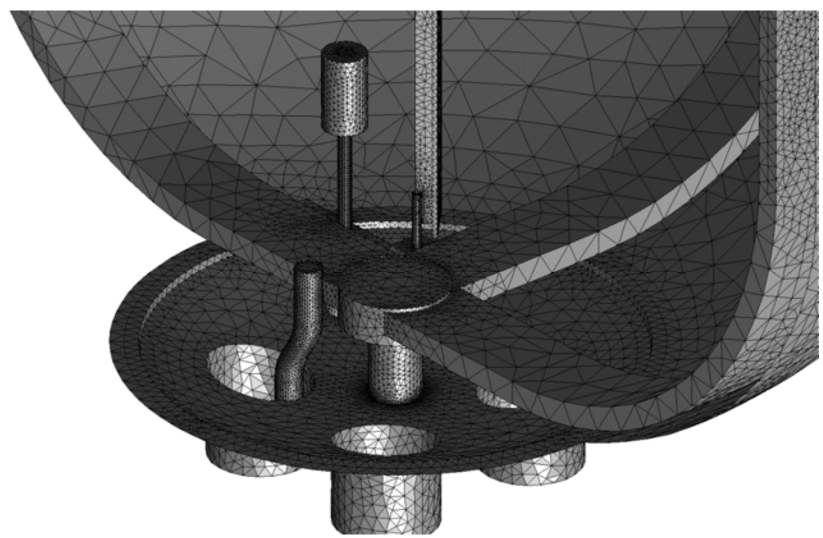
- Gauging operation takes 1 - 10 s, depending on number of frequency points (4k – 40k)

Mass Gauging – RF Mass Gauge

COMSOL – RF Module was used to calculate the tank mode frequencies



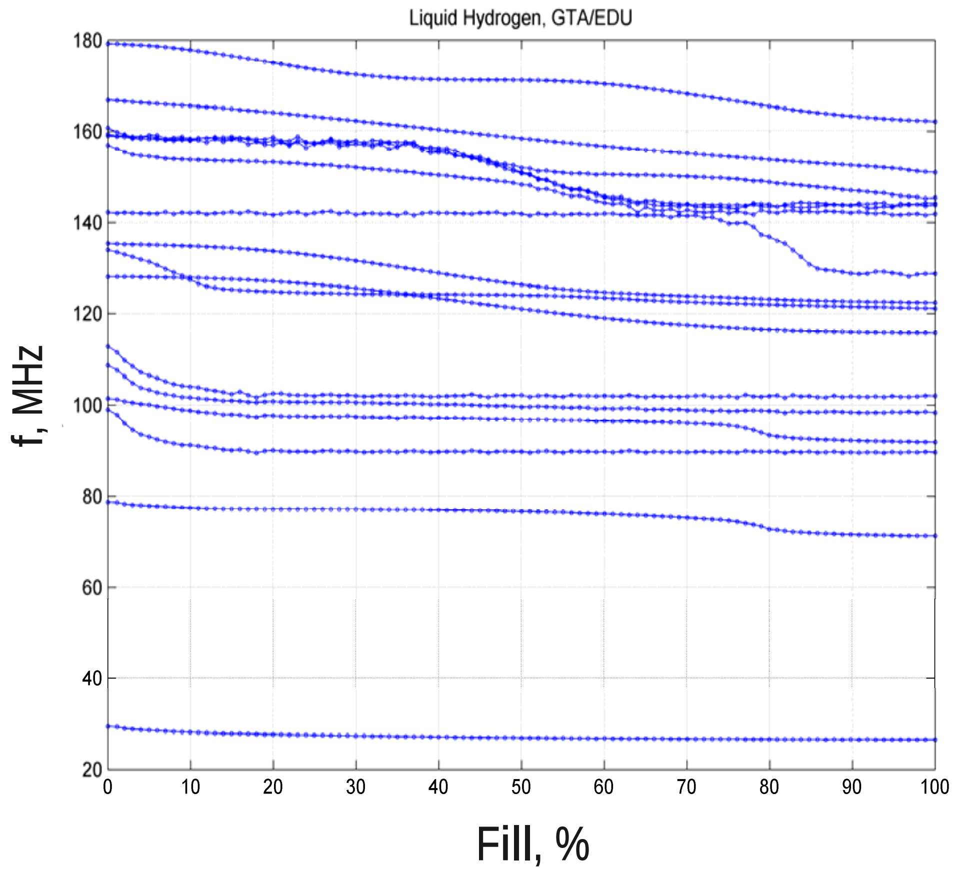
Model includes: 3 LAD arms, LAD crossover TVS tube, top diffuser, bottom diffuser, axial jet nozzle, mass gauging T-bar, horizontal ullage T rake



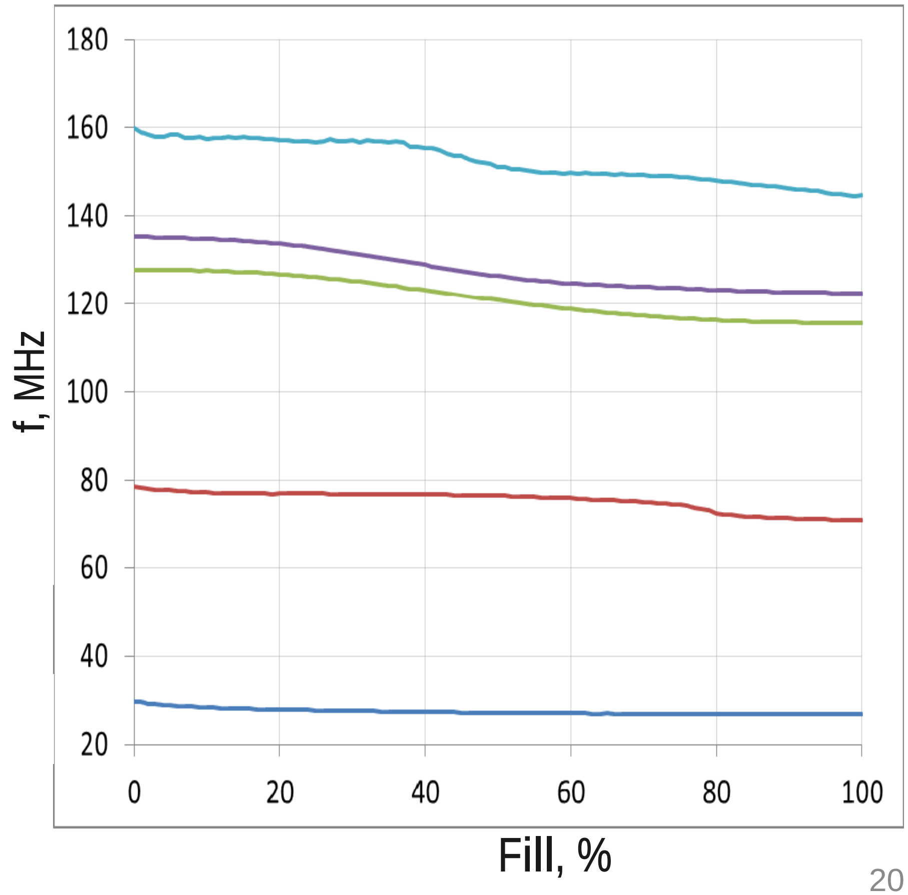
Mass Gauging – RF Mass Gauge

Computed RF modes for EDU tank

- 100 simulation files – 1% resolution
- Specified dielectric constant for liquid and vapor phases in the model

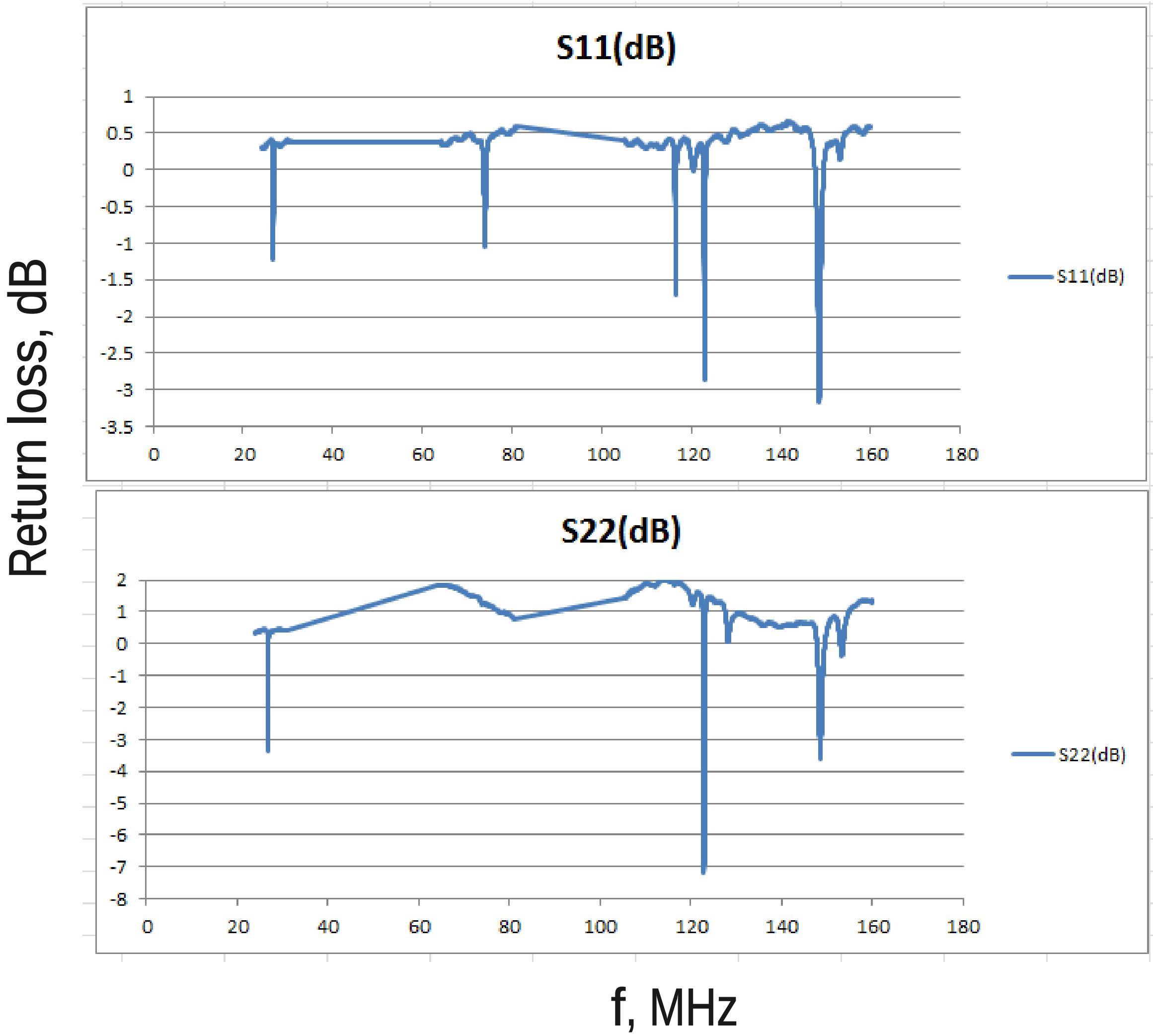


5 modes used for gauging



Mass Gauging – RF Mass Gauge

Plot of RFMG raw data from June 24/03:41:51



The RFMG software finds the frequencies of these peaks, compares it to the database of 5 modes, and returns a % fill level.

Mass Gauging – RF Mass Gauge

RFMG data

- Typically collected RFMG data once every 15 minutes during boil-off tests
    - Once every 10-20 seconds during fill/drain
- 12,900 files were collected, zipped, and sent to GRC

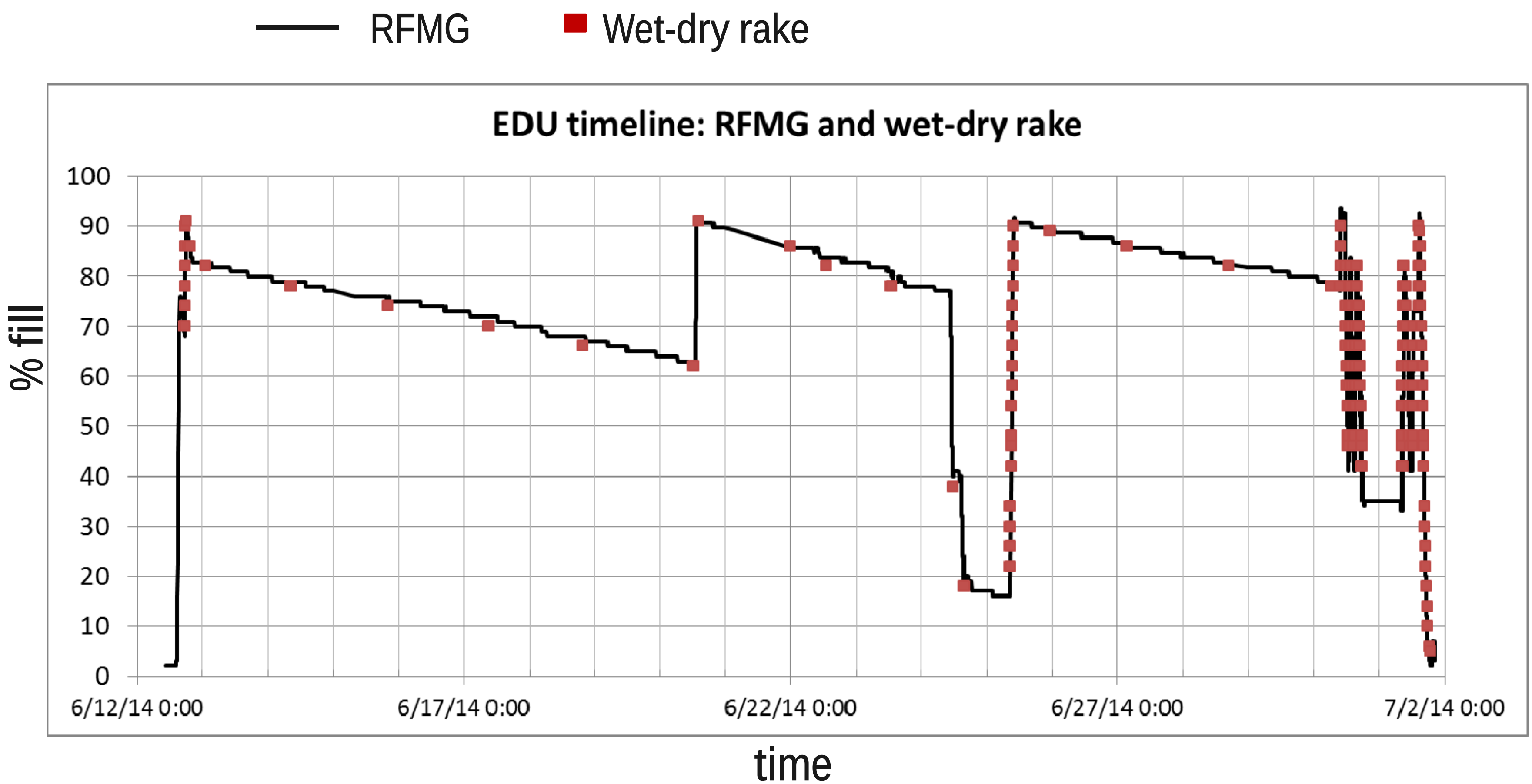
- Bad connection somewhere along Antenna 2 line before start of test. Signal came back during fill.

- A couple re-boots of the ZVL network analyzer were required during testing

- RFMG software initially set to use 3 measured modes
    - This led to poor results around 38% fill level, and several % discrepancy with wet-dry data near 90% fill
    - June 26: Updated software to use 5 measured modes, and updated the mode calibration factors
    - The 6/12 – 6/26 data reported here has been re-processed using the June 26 software update

Mass Gauging – RF Mass Gauge

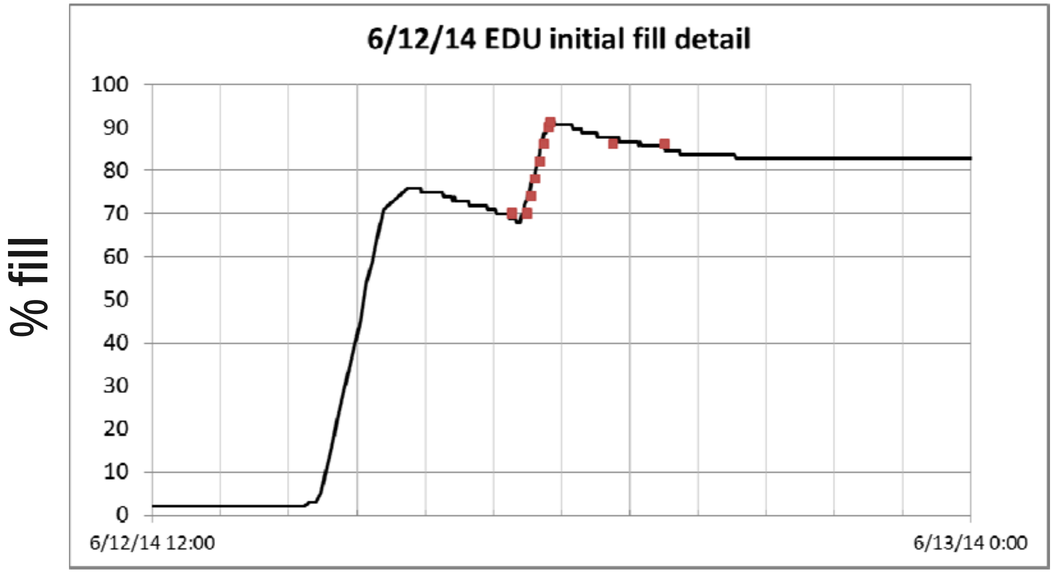
Comparison of RFMG result with wet-dry data:

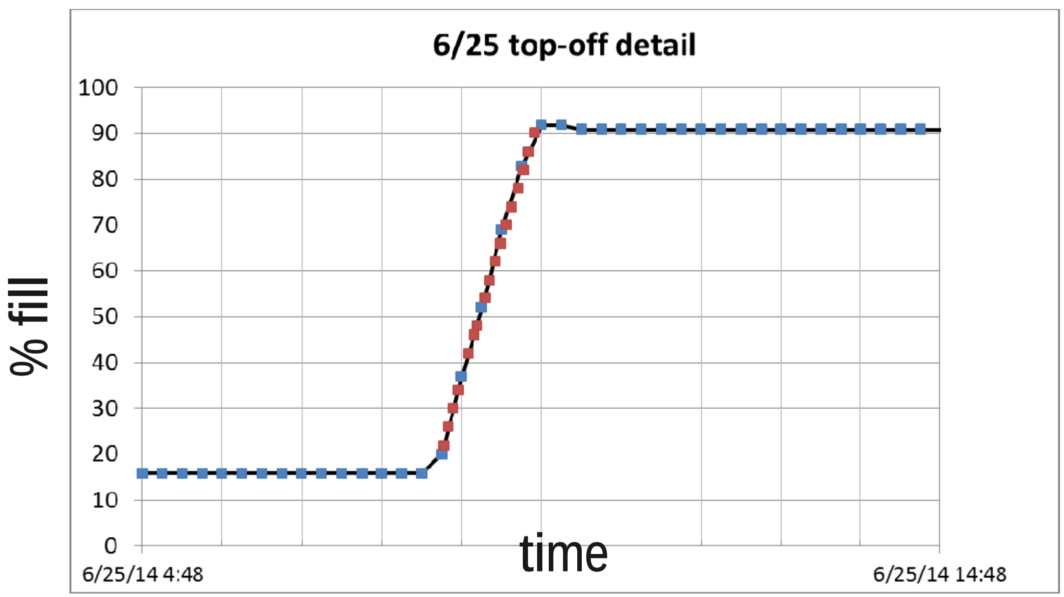


- No correction has been applied to convert wet-dry %-fill by volume to %-fill by mass (small effect)

Mass Gauging – RF Mass Gauge

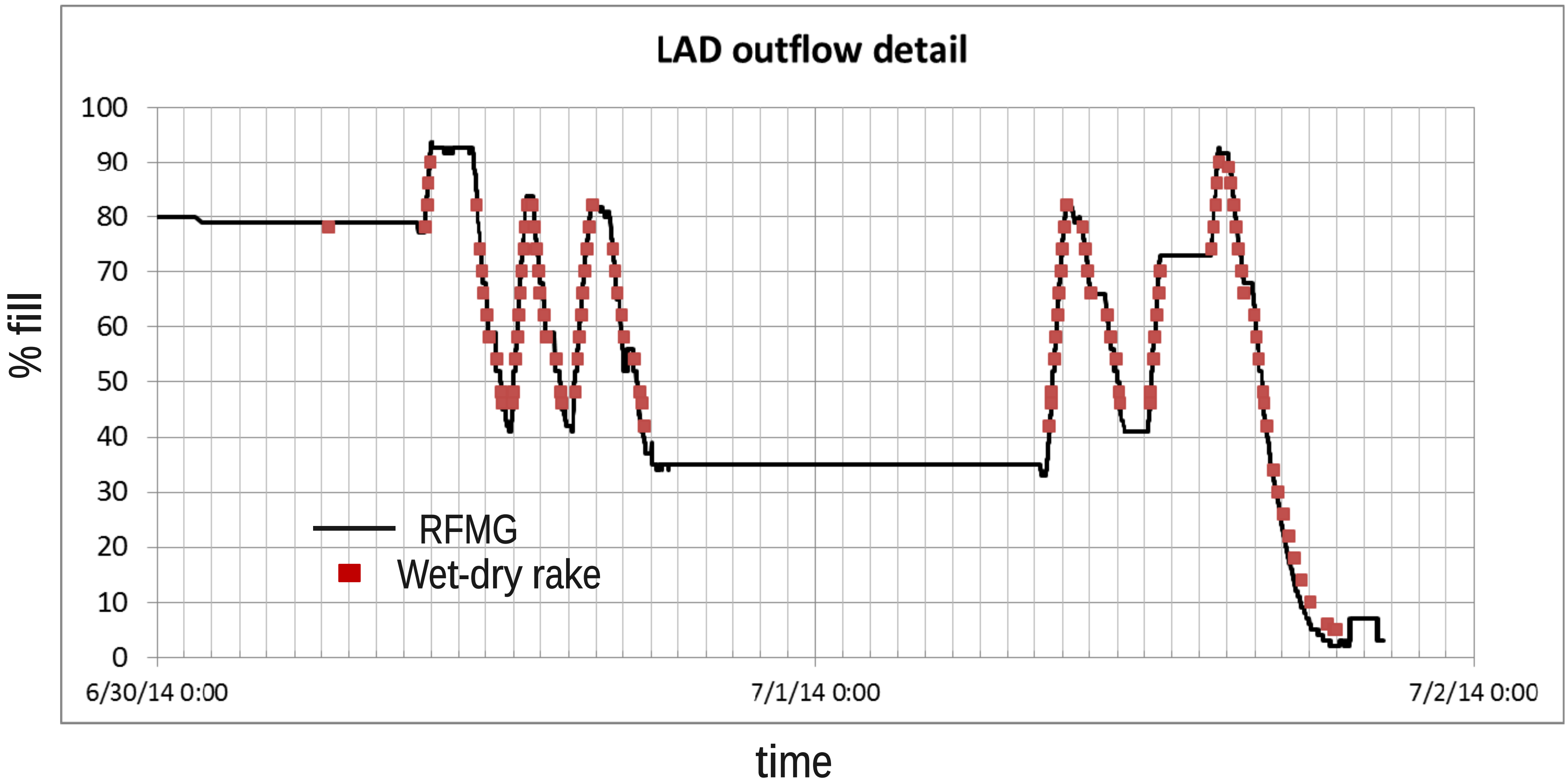
Detail of initial fill and 6/25 top-off





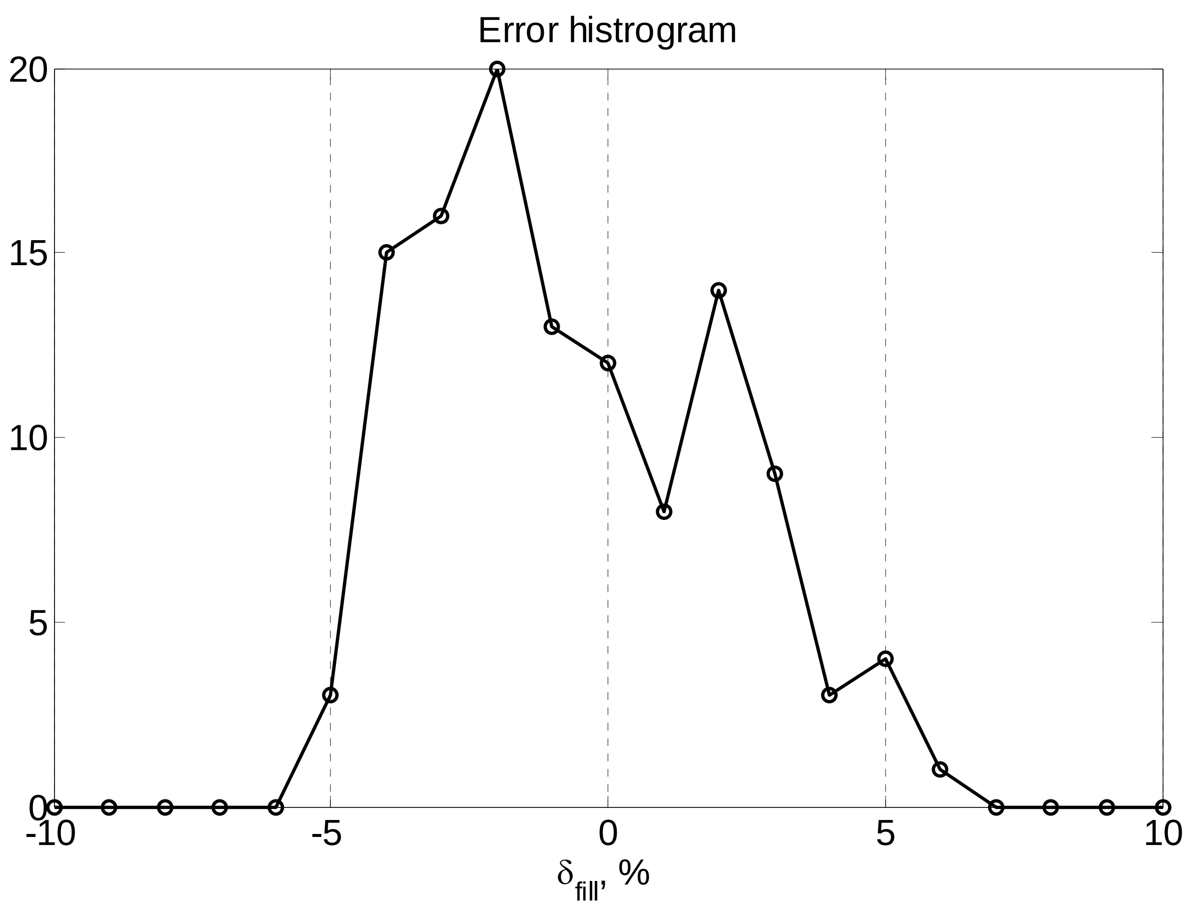
Mass Gauging – RF Mass Gauge

Excellent agreement between RFMG and wet-dry rake data



Mass Gauging – RF Mass Gauge

Comparison of RFMG output with wet-dry rake:



Wet_Dry – RFMG output, %

Mean difference: -0.6%
STDEV = 2.6%

Mass Gauging – Reduced Gravity CryoTracker

Reduced Gravity CryoTracker probes:

- CryoTracker instrument was controlled via laptop in instrument area
- Control room "mass gauge" computer running Remote Desktop was used to control and monitor the instrument
- CryoTracker software was used to manually switch the probe between T mode and mass gauging mode
- Data was recorded once every 10 s
- Unresolved software bug: CryoTracker software had to be restarted many times throughout testing

Mass Gauging – Reduced Gravity CryoTracker

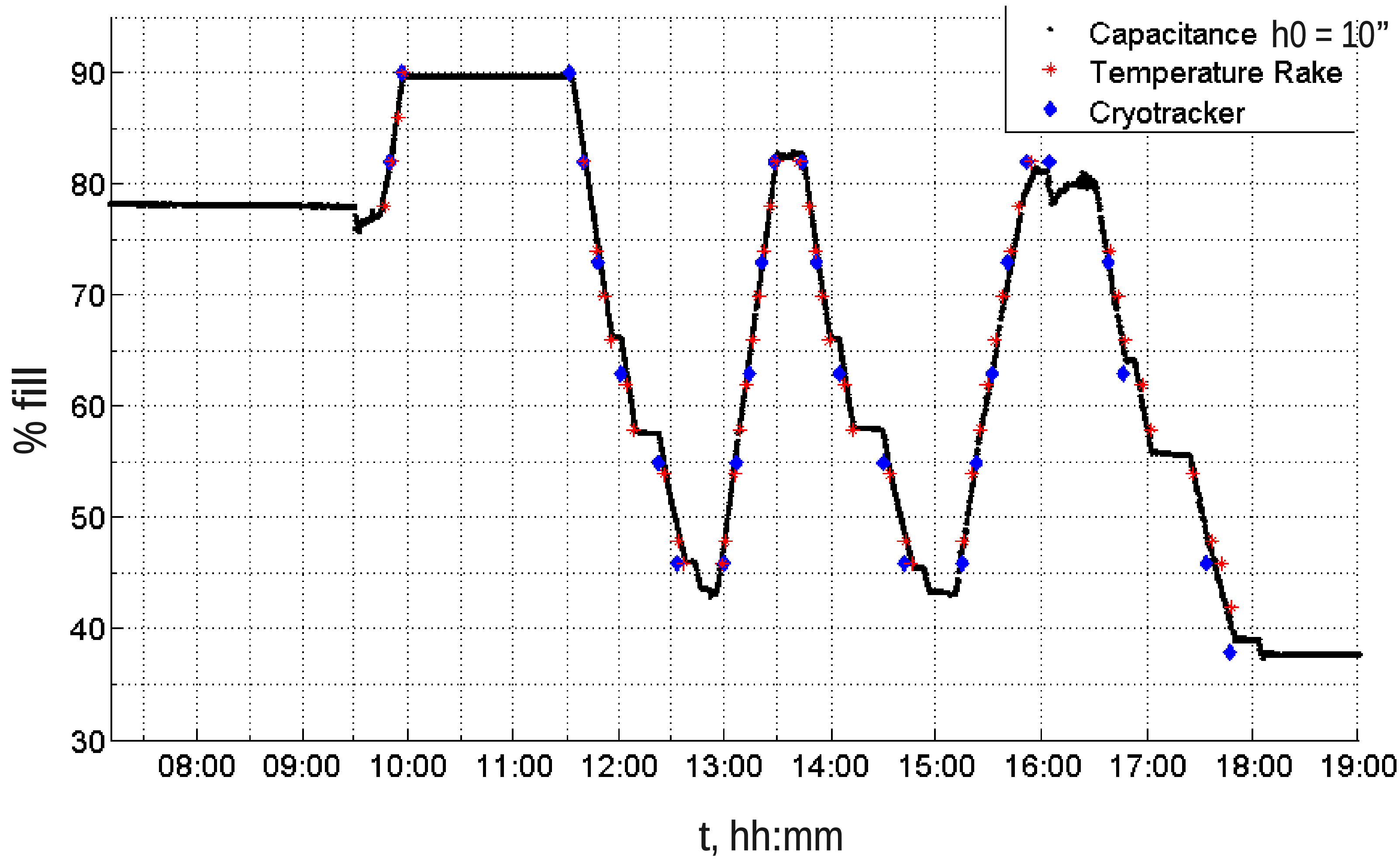
Reduced Gravity CryoTracker

- Data is similar to wet-dry rake
- Wet-dry transition points were found manually
- 72 wet-dry transition points were identified

Date: 7/1/2014										
Host Software Rev: 2.3.0										
Embedded Software Rev: 14										
Tau: 64										
Start Time: 7:10:41										
Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Pressure (	Mass (kg)
7:10:52 AM	22	25	31	34	37	39	41	40	14.7	
7:11:02 AM	1.638	1.288	1.281	1.274	1.239	1.25	1.234	1.228	14.7	87.7
7:11:12 AM	1.638	1.287	1.281	1.273	1.239	1.248	1.23	1.223	14.7	86
7:11:22 AM	1.638	1.288	1.281	1.273	1.239	1.248	1.23	1.231	14.7	86
7:11:32 AM	1.638	1.288	1.281	1.273	1.239	1.249	1.23	1.223	14.7	86
7:11:42 AM	1.638	1.289	1.281	1.273	1.239	1.25	1.232	1.229	14.7	86
7:11:52 AM	1.638	1.287	1.28	1.273	1.239	1.249	1.232	1.23	14.7	86
7:12:02 AM	1.638	1.288	1.281	1.273	1.238	1.25	1.231	1.227	14.7	86
7:12:12 AM	1.638	1.289	1.281	1.273	1.238	1.249	1.232	1.227	14.7	86
7:12:22 AM	22	29	37	39	42	44	47	50	14.7	
7:12:32 AM	21	25	31	34	37	40	40	40	14.7	
7:12:42 AM	22	24	32	34	37	39	39	45	14.7	
7:12:52 AM	22	24	32	34	37	39	40	44	14.7	
7:13:02 AM	22	24	31	33	38	39	39	48	14.7	
7:13:12 AM	23	24	31	34	37	39	39	44	14.7	
7:13:22 AM	22	24	31	32	38	38	40	47	14.7	

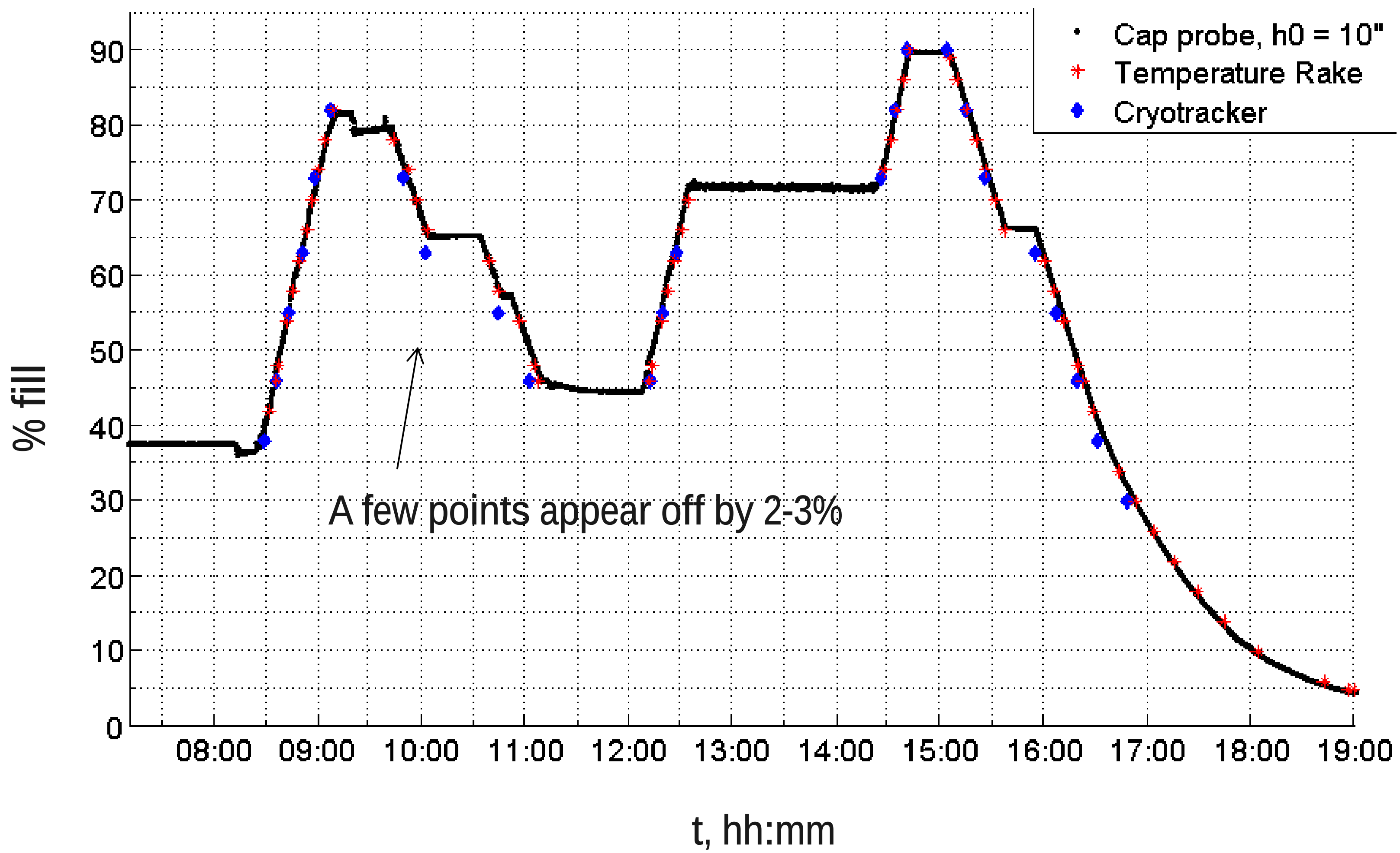
Mass Gauging – Reduced Gravity CryoTracker

Comparison of CryoTracker with cap probe and T rake: June 30



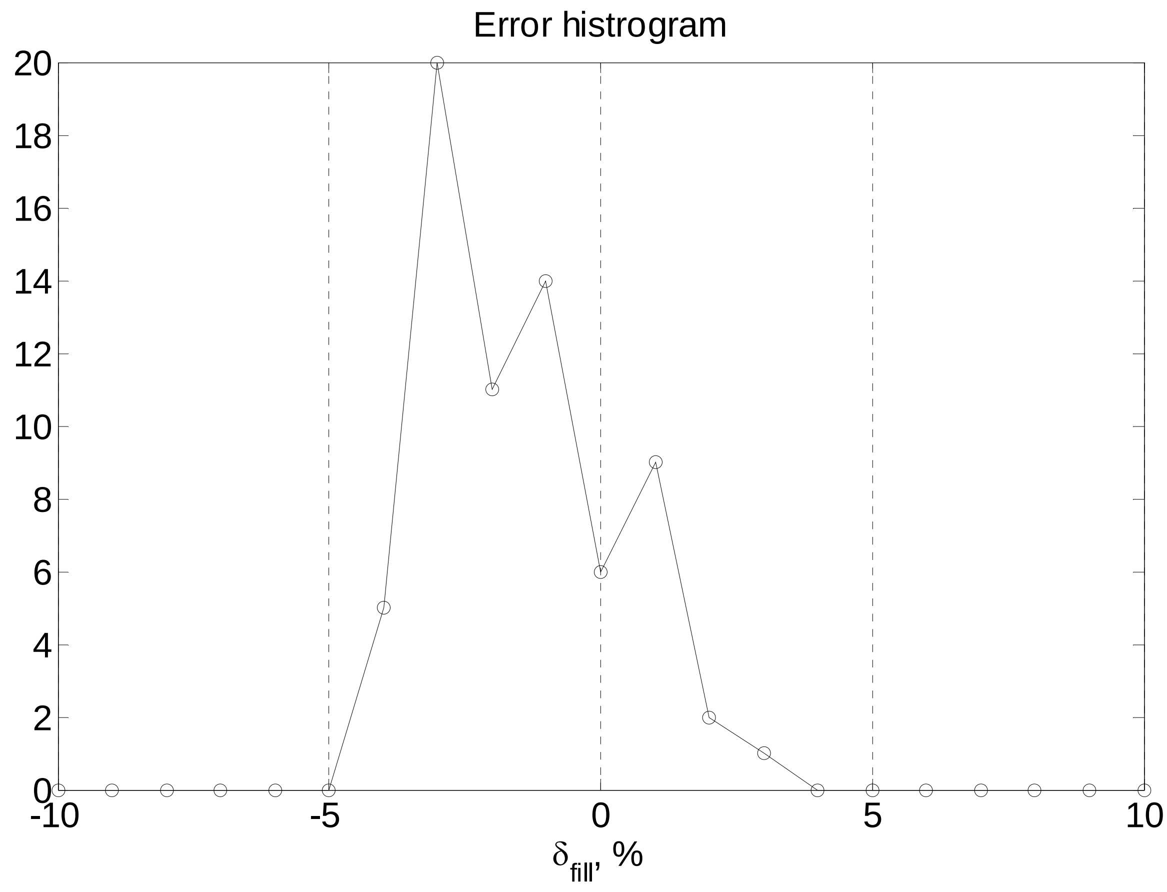
Mass Gauging – Reduced Gravity CryoTracker

Comparison of CryoTracker with cap probe and T rake: July 1



Mass Gauging – Reduced Gravity CryoTracker

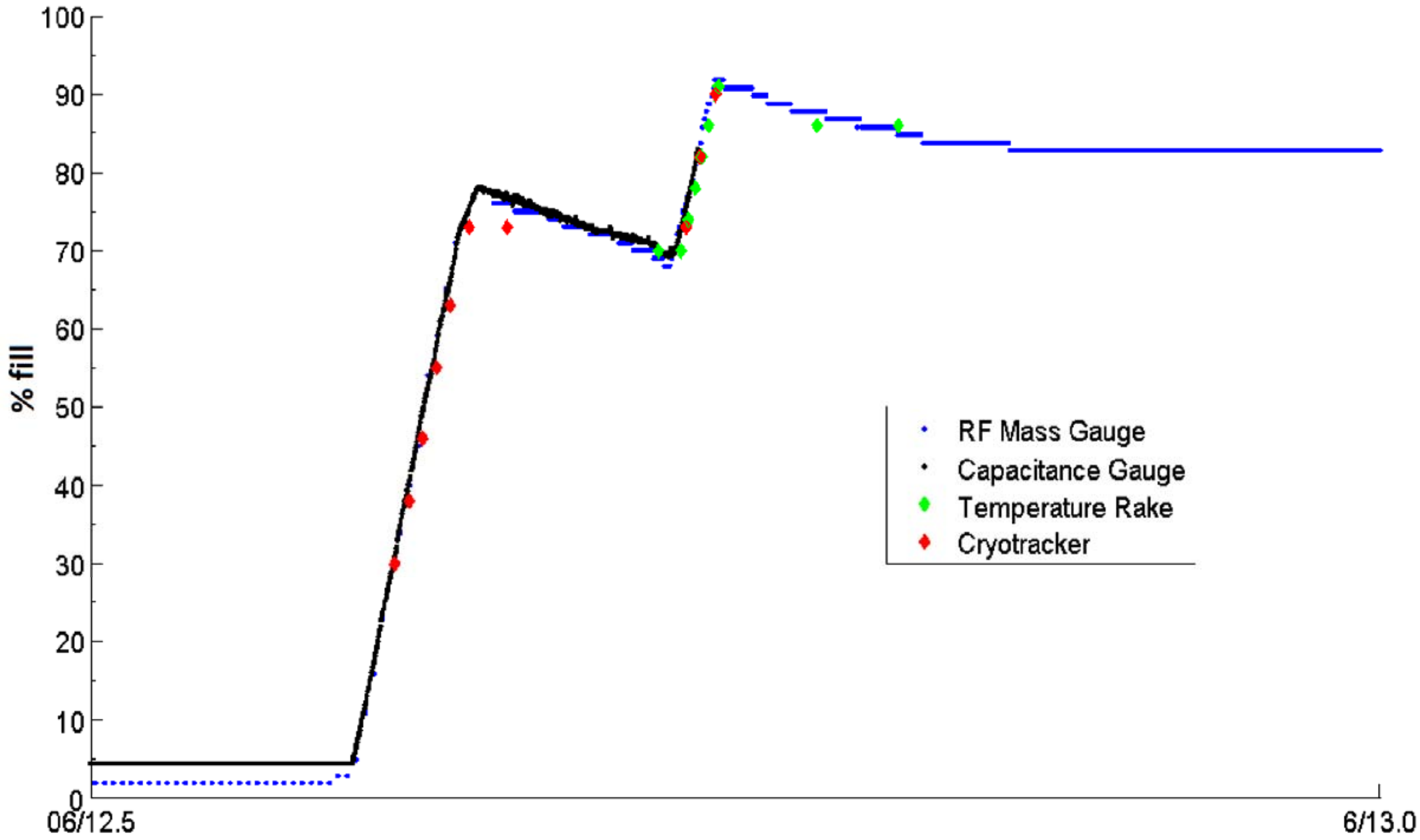
Comparison of RGCT output with cap-probe data:



Mean difference: -1.4%
STDEV = 2.2%

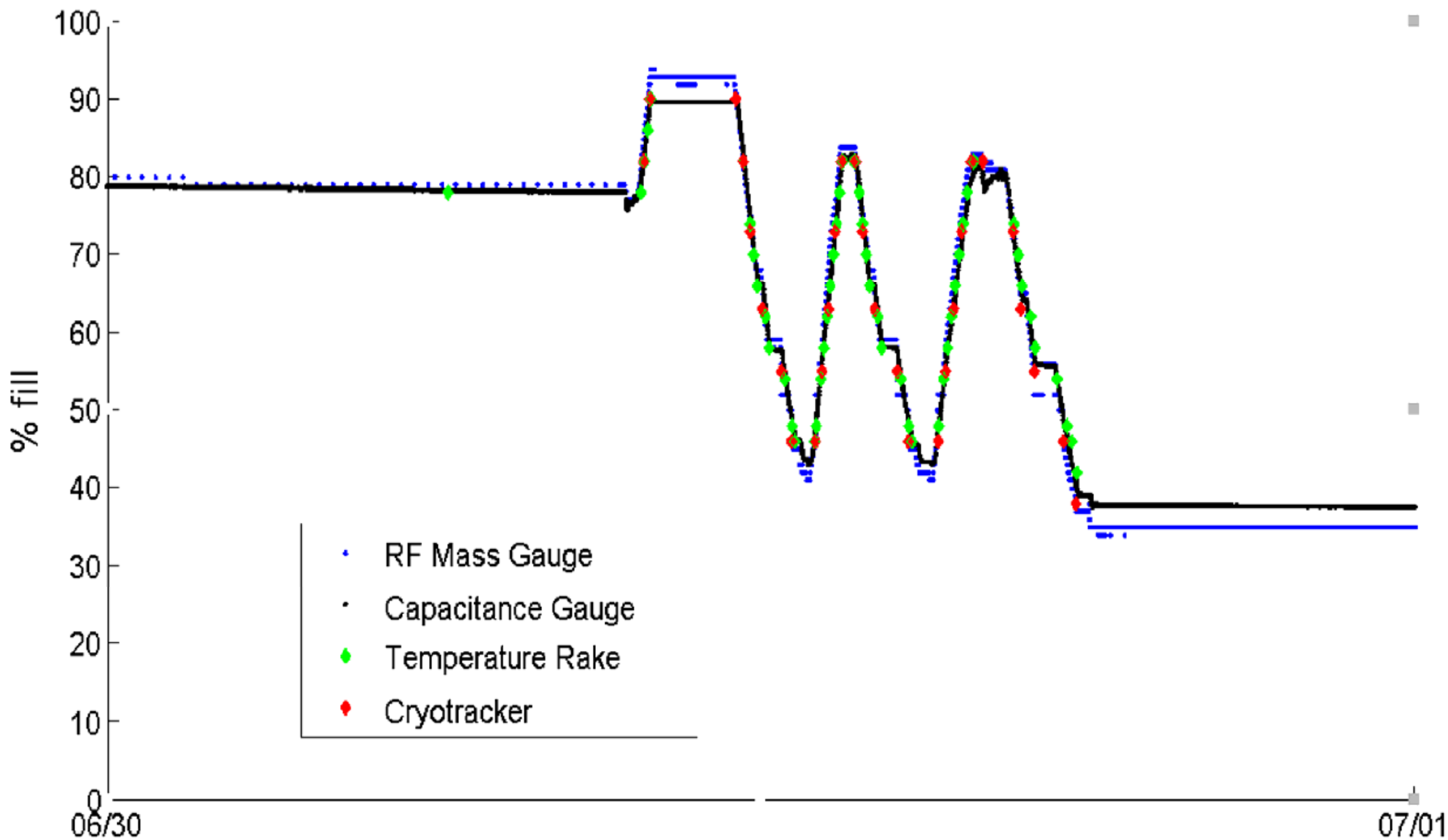
Mass Gauging – Comparison of all probes

Initial fill:



Mass Gauging – Comparison of all probes

LAD outflow testing



Mass Gauging

Conclusions:

- Very good correlation among mass gauging %-fill readings once corrections are made to cap probe data
- Wet-dry diode rake provided benchmark data for other probes, with an output resolution of ~ 4%.
- Cap probe data using h0 = 10 inches produces an excellent match with wet-dry data (mean difference = -0.3%, STDEV = 1.3%), continuous output resolution.
- Wet-dry/Cap probe data is regarded as accurate to within +-1%
- RFMG data agrees well with wet-dry sensors, using 6/26 software update (mean difference = 0.6%, STDEV = 2.6%). Output was quasi-continuous, 1% resolution.
- CryoTracker data shows good agreement with wet-dry/cap probe data at the transition points (mean difference = -1.4%, STDEV = 2.2%). Eight sensors provided course gauging between 30% and 90% fill, 8% resolution.