Via email:Ramon.lugo@ucf.edu

November 12, 2020

Ramon Lugo III
Director, Florida Space Institute
University of Central Florida
12354 Research Parkway
Partnership 1 Building, Suite 214
Orlando, Florida 32826

RE: RECOMMENDATION FOR COURSE OF ACTION AT ARECIBO OBSERVATORY
TT Project No. U20209

Dear Ray:

This letter is to inform you of our opinion as engineer of record for the stabilization and remediation of the damaged telescope, which is to decommission the telescope and perform a controlled demolition of the structure as soon as pragmatically possible. As you know, on the morning of August 10 a 3¼-inch-diameter cable, spanning from Tower 4 to the platform, failed as the tower end of the cable pulled from its socket and fell to the ground. This cable was one of the auxiliary system of twelve cables installed twenty-seven years ago. The auxiliary cables supplemented the cables from the telescope's original construction in the 1960s to accommodate the weight added to the receiver platform by the installation of the Gregorian dome.

Thornton Tomasetti, Inc. [TT] was retained to produce the design of any components necessary to stabilize the structure and then to design the remediation to engage permanent repairs. The assignment required TT to develop a digital model of the structure to determine the state of load effects in the platform components, towers and cables in their current and possible future configurations. We calibrated the model using survey data, data from instrumentation installed on the telescope after the failure and data obtained by the observatory upon the cable's failure. The model was checked internally and peer reviewed by an external party, Wiss, Janney, Elstner Associates, Inc. [WJE]. The model is a tool that predicts load effects, or forces and deformations of the structure, hence the demands on its elements. The model does not predict capacity of the elements. The true capacity of these original cables and auxiliary sockets as they exist today is unknown, because the specific cause and extent of the deterioration in each of these elements is not currently known. Each has failed at forces significantly less than the specified minimum breaking strength.

The structural design is highly redundant (meaning it has the ability to survive collapse after the loss of a critical element). Each of the three towers has four 3-inch-diameter original cables spanning to the near apex of the triangular platform and two 3¼-inch auxiliary cables connecting farther back on the platform. When the auxiliary cable that spans to Tower 4 failed in August, load was shed to the four original cables and the remaining auxiliary cable still connecting the platform to the tower. After the failure, observatory staff, TT, WJE and WSP inspected/reviewed the remaining structure for signs of distress and deterioration. Given the generally good appearance of the remaining elements; suitable factor-of-safety remaining in the platform elements, as shown through analysis; and adequate redundancy of the cable system, we believed the platform to be stable then and for some time forward. Our analysis had shown that the loss of another cable would not cause catastrophic collapse of the platform. Therefore, we believed work to stabilize the structure could begin, with continuous monitoring and safe operational procedures. The observatory procured materials and supplies and planned for installation.

As you know, TT proposed the stabilization scheme and until recently was developing remedial works to return the telescope to operating condition, with enhanced capability and performance such that the 60-year-old original cables would have less tension force in the them than in the past during normal operating conditions. Reduction of the load in these cables seemed prudent due to their age and a few documented wire breaks on the original cables over the years. We recommended that all remaining cables be inspected to determine their condition, to be certain that the wire breaks that were documented in the past were the full extent of the breaks and that the internal core of each cable was in good condition. Furthermore, TT recommended the replacement of all of the auxiliary cables, since the one 3¼-inch auxiliary cable completely pulled from its socket and numerous other auxiliary cables exhibited unusual slip at their sockets.

Another cable failed on November 6. This cable was one of the four 3-inch-diameter original cables also supporting the platform from Tower 4. These original cables had been operating at a factor of safety of 1.67, based upon specified minimum breaking strength for the cable just prior to failure. This corresponded to a load or tension force of 647 kips (1 kip = one thousand pounds) in the original cables. The tension in the remaining three original cables has increased from the 647 kips to 790 kips. This places them at a factor of safety of 1.32 (force in cable/specified minimum breaking strength = 790/1044). This is nearly 75% of the specified minimum breaking strength. The original cable failed near the anchor socket at the tower but did not pull from the socket. The design of the original structure and the upgrade in the 1990s intended a factor of safety of 2.1 or more for the cables.

With the loss of two cables, there are now three original cables (of four) and one auxiliary cable (of two) connecting the platform to Tower 4. Should another of these three original cables fail, the two remaining original cables will undergo static force demands at or above the specified minimum breaking strength. A catastrophic failure would be very likely. These cables are not capable of handling the required dynamic demands of a sudden failure of an adjacent cable. The structural redundancy is no longer available and cannot be factored into determining safety.

We have noted wire breaks on the three remaining 3-inch-diameter original cables from Tower 4, which occurred during the November event. We continue to monitor the structure and continue to note wire breaks since the failure last week. Furthermore, there is no evidence that the existing original cables can achieve the specified minimum breaking strength and certainly evidence to the contrary, since one failed at 62% of this strength. The failure event may have occurred over a period of eight minutes as evidenced by the increase in stress, measured from instrumentation installed on the south auxiliary cable to Tower 4, just prior to failure. Weather at the time of failure was calm, with no unusual winds or ambient temperatures and no ground shaking. Failure was unexpected.

Given the likelihood of additional cable failure, unless redundancy can be added to the structure at Tower 4 (by connecting more cables to the platform from Tower 4), it is unsafe to work on the platform or around the towers unless hazards are mitigated. However, mitigation cannot be practically achieved without working for long periods in these locations. There are no means within engineering certainty to provide an estimate of the factor of safety other than significantly reducing tension in these 3-inch-diameter original cables. We have modeled and studied several options, and it is unlikely any of these methods will yield sufficient reductions without placing crews in jeopardy.

It has been suggested that proof-loading the structure for a period of time – to demonstrate that the critical structural elements can sustain forces approximately 10% more than the predicted forces in these elements during the implementation of any remedial work – will provide a calculable margin of safety over some duration, and that repeated proof-loading could provide the means to ensure safety throughout the duration of work. However, we believe that even if proof loading does not cause collapse or further failure of an element, it will cause damage and reduce reserve capacity, making the structure less safe. If we accept collapse to be an

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acceptable outcome, we need to understand the collapse mechanism to reduce risk. Collapse from a proof-testing event will not be predictable and hence creates undue risk.

Now that we have witnessed two cables fail, one from the original set of cables and one from the auxiliary cables, both at tension forces significantly below their design strengths, it would appear that remediation will require replacement of all of the cables. This factor needs to be considered, as does the timing of the replacement program.

We believe the structure will collapse in the near future if left untouched. Controlled demolition, designed with a specific collapse sequence determined and implemented with the use of explosives, will reduce the uncertainty and danger associated with collapse. Although it saddens us to make this recommendation, we believe the structure should be demolished in a controlled way as soon as pragmatically possible. It is therefore our recommendation to expeditiously plan for decommissioning of the observatory and execute a controlled demolition of the telescope.

Very truly yours,

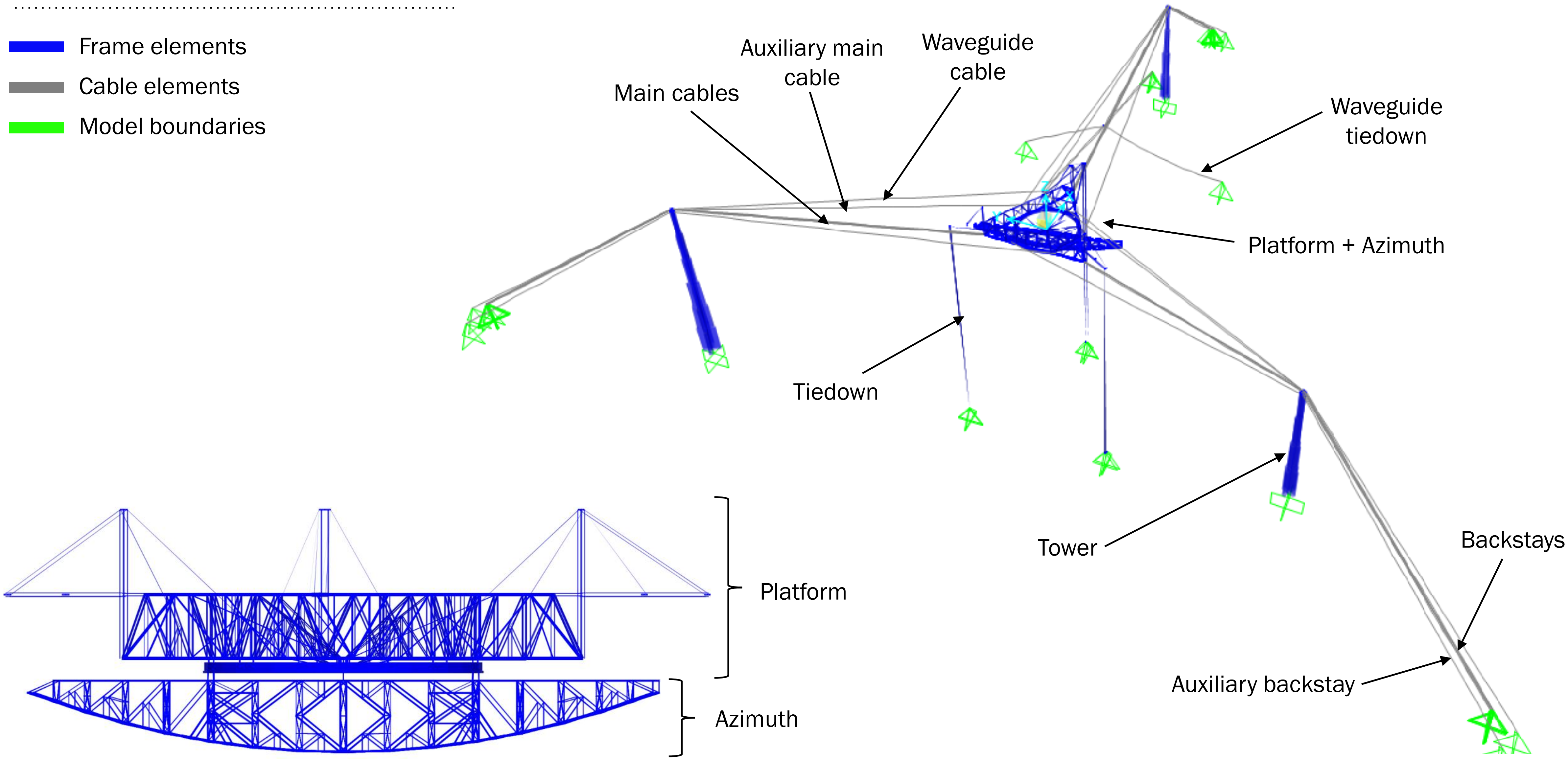
THORNTON TOMASETTI, INC.

John Abruzzo, PE, SE
Managing Principal

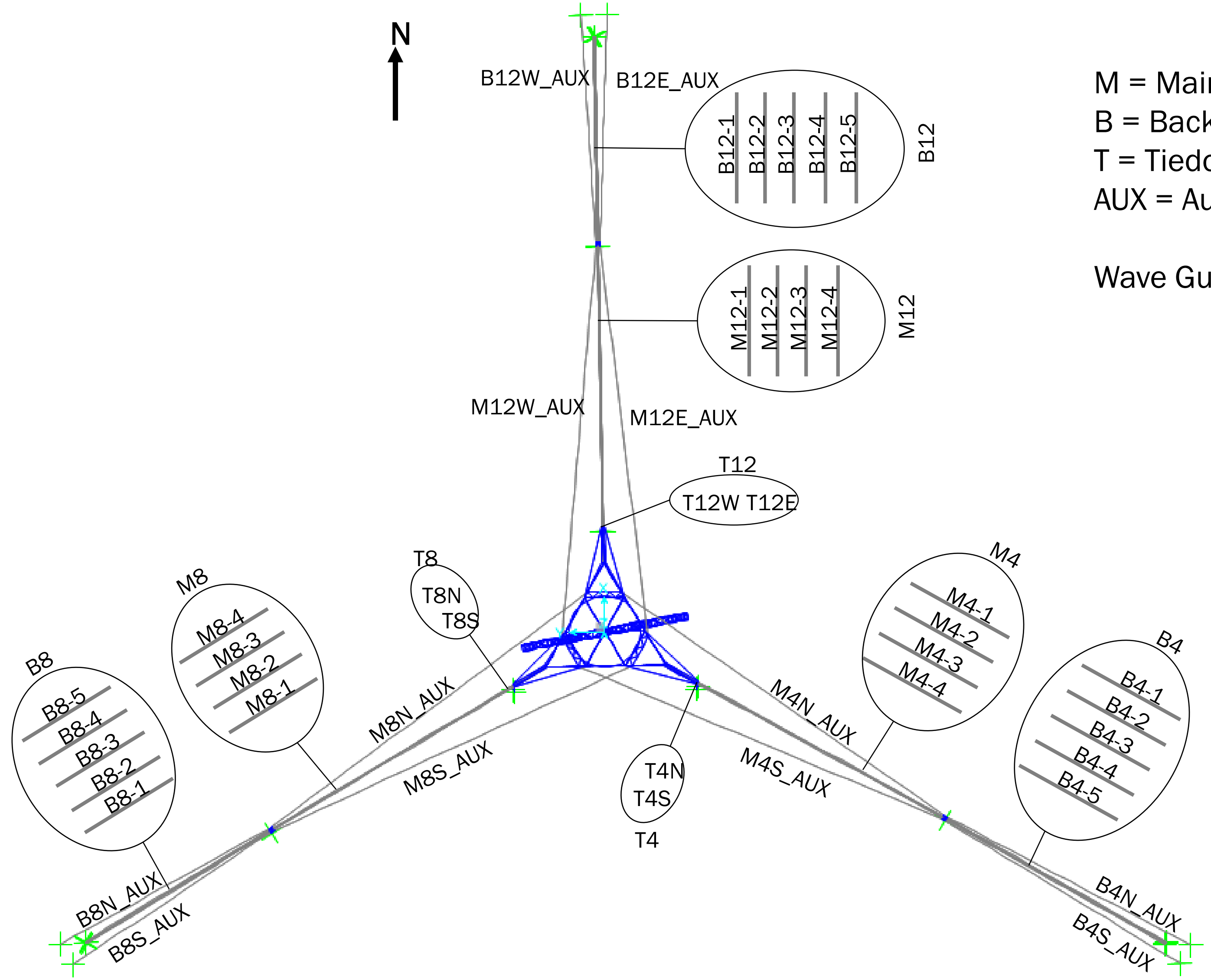
Attachments:
Model Calibrations
Results of model for various scenarios

Copy:
Francisco Cordova
Director, Arecibo Observatory

Digital Model Scope and Nomenclature



Digital Model Cable Nomenclature



M = Main cable
B = Backstay cable
T = Tiedown cable
AUX = Auxiliary cable (added 1992)

Wave Guide cables not shown

Platform Nomenclature

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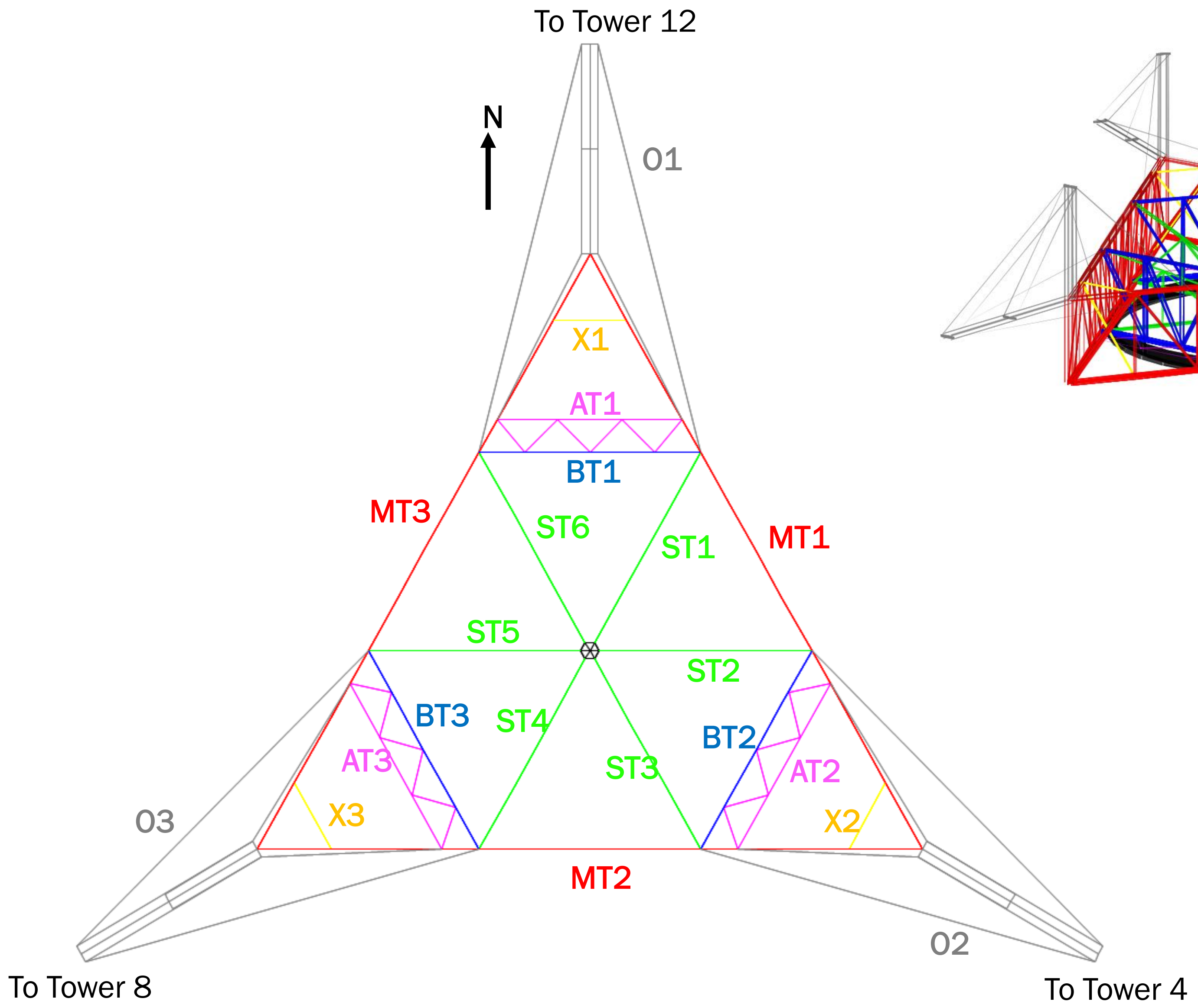
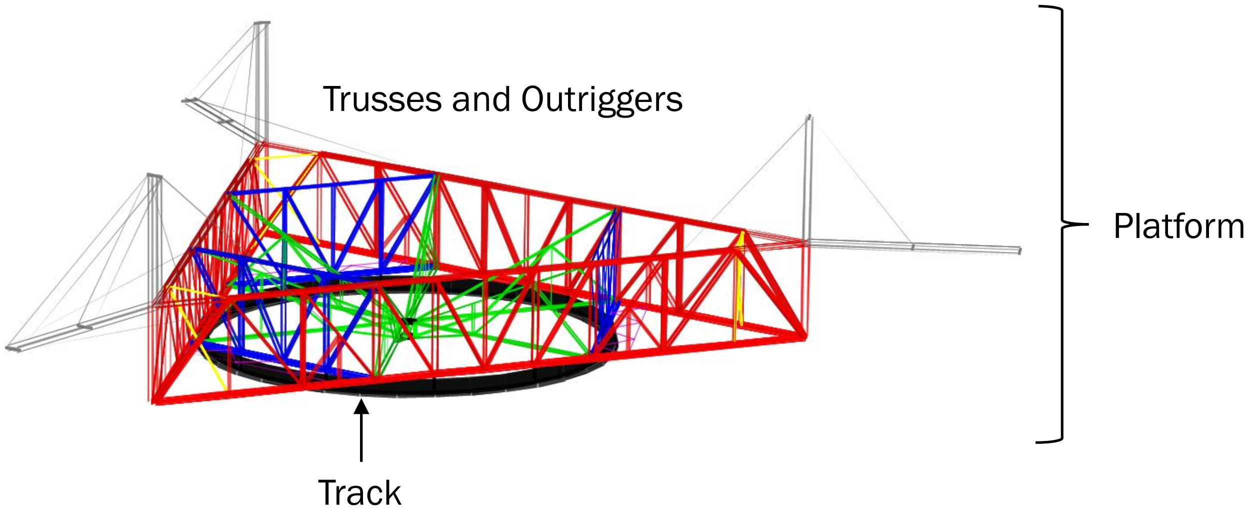


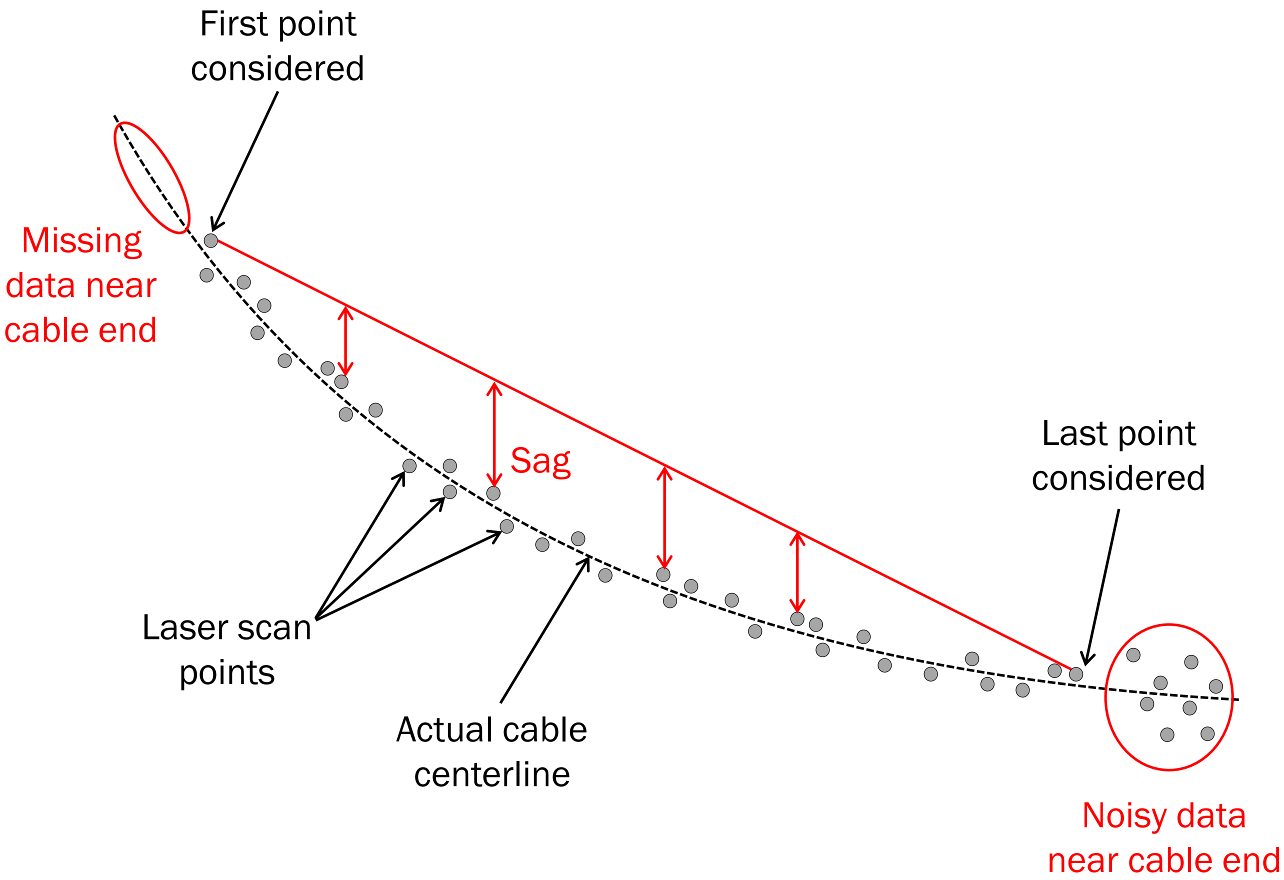


Original structure:

- MT = Main Trusses
- BT = Bracing Trusses
- ST = Secondary Bracing Trusses
- Track

1992 upgrade structure:

- AT = Auxiliary trusses
- X = X-Bracing
- O = Outriggers



For each cable:

1) Select first and last points along top of cable, staying away from cable ends where data is missing or noisy.
2) Determine equation of straight line between first and last points.
3) For 10 points on top cable and approximately evenly-spaced between first and last points, calculate elevation difference between point and straight line. The maximum difference is the measured sag.
4) Using catenary equations, calculate cable force such that maximum sag matches measured sag. For this step, the cable is assumed to span between the first and last points considered above, and not the start and end points of the actual cable.
5) Using catenary equations, calculate vertical component of cable force at connection with suspended platform. The sum of these results is the suspended platform weight (+ tiedown forces).

Sag Survey (Before Second Cable Failure)

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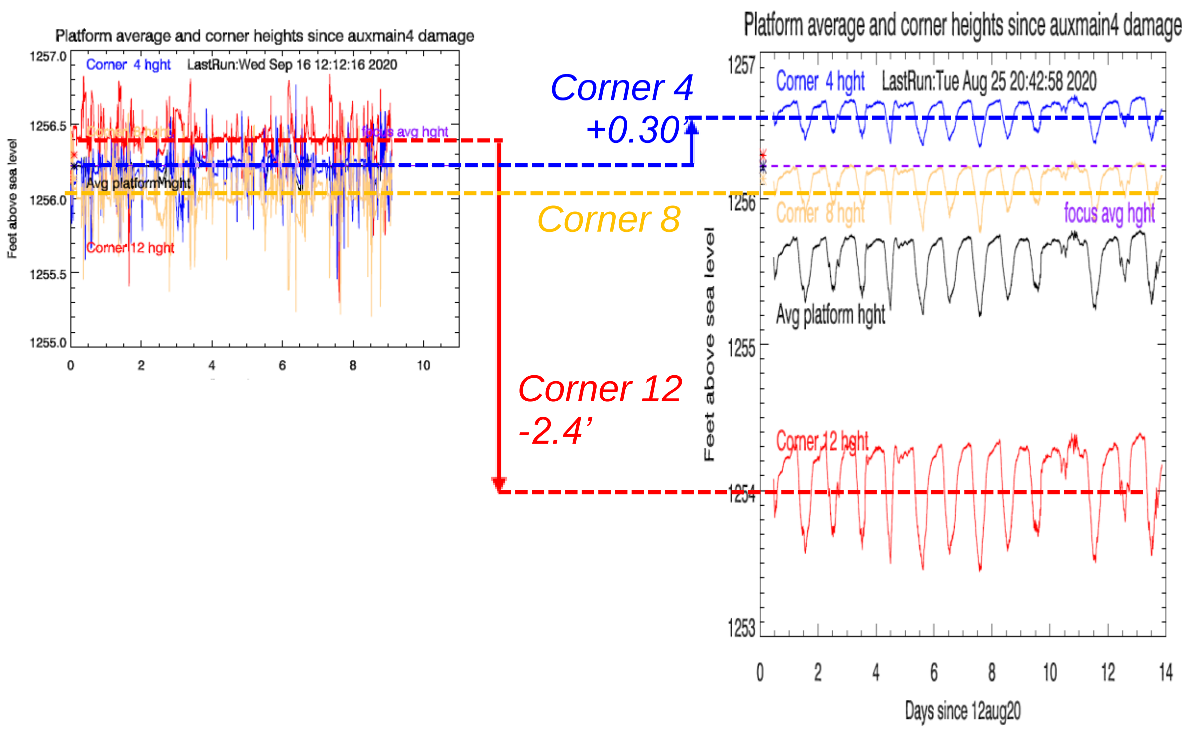
Cables(s)	Number of Cables	Horizontal Force [kip]	Average Axial Force [kip]	Vertical Force at Platform End [kip]
M4	4	629	645	137
M4S	1	599	609	98
M8	4	483	495	104
M8N	1	522	531	84
M8S	1	724	736	120
M12	4	501	514	108
M12E	1	390	396	61
M12W	1	683	694	113

Cables(s)	Number of Cables	Horizontal Force [kip]	Average Axial Force [kip]
B4	5	465	572
B4N	1	535	657
B4S	1	535	657
B8	5	485	540
B8N	1	535	598
B8S	1	540	603
B12	5	455	560
B12E	1	575	706
B12W	1	490	601

Total vertical force on platform = 1,871 kip
Total tiedown force = 45 kip
→ Weight of suspended structure = 1,871 – 45 = 1,826 kip

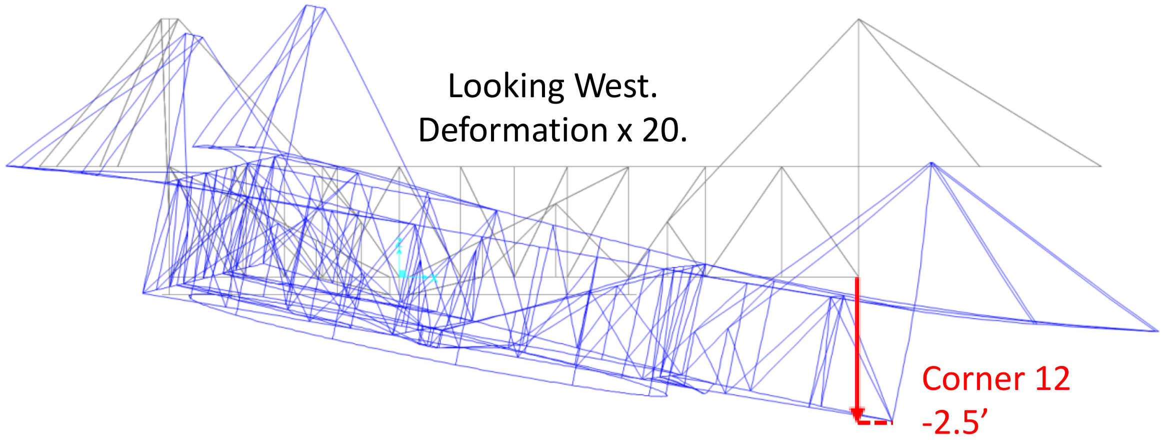
Validation: Platform Corner Elevation Change During Failure

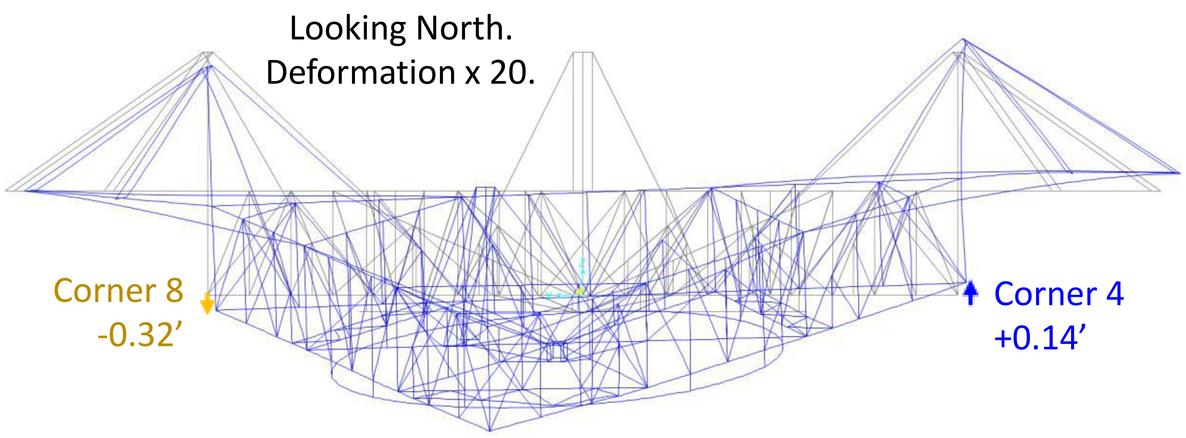
Monitoring



	Corner 4	Corner 8	Corner 12
Monitoring	0.30’ (3.6")	0’ (0")	-2.4’ (-28.8")
FE Model	0.14’ (1.6")	-0.32’ (-3.9")	-2.5’ (30.1")

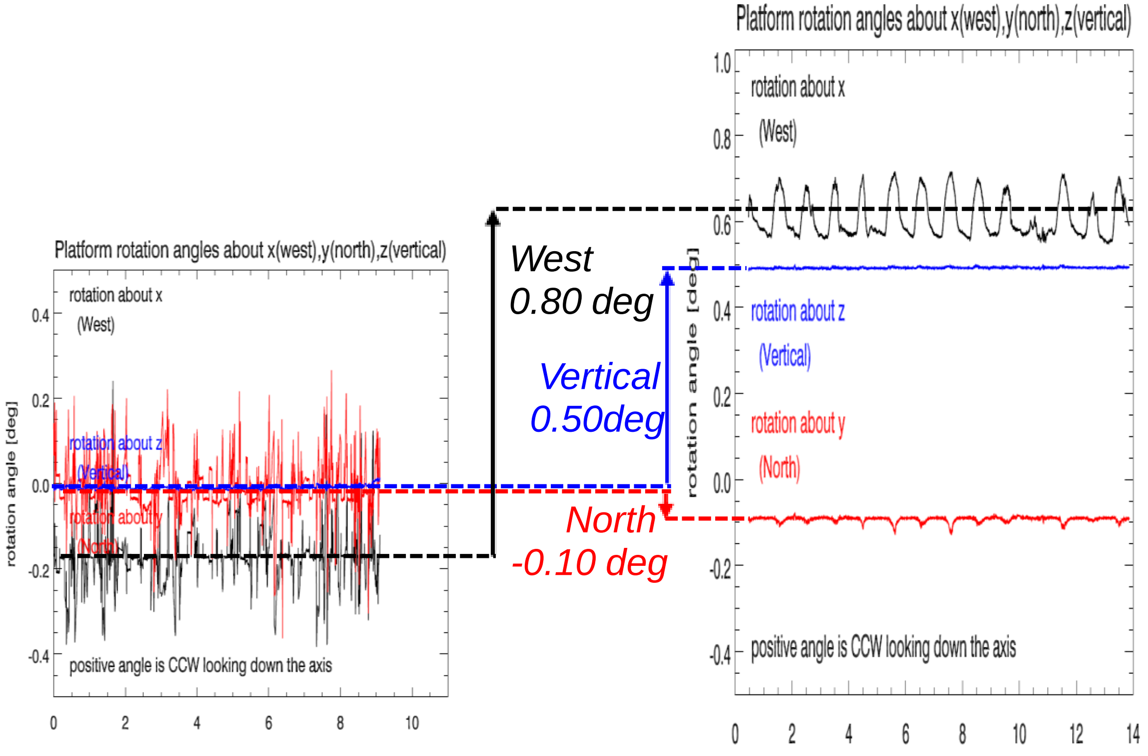
FE Model



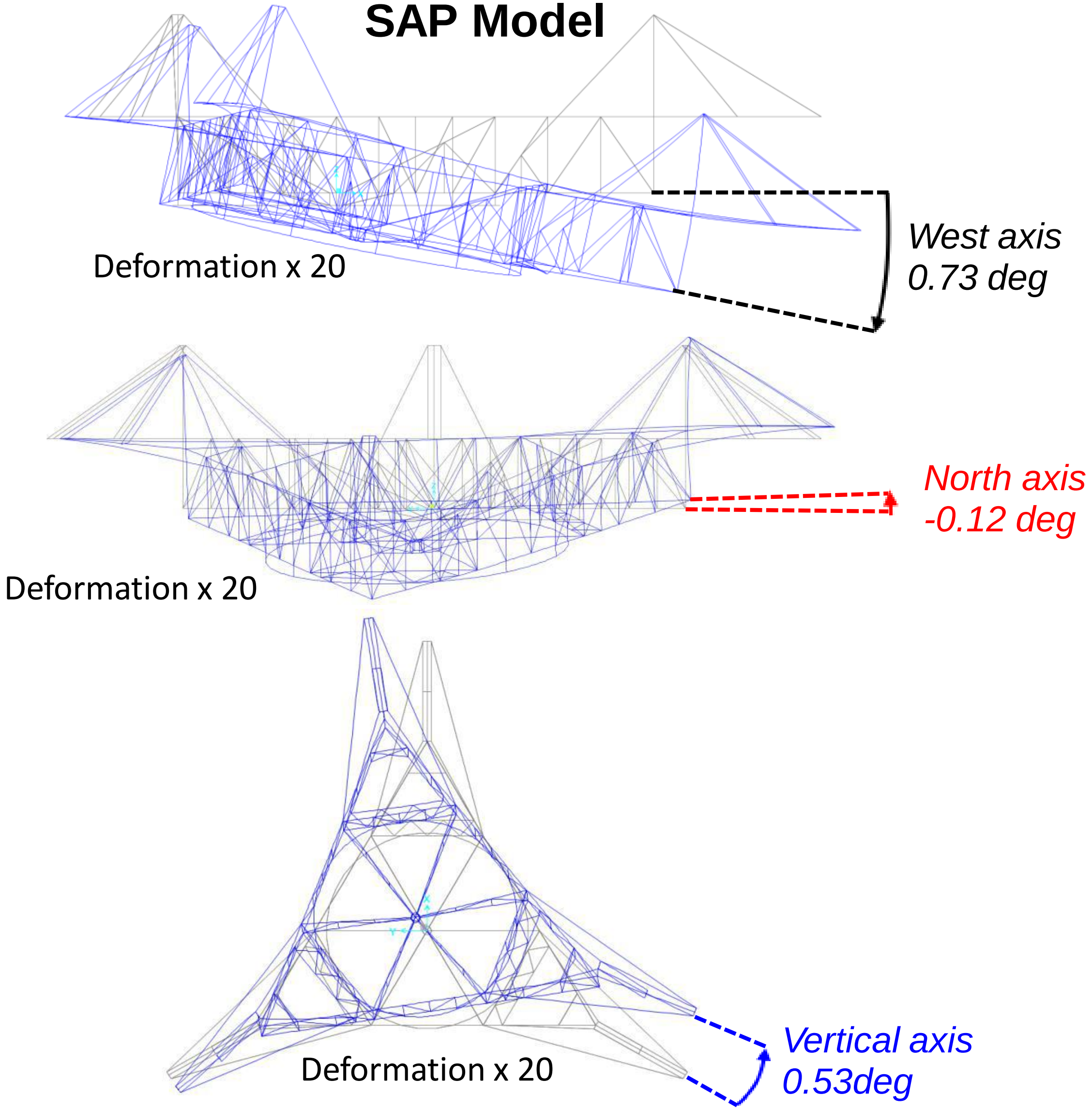


Validation: Platform Rotation During

Monitoring



SAP Model

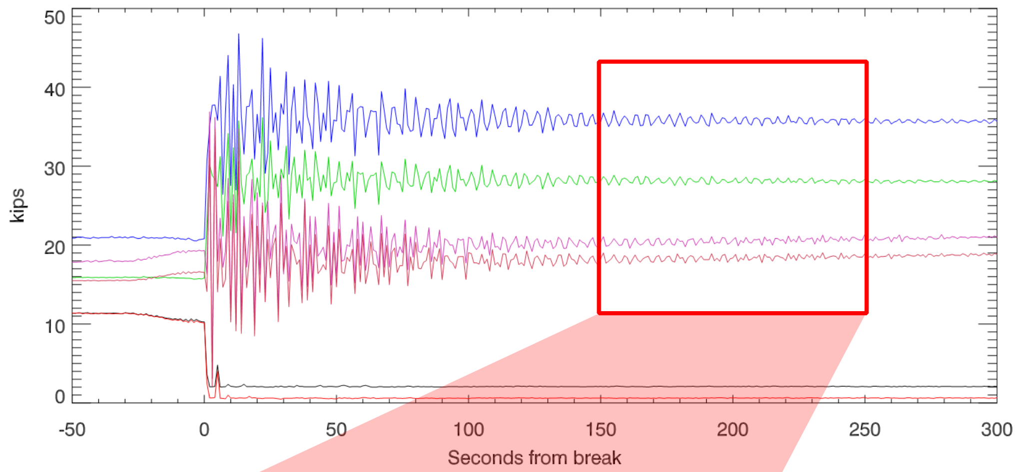


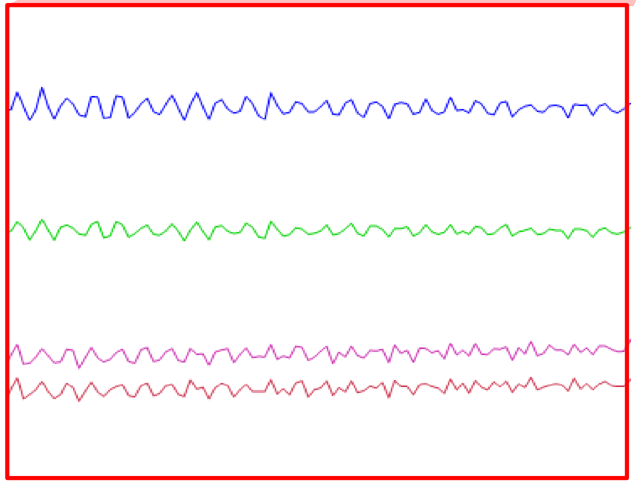
	West axis	North axis	Vertical axis
Monitoring	0.80^{o}	-0.10^{o}	0.50^{o}
FE Model	0.73^{o}	-0.12^{o}	0.53^{o}

Validation: Natural Frequency After Failure

Monitoring

Tiedown forces during failure



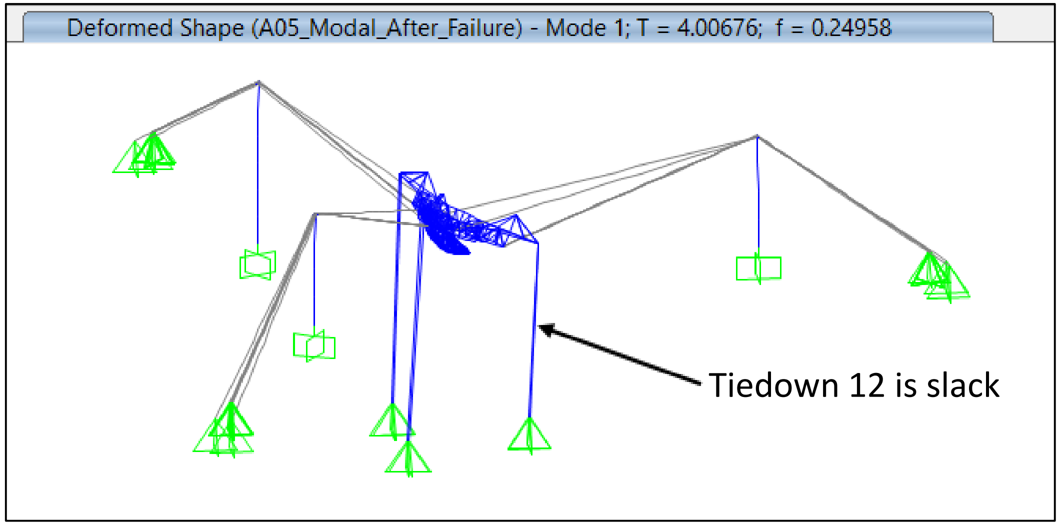


td12-a td12-b
td4 -a td4 -b
td8 -a td8 -b

24.5 cycles in 100 sec
→ **f = 0.245 Hz**
→ **T = 4.08 s**

FE Model

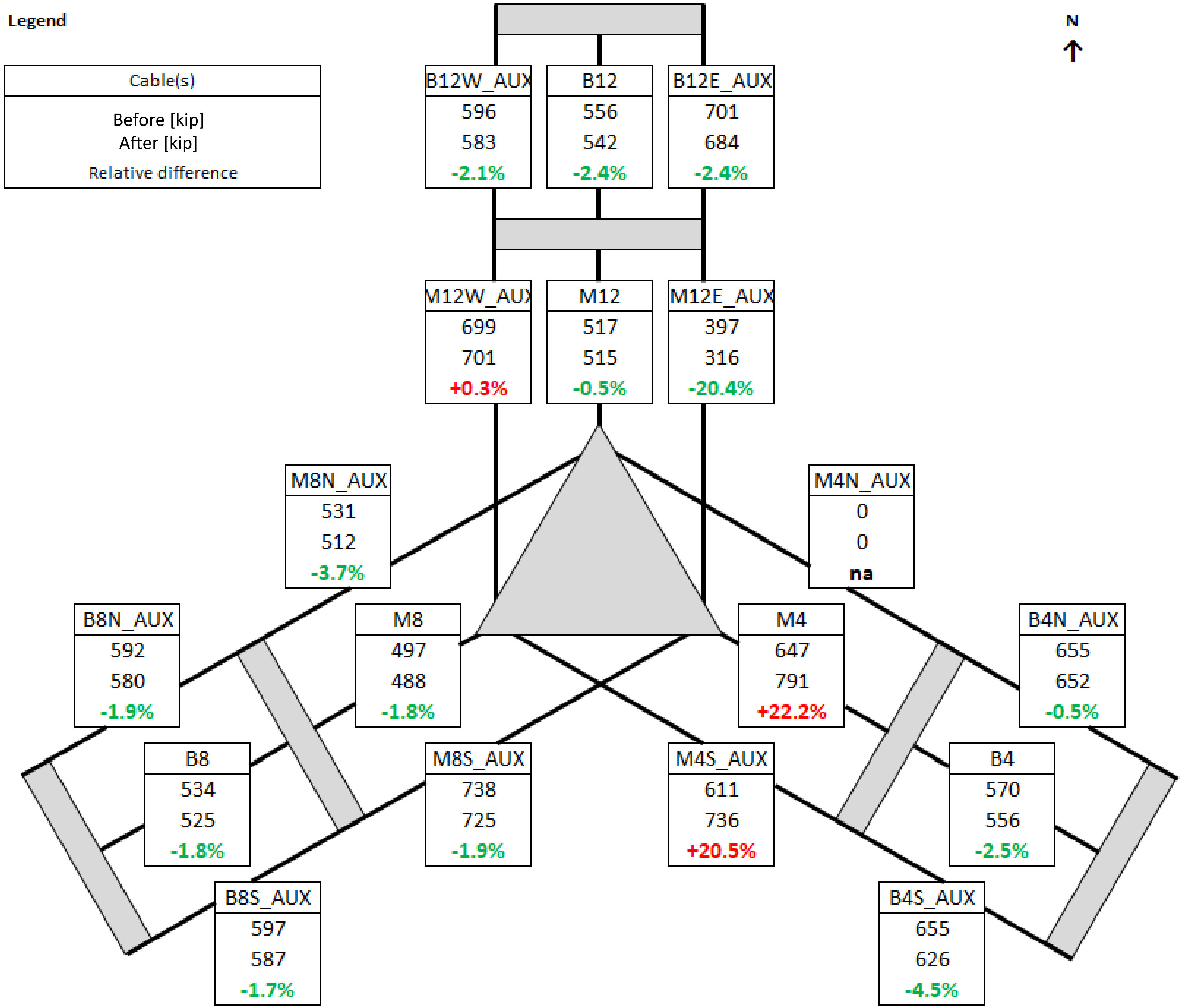
Modal analysis with total structure mass of 1,826 kip and tiedown 12 removed



→ **f = 0.233 Hz**
→ **T = 4.30 s**

Cable Force Change

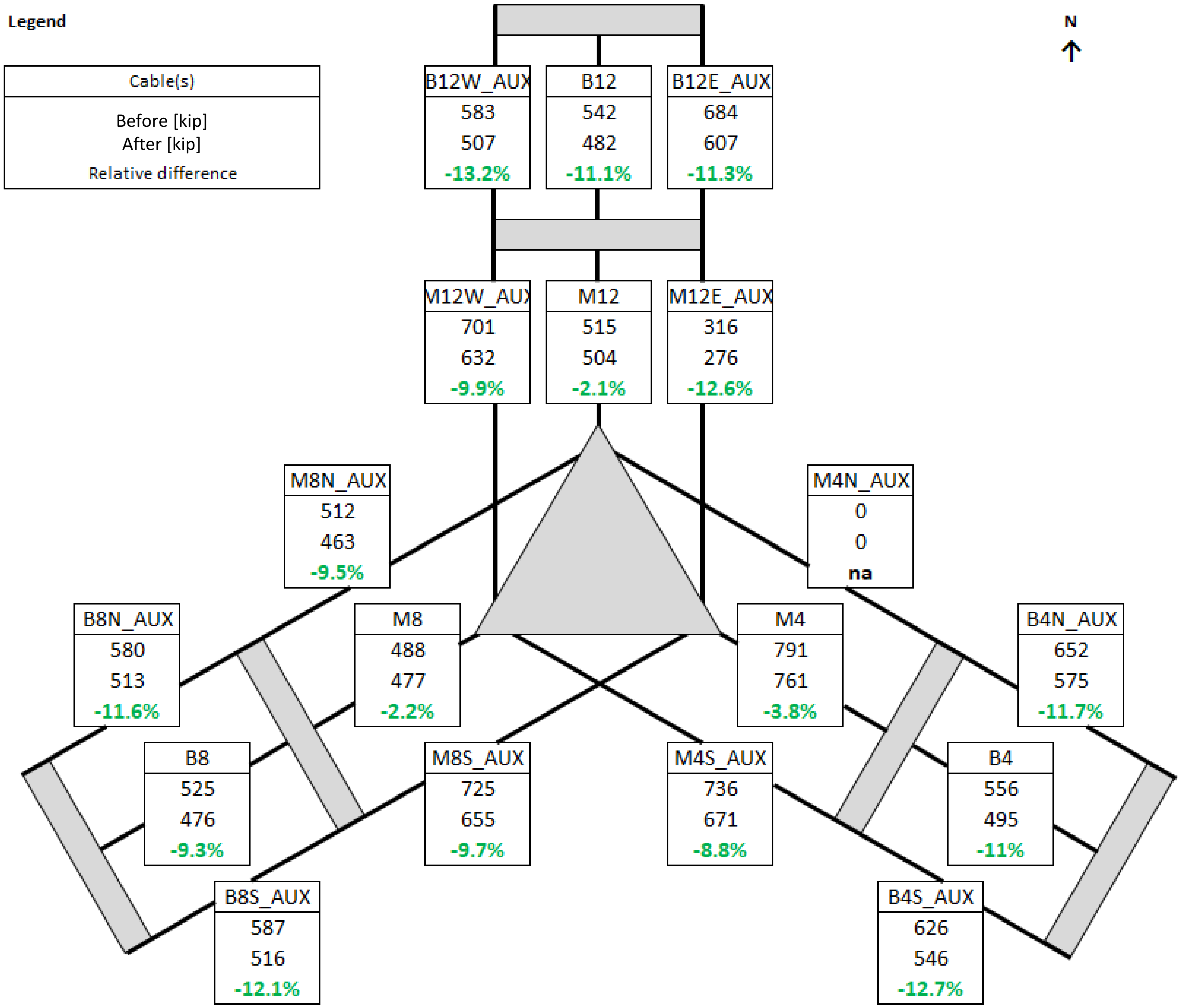
Due to Second Cable Failure



Cable Force Change

If De-Jacking all Backstays by 18"

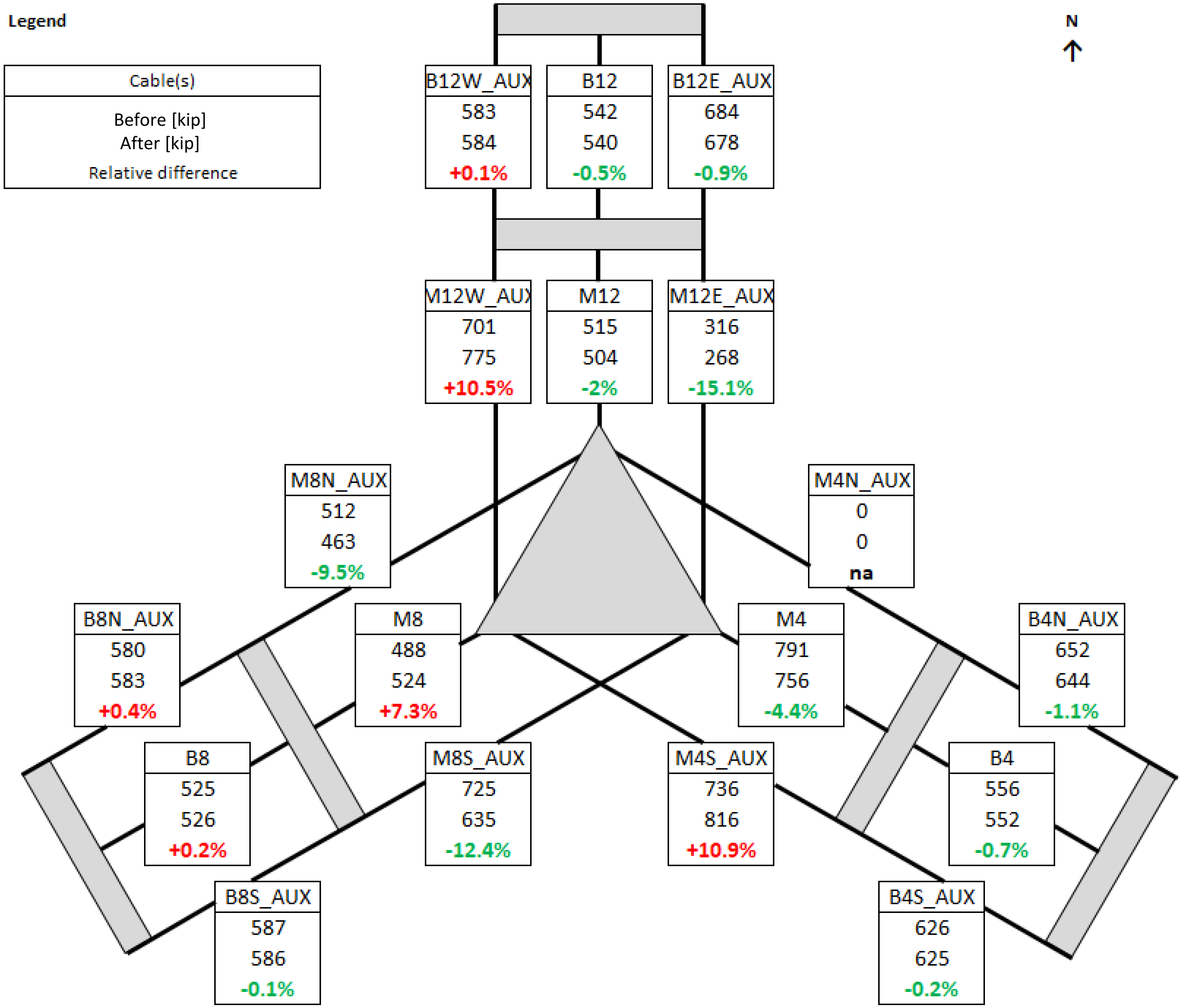
(starting from current condition)



Cable Force Change

If Moving Gregorian Out

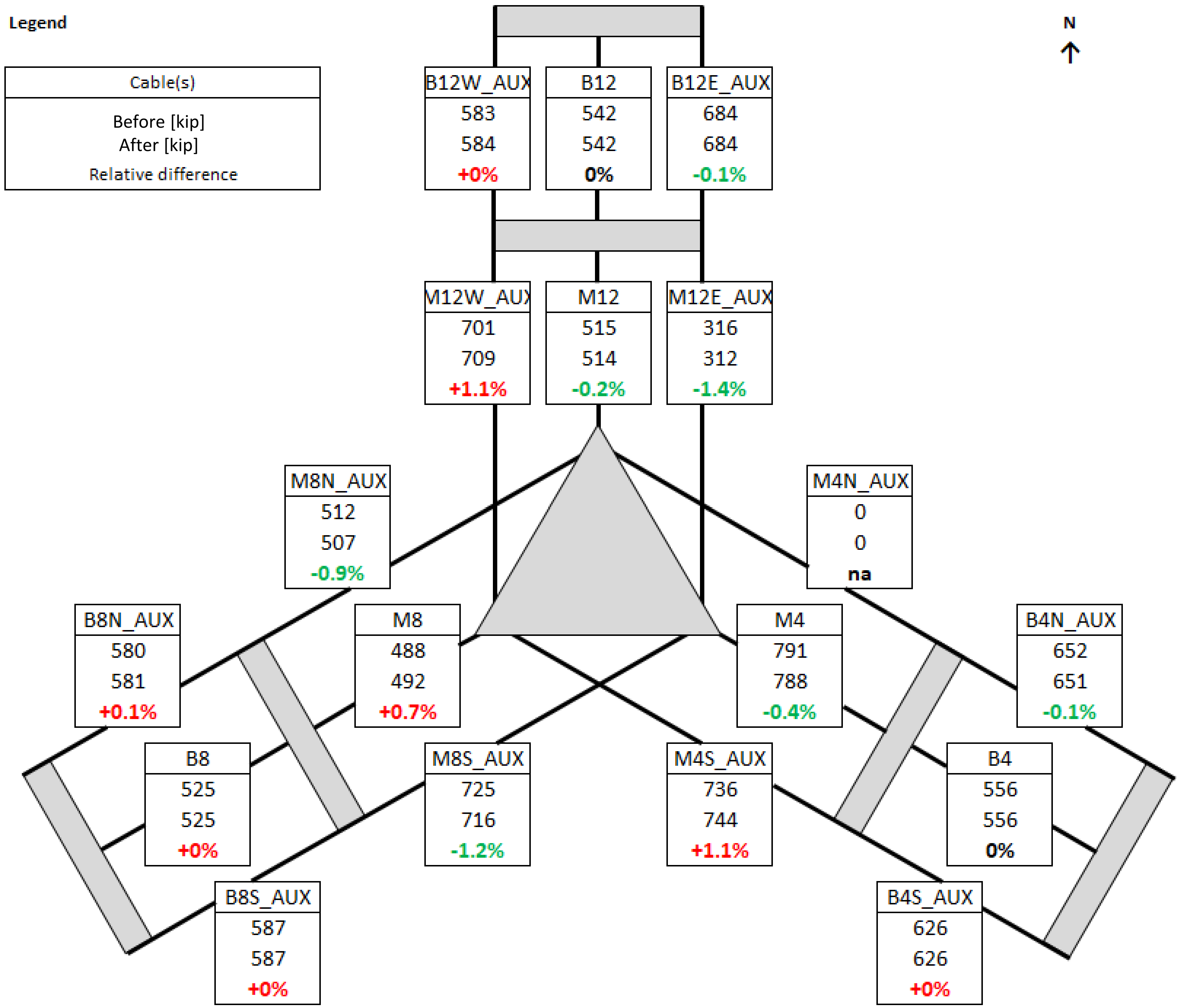
(starting from current condition)



Cable Force Change

If Moving Line Feed In

(starting from current condition)



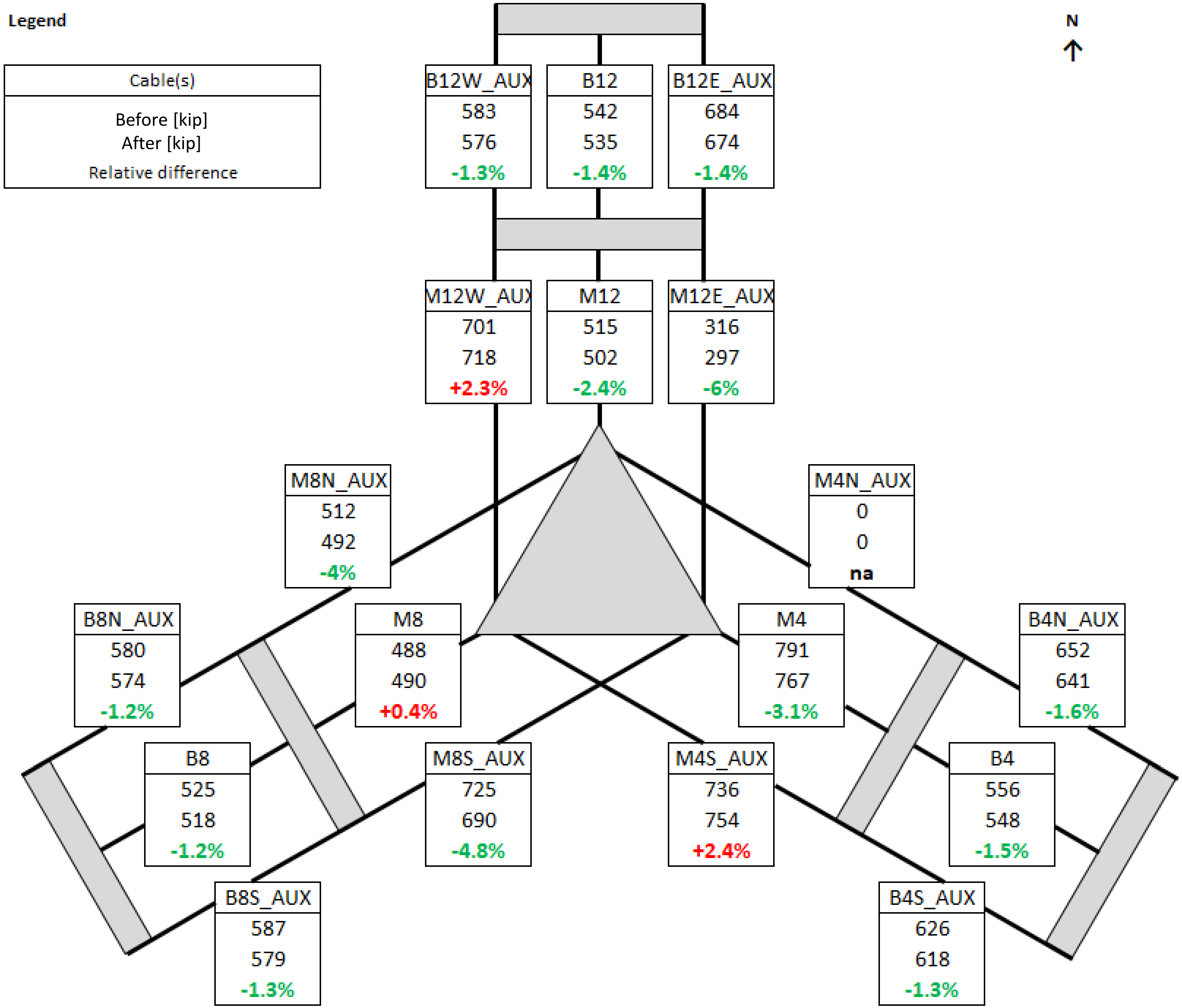
Cable Force Change

If Dropping 38kip Counterweight

(starting from current condition)

Legend

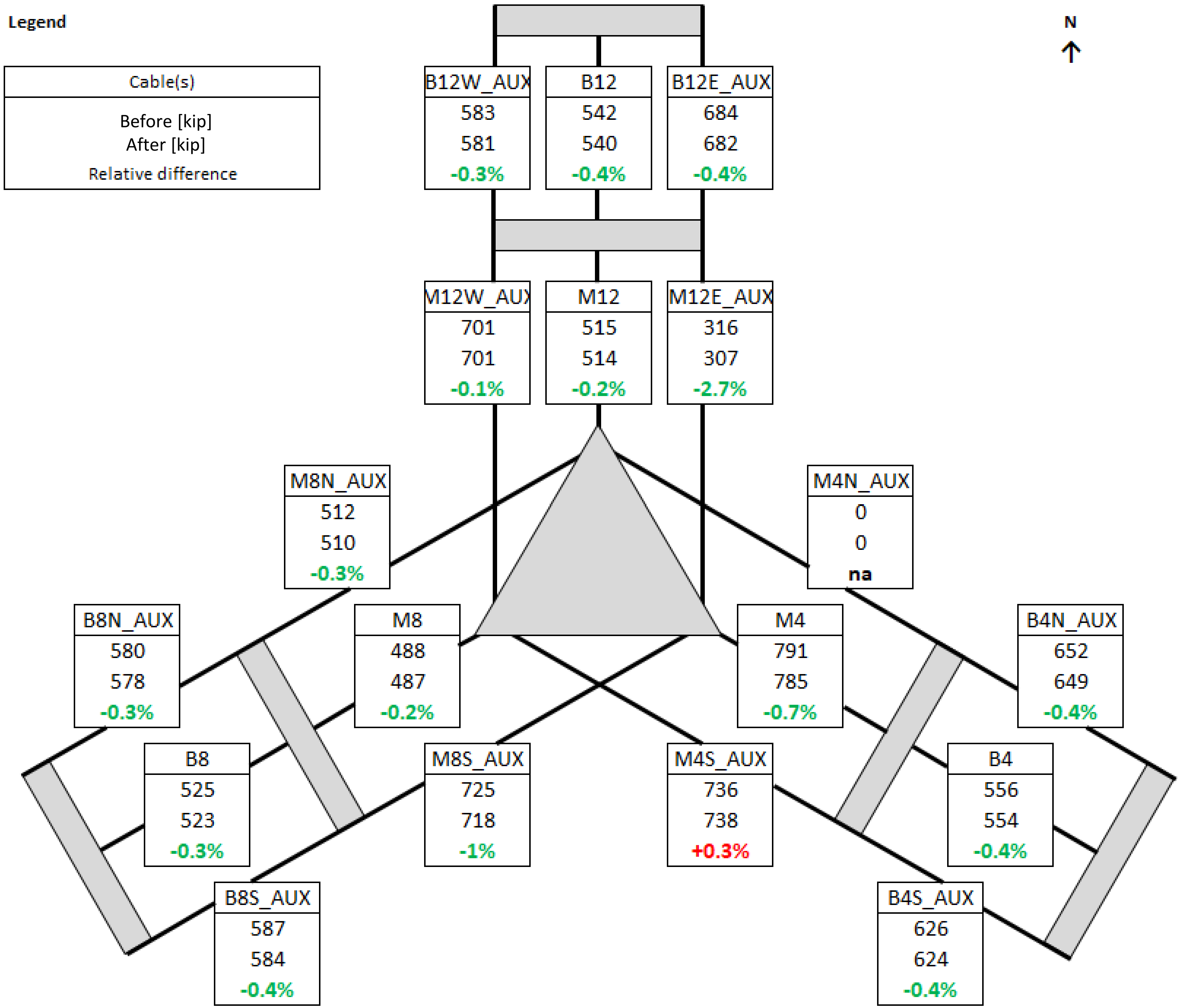
Cable(s)
Before [kip] After [kip] Relative difference



Cable Force Change

If Cutting M4-4

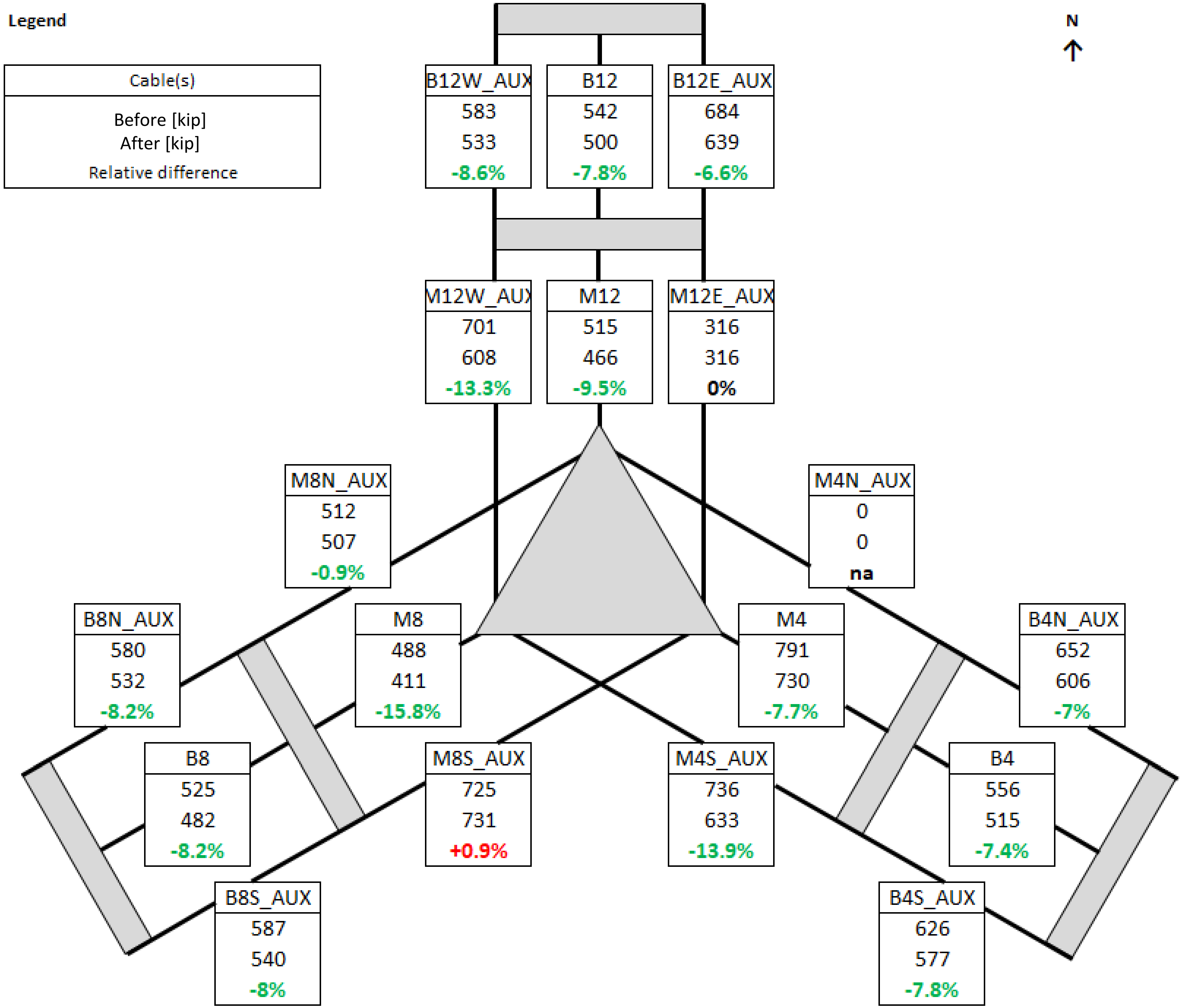
(starting from current condition)



Cable Force Change

If Dropping Gregorian

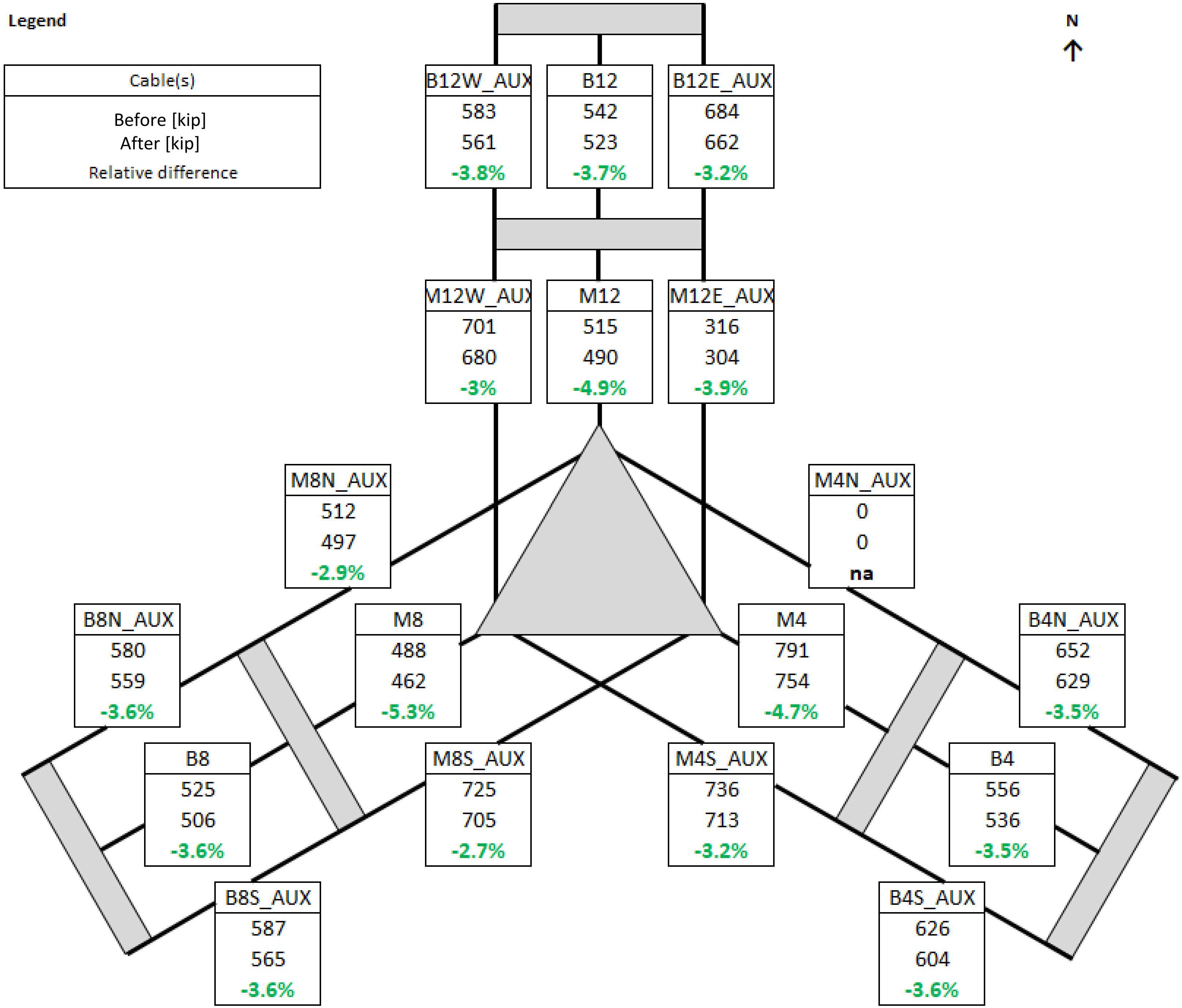
(starting from current condition)



Cable Force Change

If Dropping 100kip Uniformly from Platform

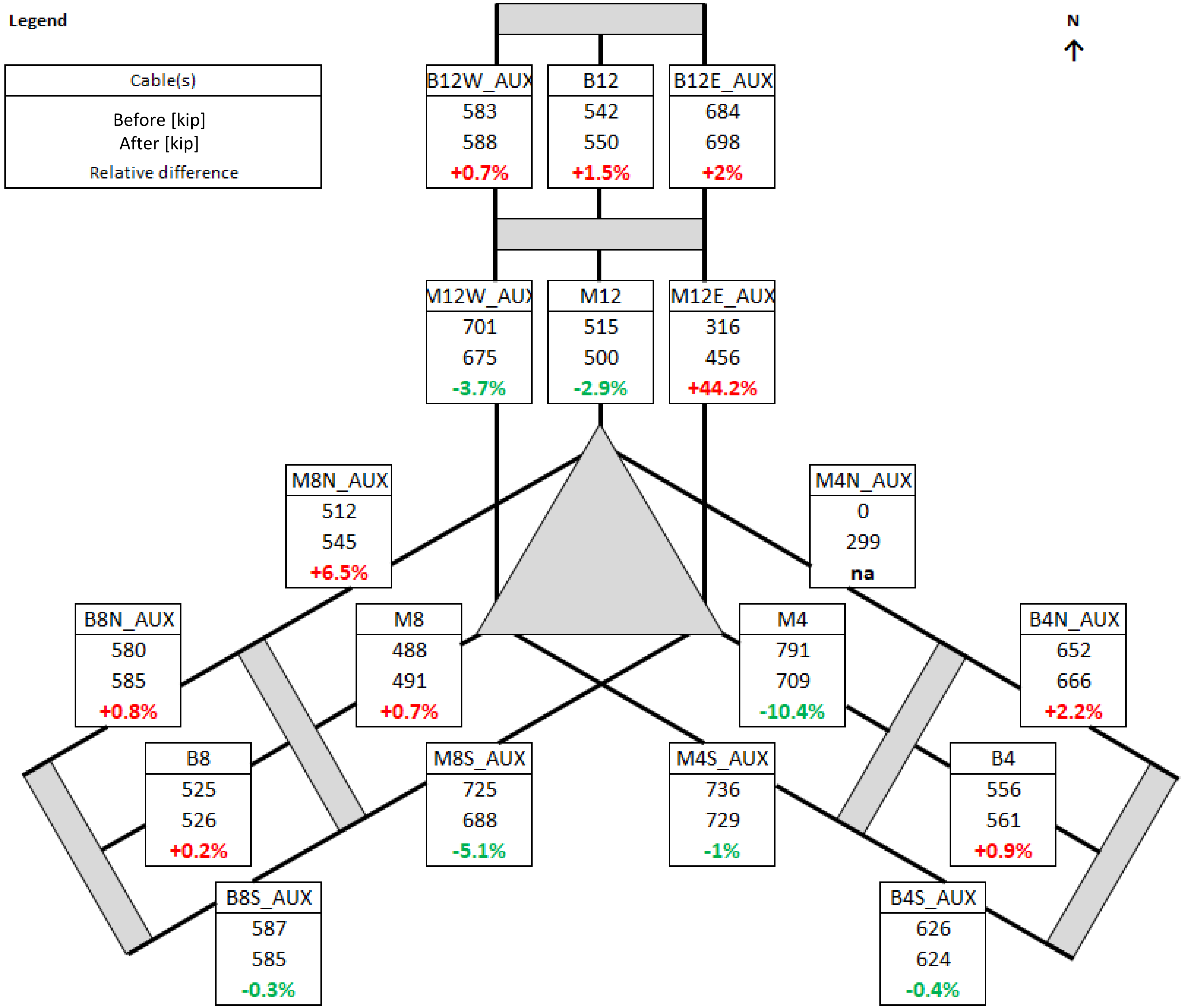
(starting from current condition)



Cable Force Change

If Reconnecting M4N_AUX and Re-tensioning by 300kip

(starting from current condition)



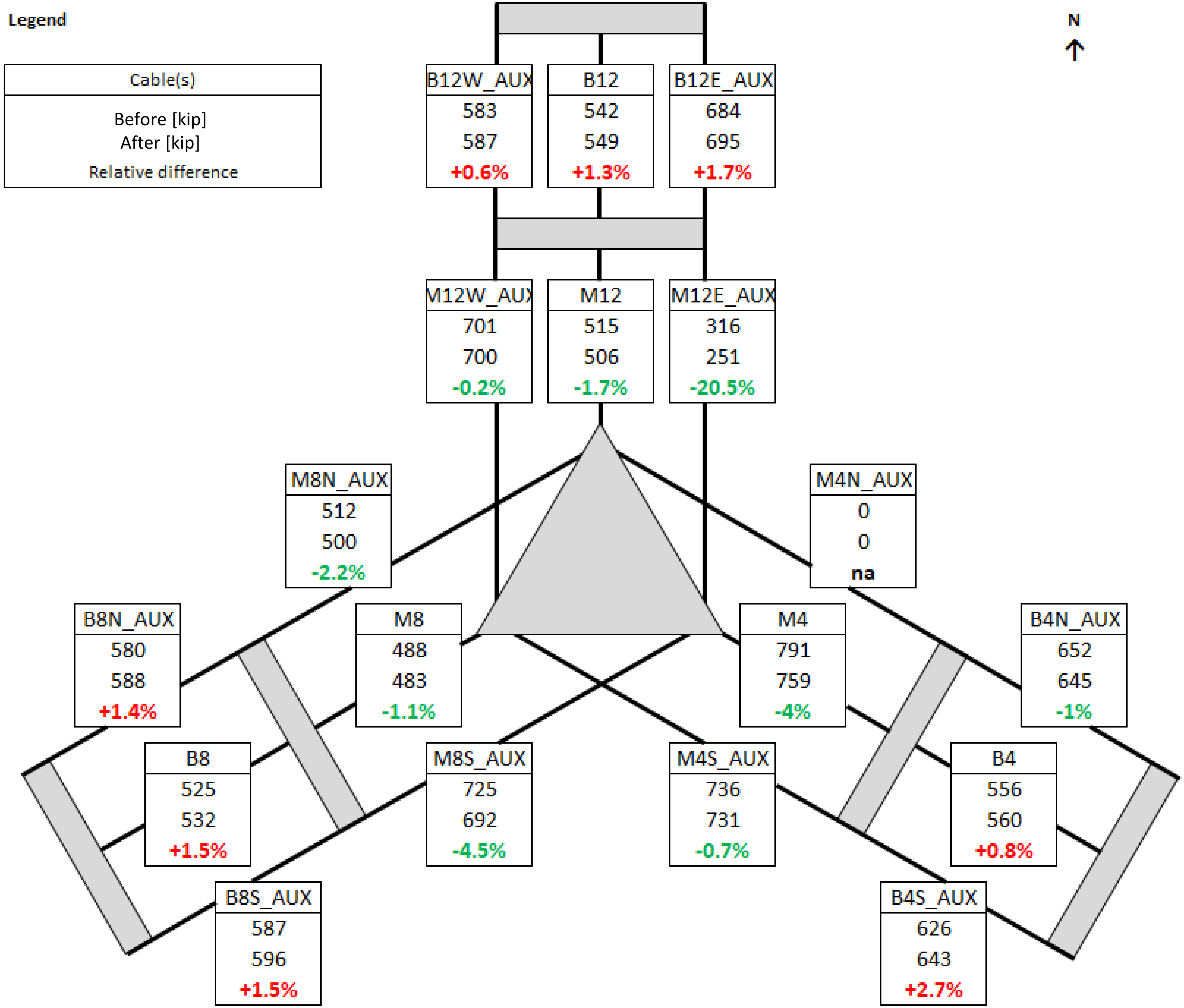
Cable Force Change

If Lifting Platform from Waveguide System

(starting from current condition)

Legend

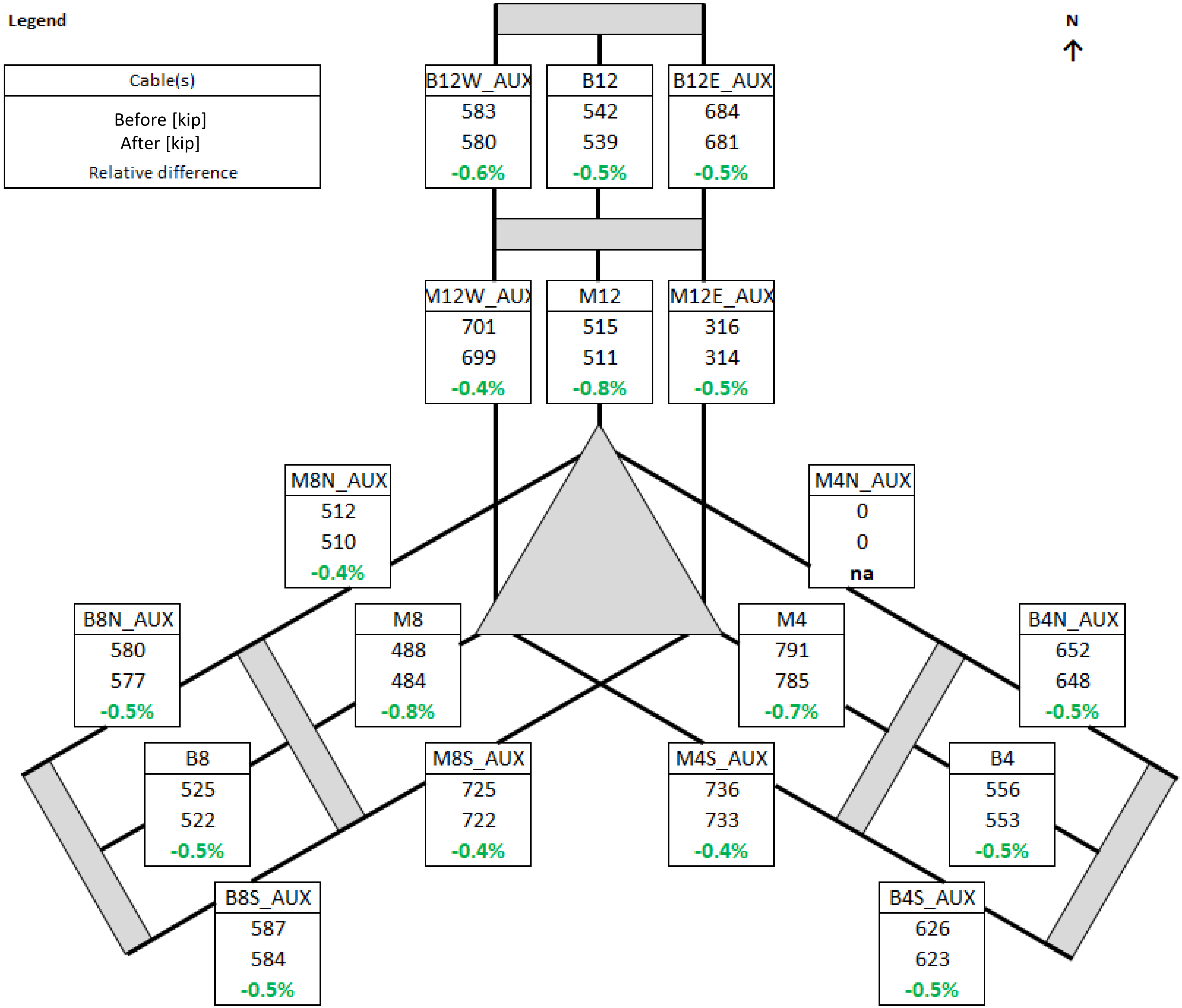
Cable(s)
Before [kip] After [kip]
Relative difference



Cable Force Change

If Dropping Tiedowns

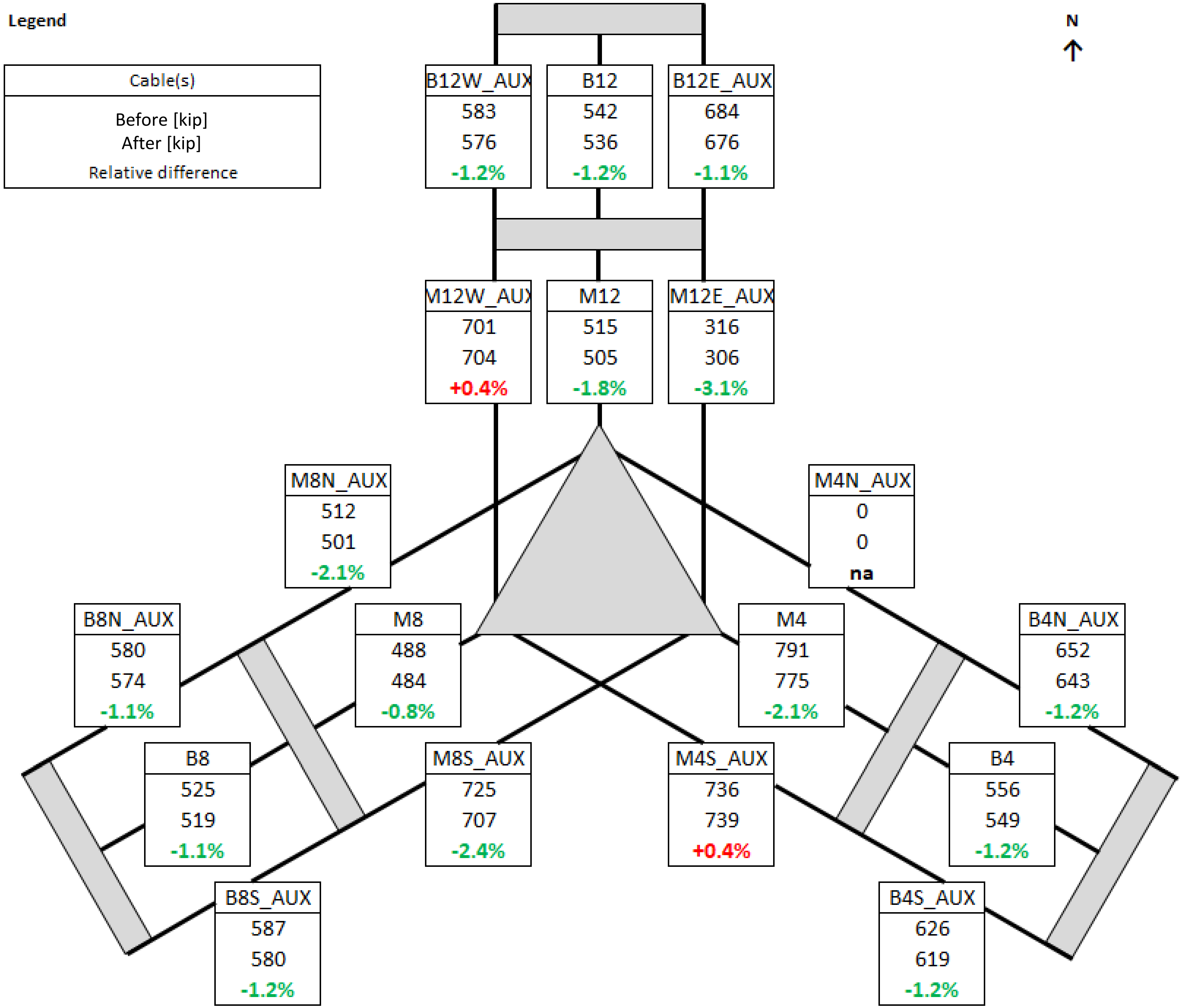
(starting from current condition)



Cable Force Change

If Dropping Line Feed

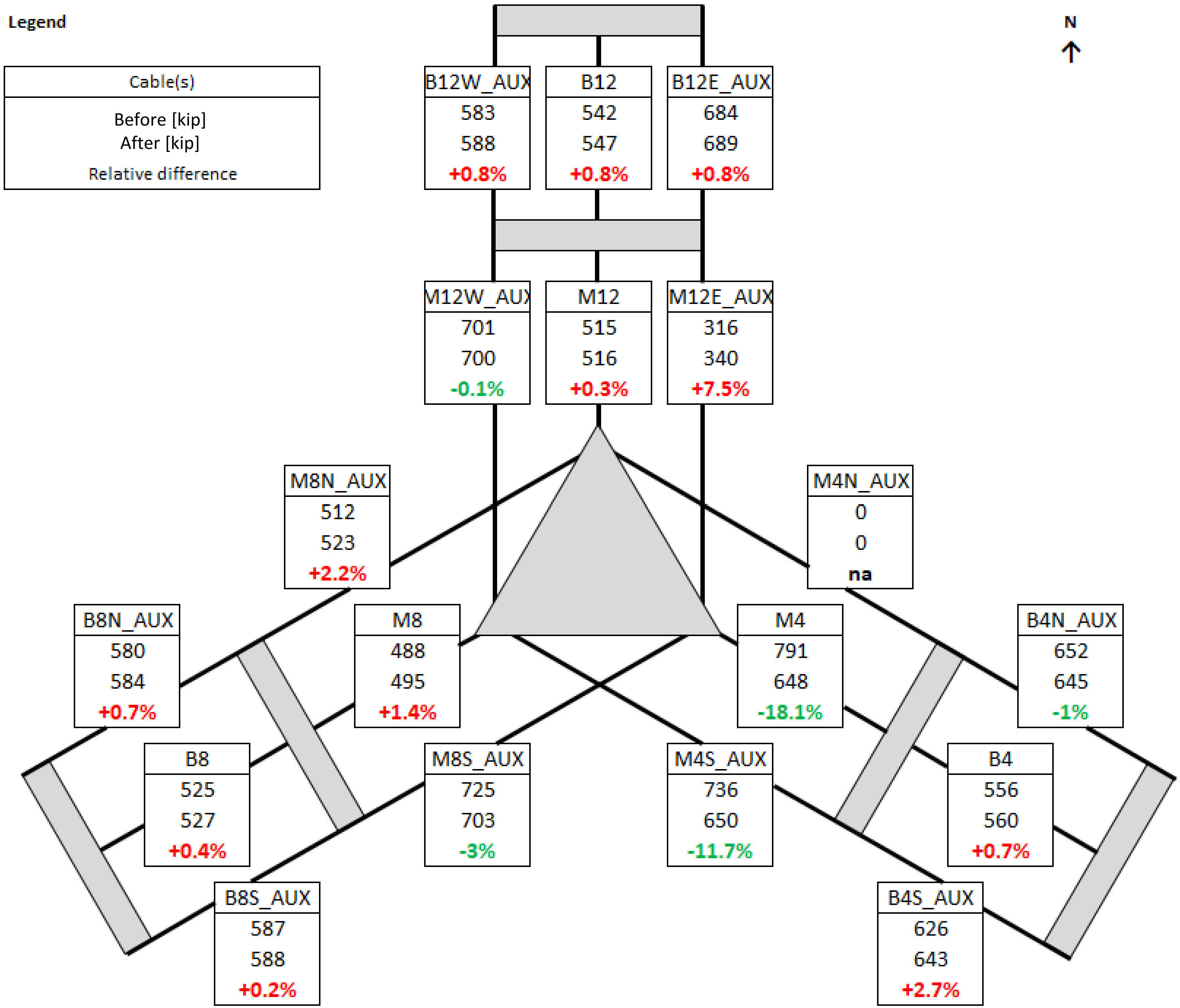
(starting from current condition)



Cable Force Change

If Adding Two 55mm Cables where M4-4 was, Tensioned to 50% Breaking Strength

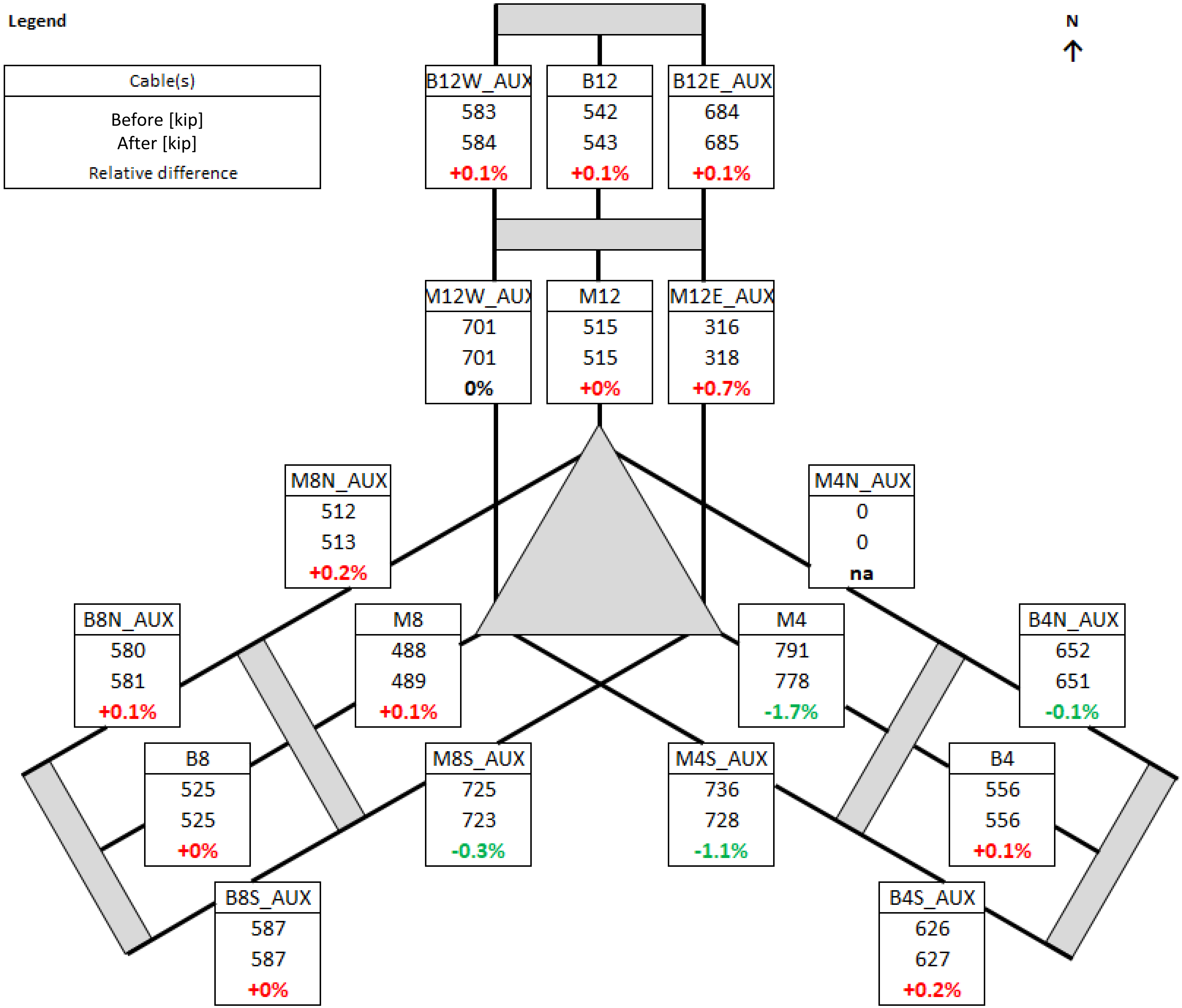
(starting from current condition)



Cable Force Change

If Adding a 1in Wire Rope where M4-4 was, Tensioned to Breaking Strength

(starting from current condition)



Cable Force Change

Cable(s)	Effect of Second Cable Failure	Starting From Current Condition												
		If Dejacking all Backstays by 18"	If Moving Gregorian Out	If Moving Line Feed In	If Dropping Counterweight	If Cutting M4-4	If Dropping Gregorian	If Dropping 100kip Uniformly from Platform	If Reconnecting M4N_AUX and Re-Tensionning to 300kip	If Lifting Platform From Waveguide Cables	If dropping Tiedowns	If dropping Line Feed	If adding 2 x 55mm cables where M4-4 was, tensionned to 50% breaking strength	If adding a 1in wire rope where M4-4 was, tensionned to breaking strength
M4	22.2%	-3.8%	-4.4%	-0.4%	-3.1%	-0.7%	-7.7%	-4.7%	-10.4%	-4.0%	-0.7%	-2.1%	-18.1%	-1.7%
M4N_AUX	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
M4S_AUX	20.5%	-8.8%	10.9%	1.1%	2.4%	0.3%	-13.9%	-3.2%	-1.0%	-0.7%	-0.4%	0.4%	-11.7%	-1.1%
M8	-1.8%	-2.2%	7.3%	0.7%	0.4%	-0.2%	-15.8%	-5.3%	0.7%	-1.1%	-0.8%	-0.8%	1.4%	0.1%
M8N_AUX	-3.7%	-9.5%	-9.5%	-0.9%	-4.0%	-0.3%	-0.9%	-2.9%	6.5%	-2.2%	-0.4%	-2.1%	2.2%	0.2%
M8S_AUX	-1.9%	-9.7%	-12.4%	-1.2%	-4.8%	-1.0%	0.9%	-2.7%	-5.1%	-4.5%	-0.4%	-2.4%	-3.0%	-0.3%
M12	-0.5%	-2.1%	-2.0%	-0.2%	-2.4%	-0.2%	-9.5%	-4.9%	-2.9%	-1.7%	-0.8%	-1.8%	0.3%	0.0%
M12E_AUX	-20.4%	-12.6%	-15.1%	-1.4%	-6.0%	-2.7%	0.0%	-3.9%	44.2%	-20.5%	-0.5%	-3.1%	7.5%	0.7%
M12W_AUX	0.3%	-9.9%	10.5%	1.1%	2.3%	-0.1%	-13.3%	-3.0%	-3.7%	-0.2%	-0.4%	0.4%	-0.1%	0.0%
B4	-2.5%	-11.0%	-0.7%	0.0%	-1.5%	-0.4%	-7.4%	-3.5%	0.9%	0.8%	-0.5%	-1.2%	0.7%	0.1%
B4N_AUX	-0.5%	-11.7%	-1.1%	-0.1%	-1.6%	-0.4%	-7.0%	-3.5%	2.2%	-1.0%	-0.5%	-1.2%	-1.0%	-0.1%
B4S_AUX	-4.5%	-12.7%	-0.2%	0.0%	-1.3%	-0.4%	-7.8%	-3.6%	-0.4%	2.7%	-0.5%	-1.2%	2.7%	0.2%
B8	-1.8%	-9.3%	0.2%	0.0%	-1.2%	-0.3%	-8.2%	-3.6%	0.2%	1.5%	-0.5%	-1.1%	0.4%	0.0%
B8N_AUX	-1.9%	-11.6%	0.4%	0.1%	-1.2%	-0.3%	-8.2%	-3.6%	0.8%	1.4%	-0.5%	-1.1%	0.7%	0.1%
B8S_AUX	-1.7%	-12.1%	-0.1%	0.0%	-1.3%	-0.4%	-8.0%	-3.6%	-0.3%	1.5%	-0.5%	-1.2%	0.2%	0.0%
B12	-2.4%	-11.1%	-0.5%	0.0%	-1.4%	-0.4%	-7.8%	-3.7%	1.5%	1.3%	-0.5%	-1.2%	0.8%	0.1%
B12E_AUX	-2.4%	-11.3%	-0.9%	-0.1%	-1.4%	-0.4%	-6.6%	-3.2%	2.0%	1.7%	-0.5%	-1.1%	0.8%	0.1%
B12W_AUX	-2.1%	-13.2%	0.1%	0.0%	-1.3%	-0.3%	-8.6%	-3.8%	0.7%	0.6%	-0.6%	-1.2%	0.8%	0.1%

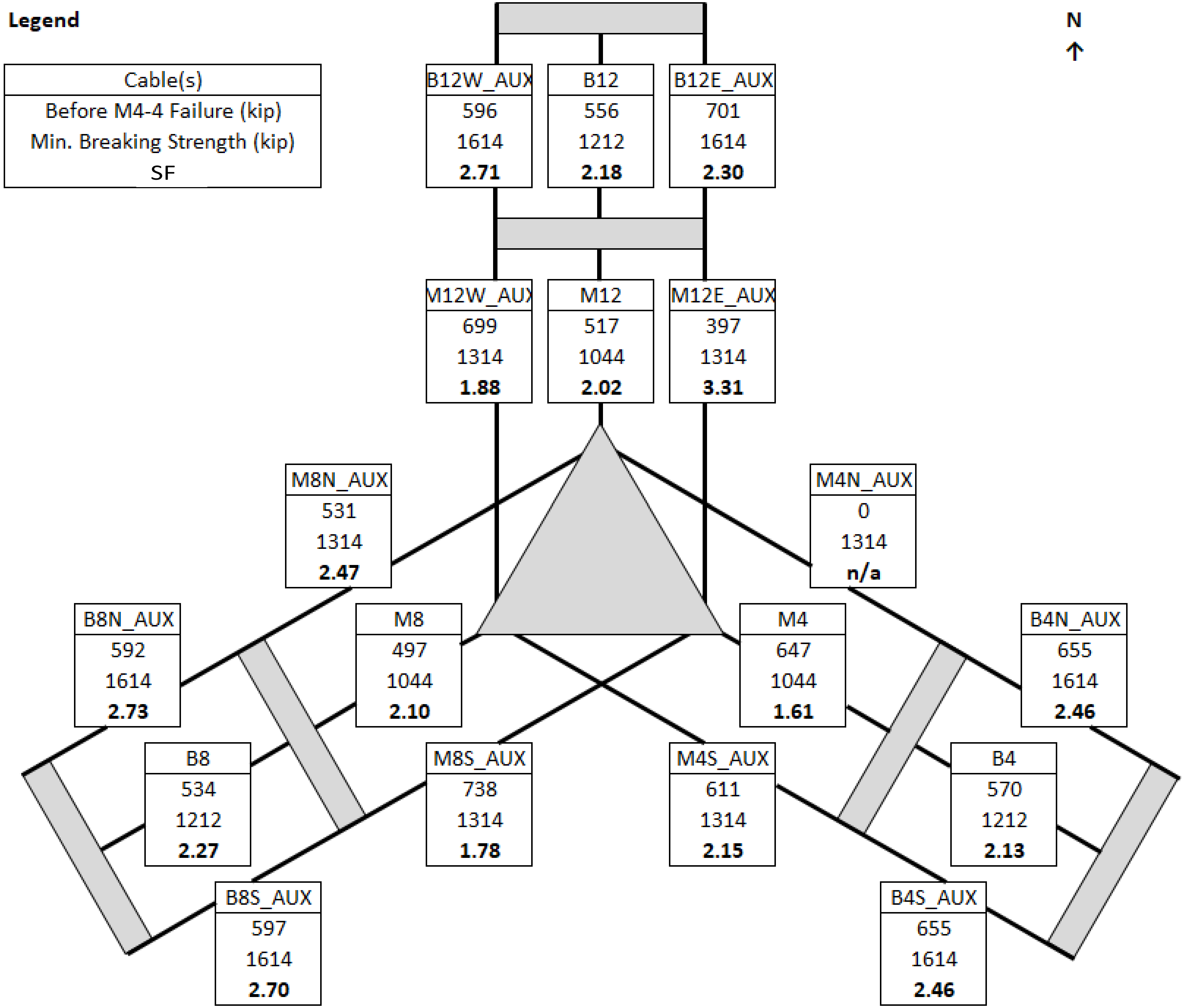
Cable Safety Factors

Before Second Cable Failure

Legend

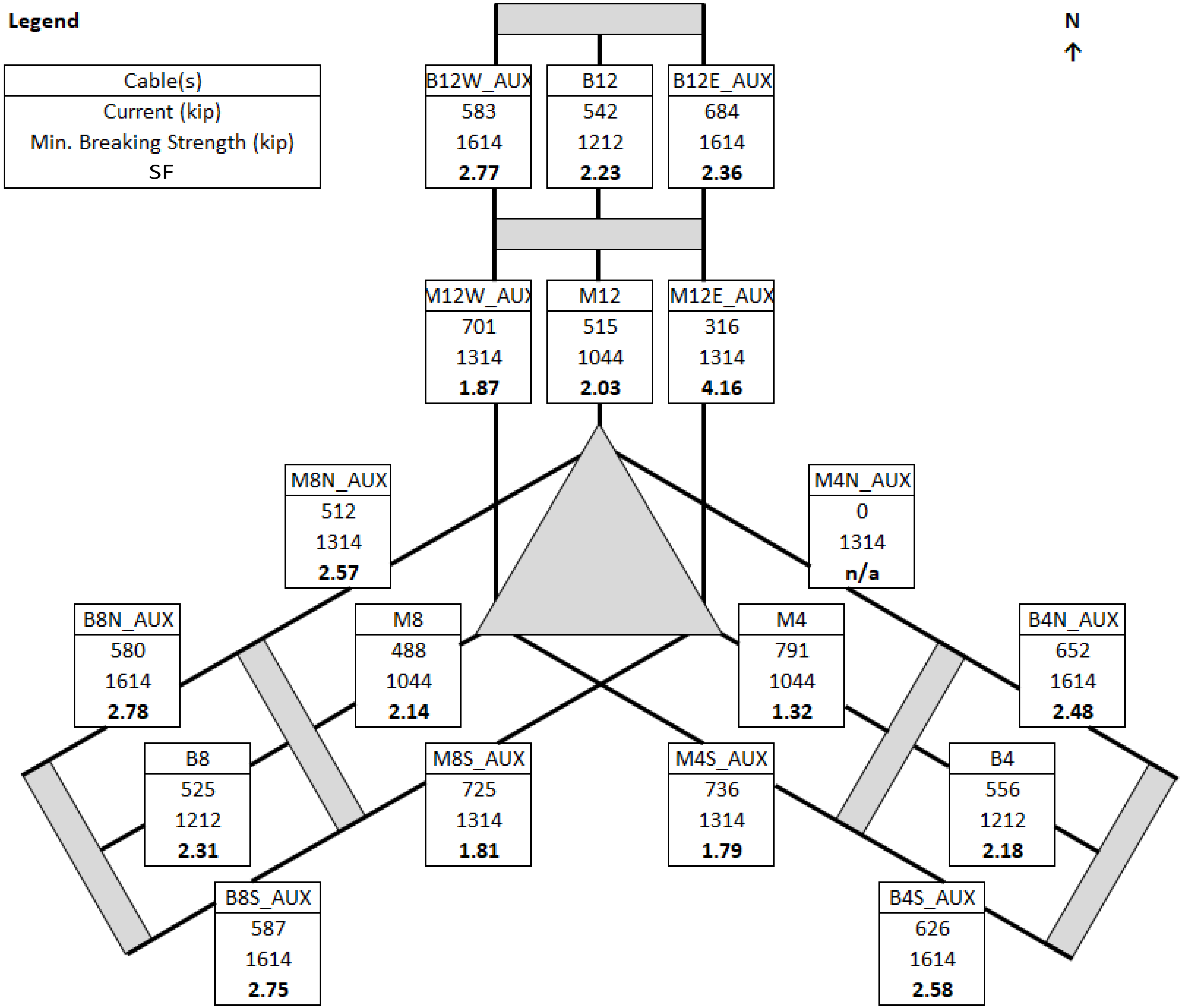
Cable(s)
Before M4-4 Failure (kip)
Min. Breaking Strength (kip)
SF

N ↑



Cable Safety Factors

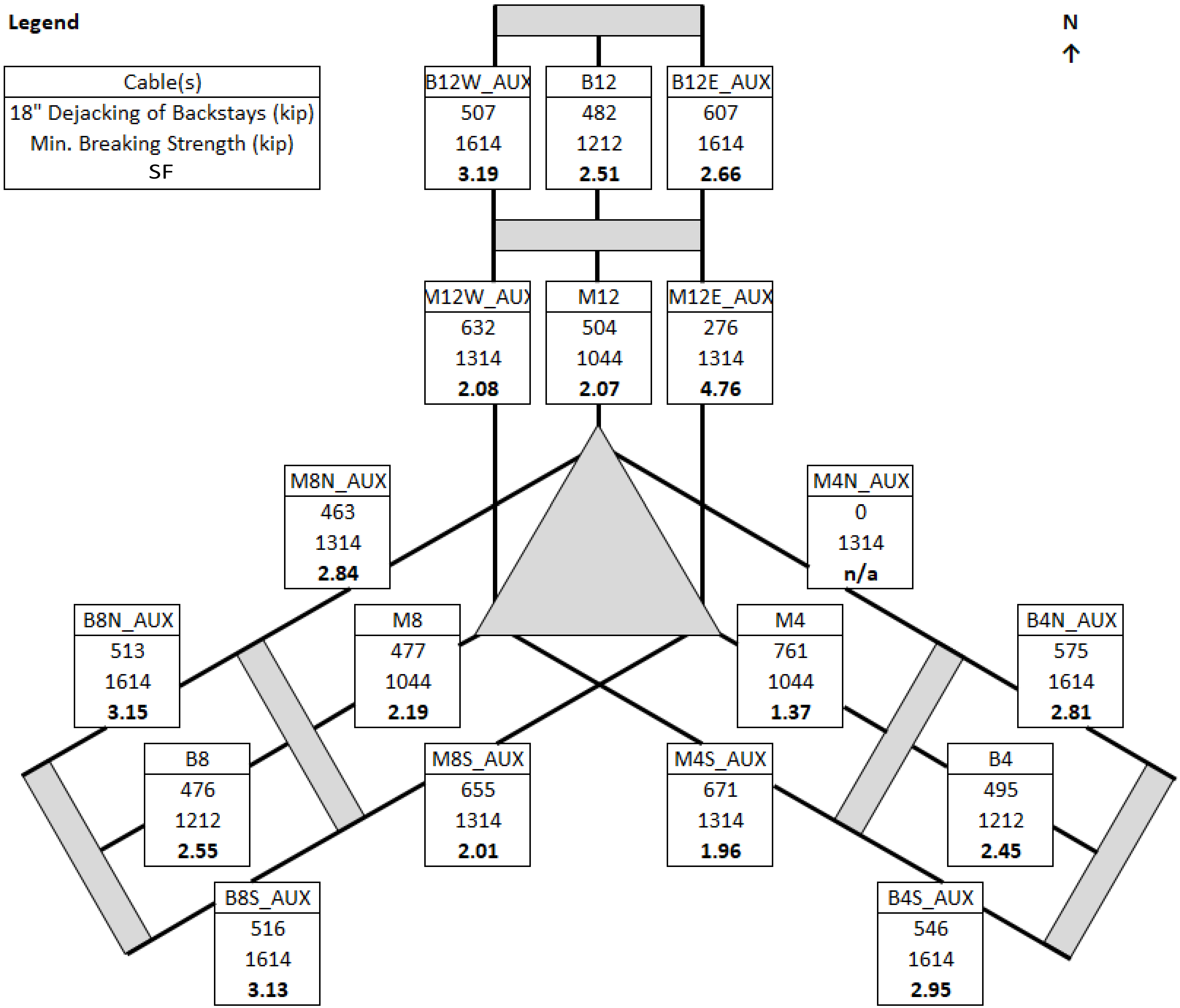
Current Condition



Cable Safety Factors

If De-Jacking all Backstays by 18"

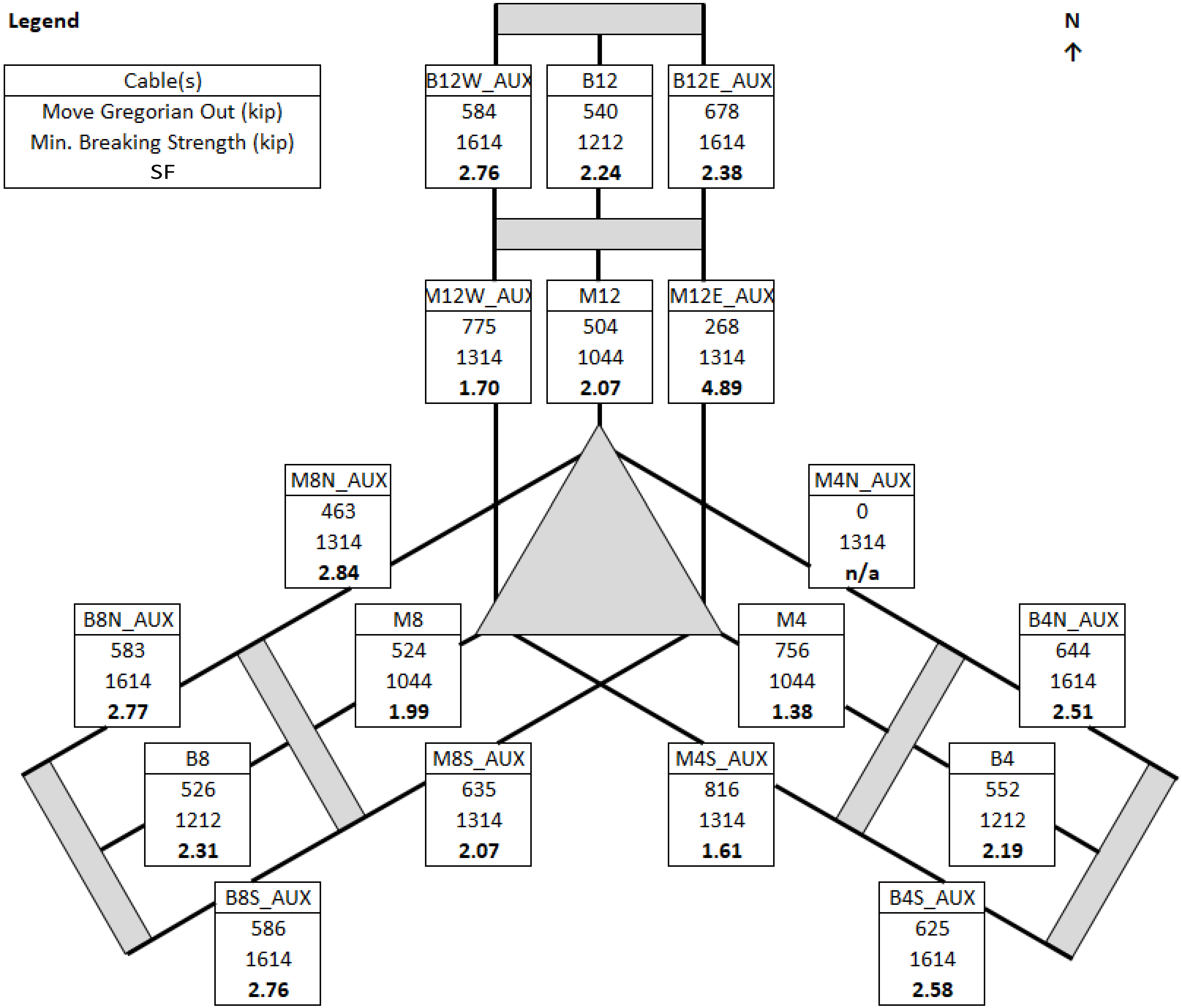
(starting from current condition)



Cable Safety Factors

If Moving Gregorian Out

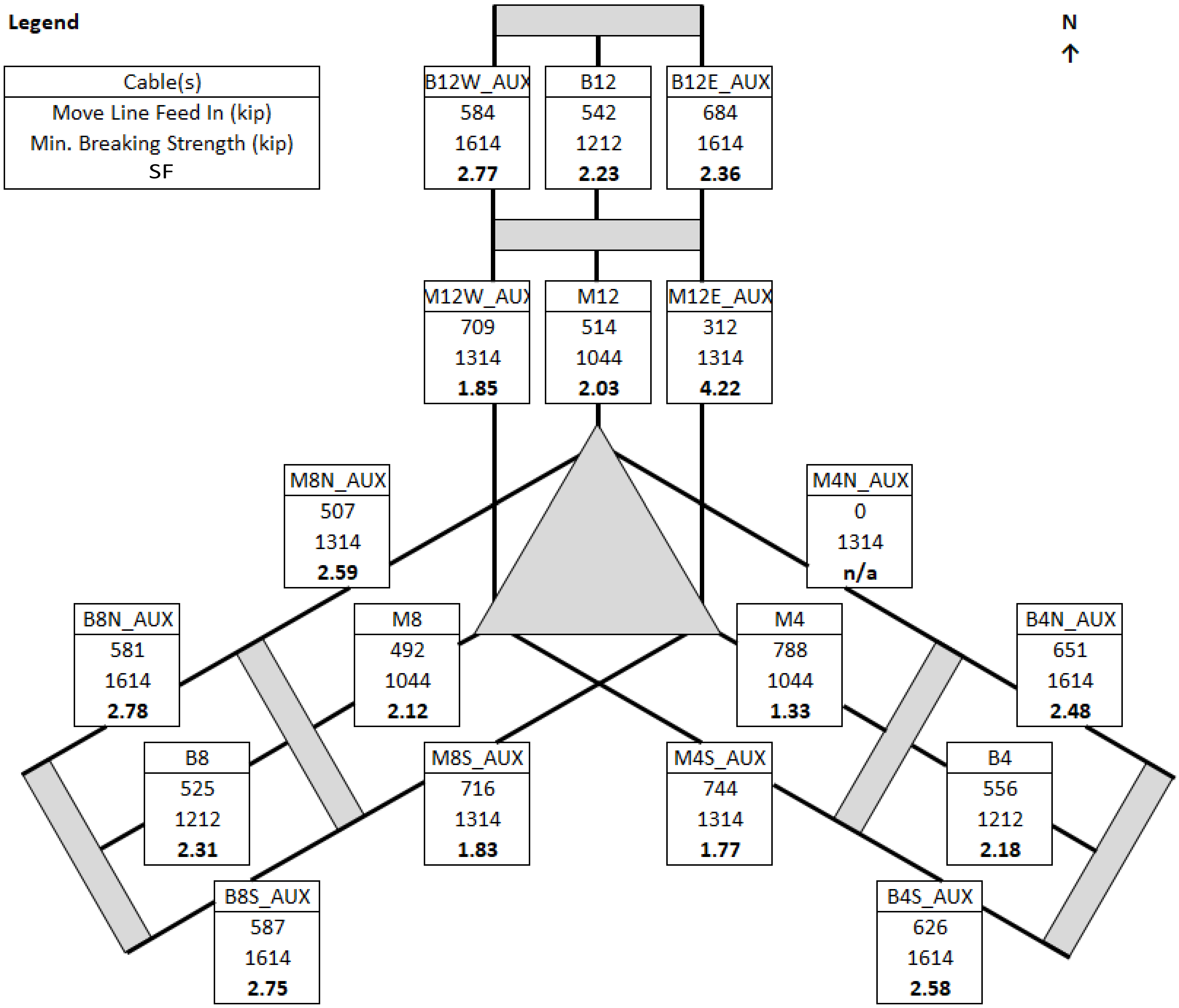
(starting from current condition)



Cable Safety Factors

If Moving Line Feed In

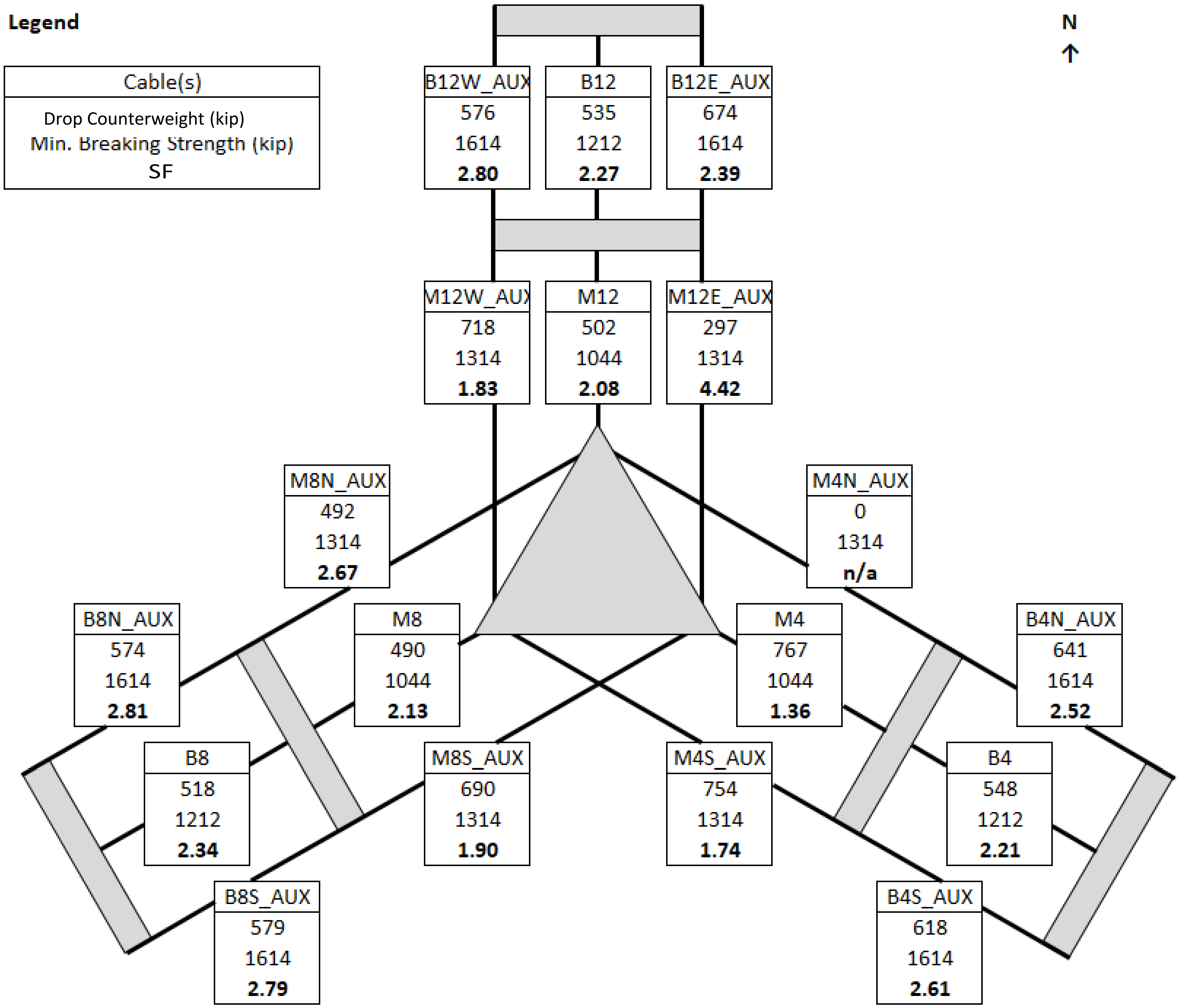
(starting from current condition)



Cable Safety Factors

If Dropping 38kip Counterweight

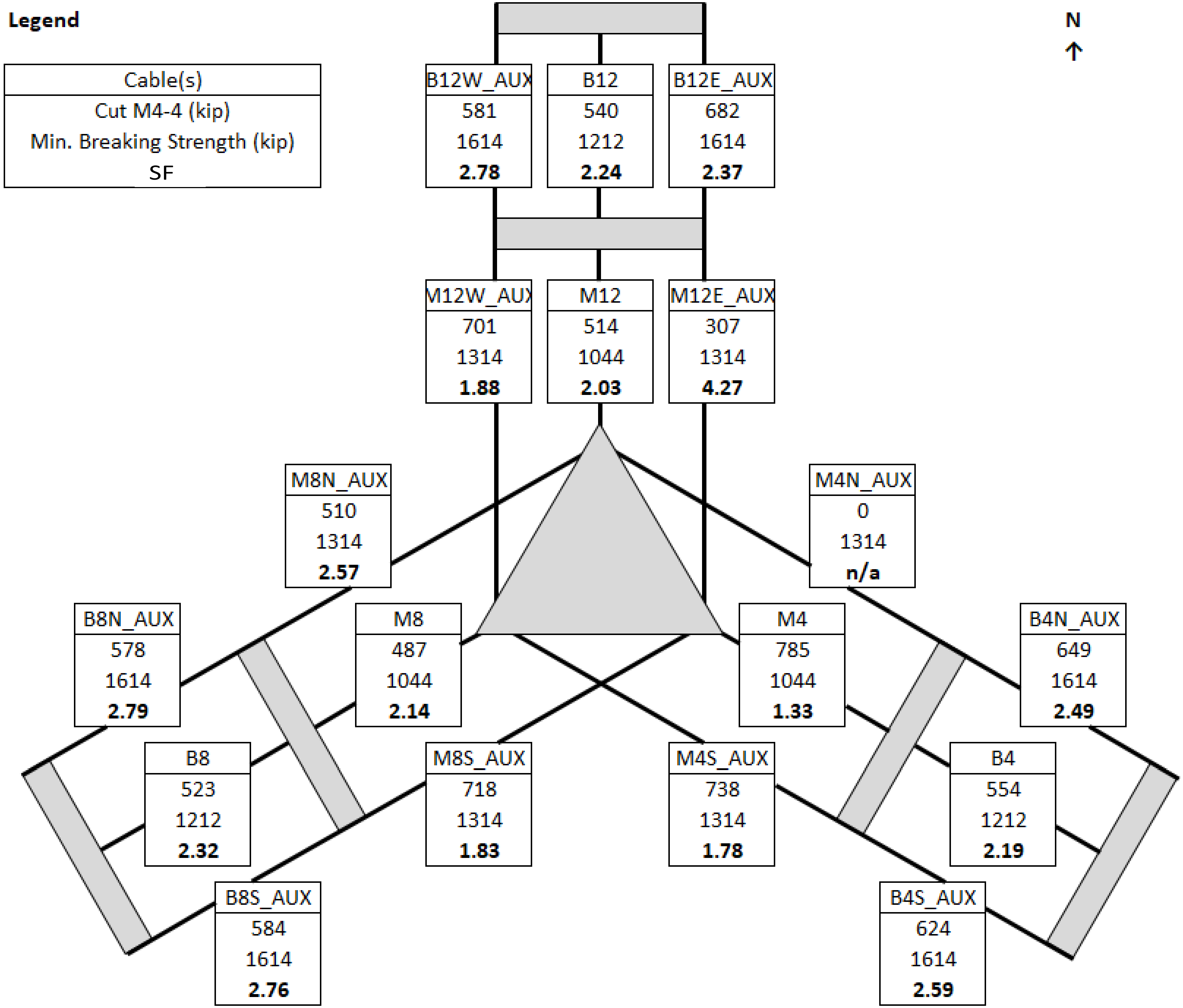
(starting from current condition)



Cable Safety Factors

If Cutting M4-4

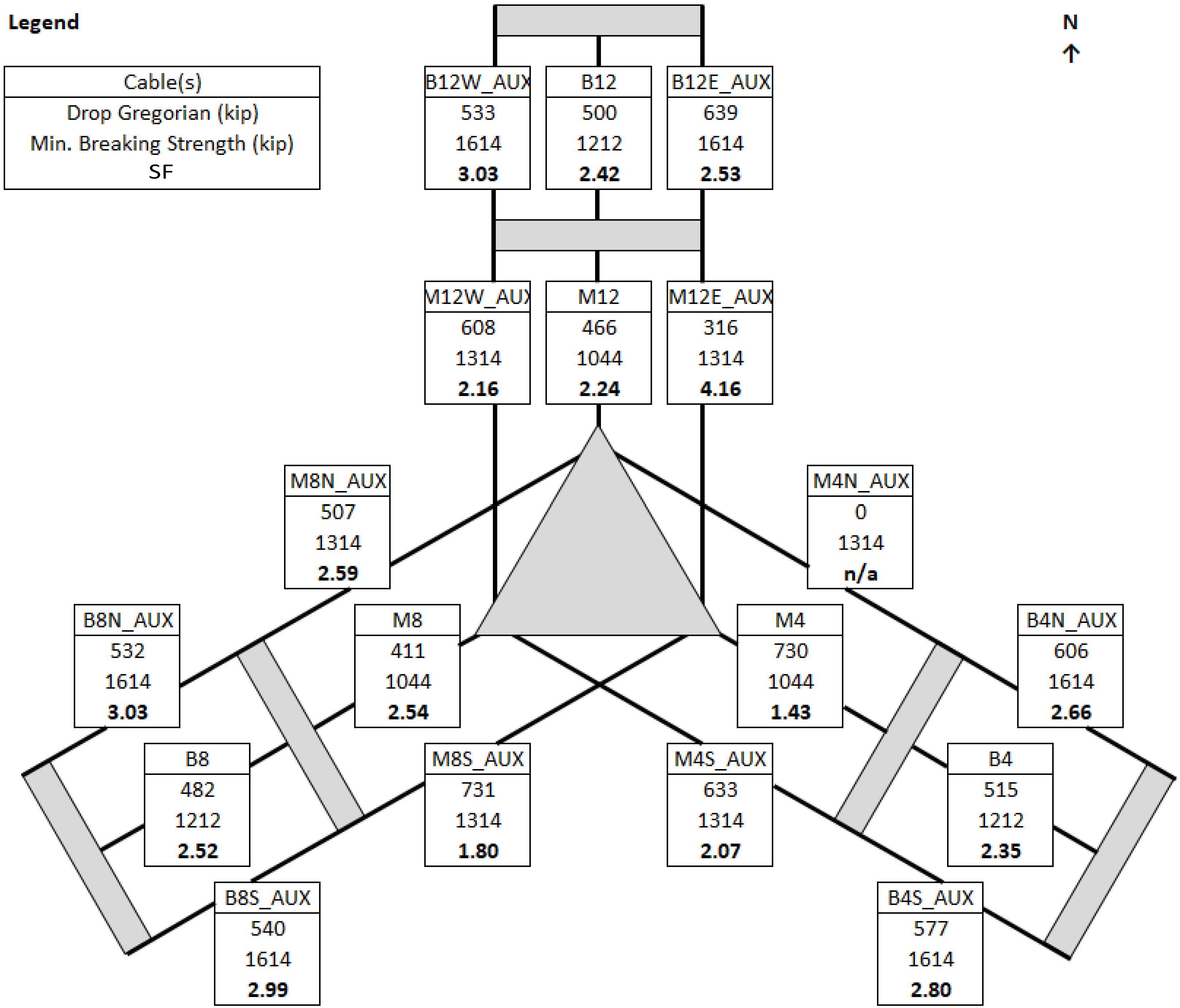
(starting from current condition)



Cable Safety Factors

If Dropping Gregorian

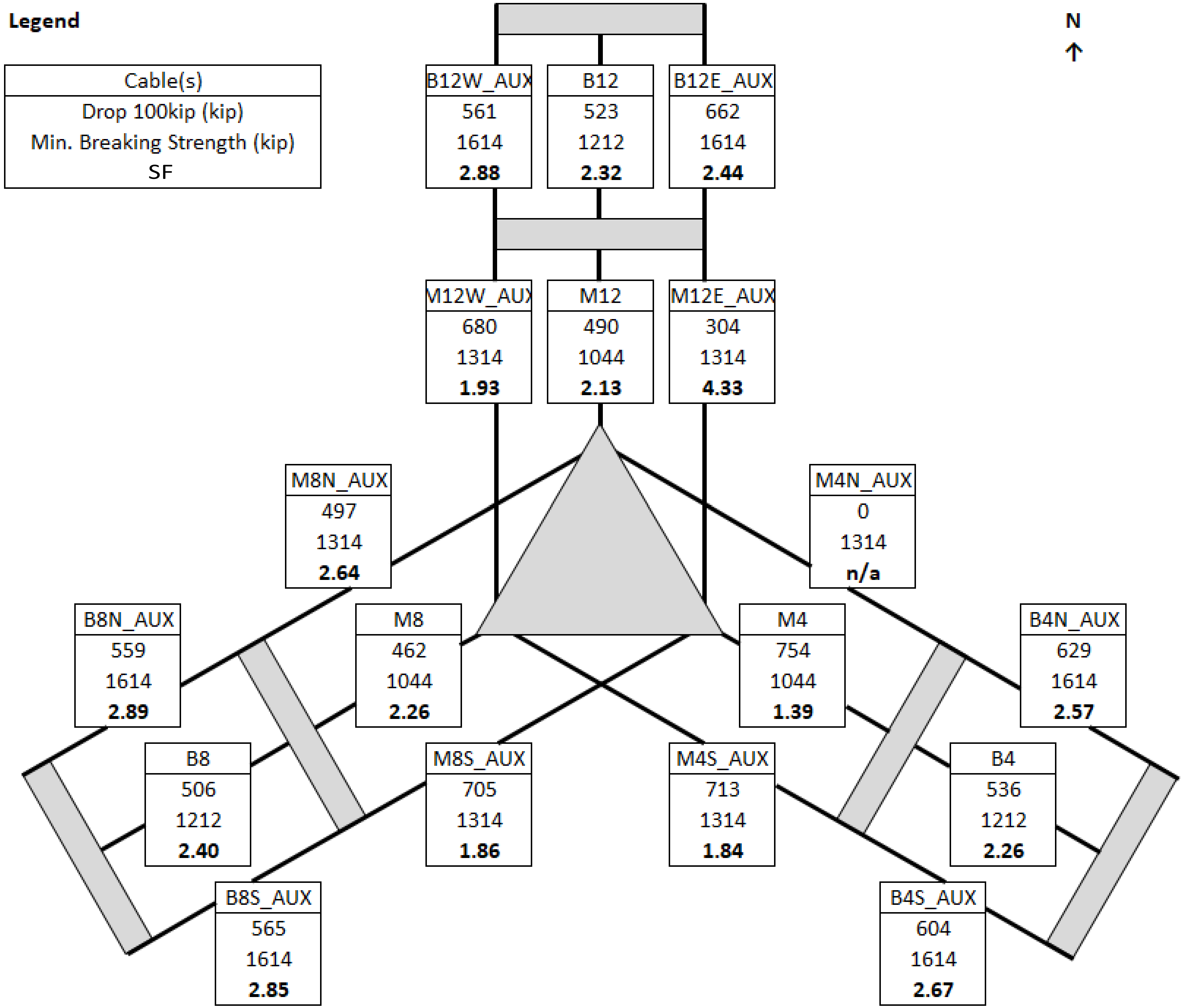
(starting from current condition)



Cable Safety Factors

If Dropping 100kip Uniformly from Platform

(starting from current condition)



Cable Safety Factors

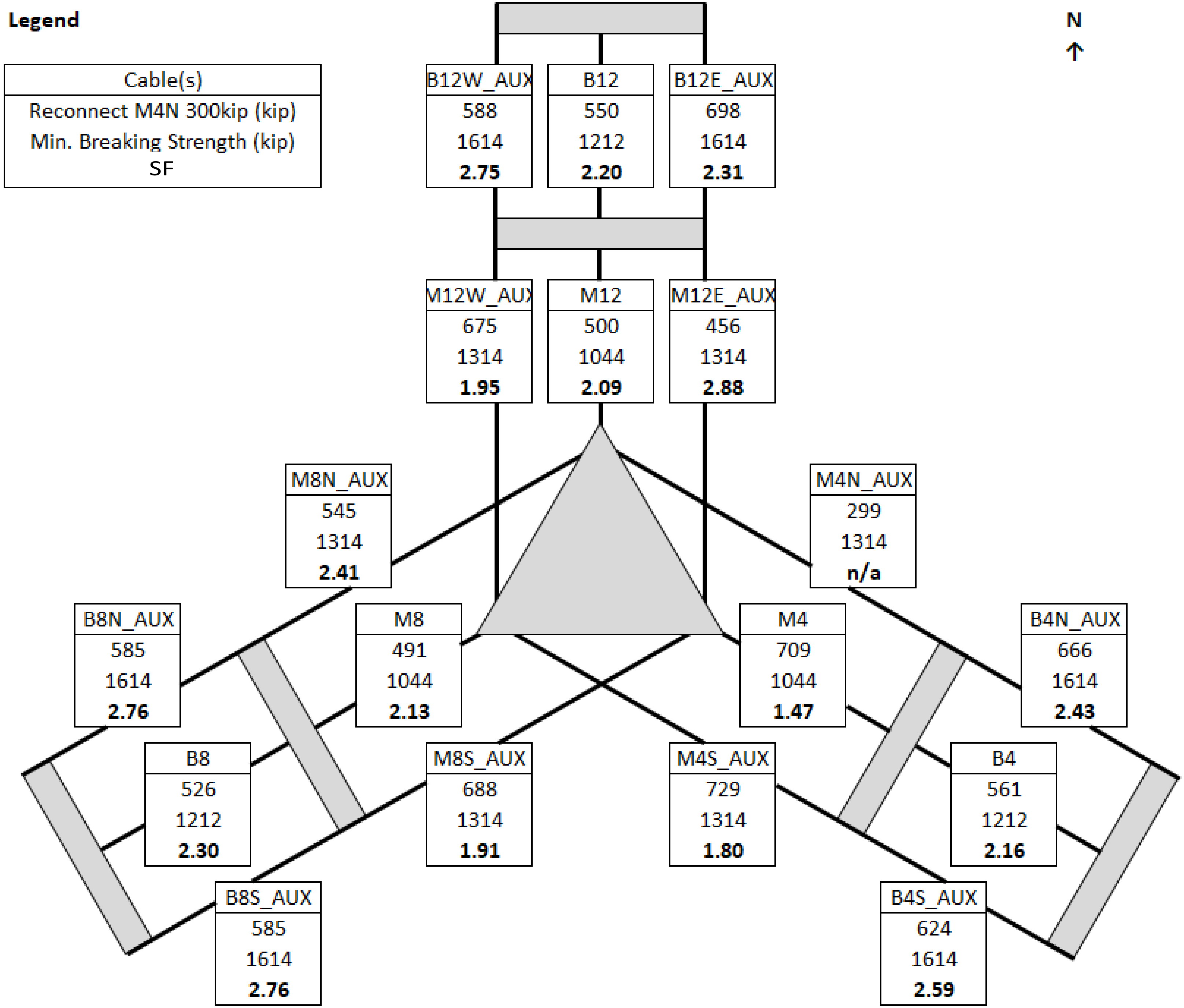
If Reconnecting M4N_AUX and Re-tensioning by 300kip

(starting from current condition)

Legend

Cable(s)
Reconnect M4N 300kip (kip)
Min. Breaking Strength (kip)
SF

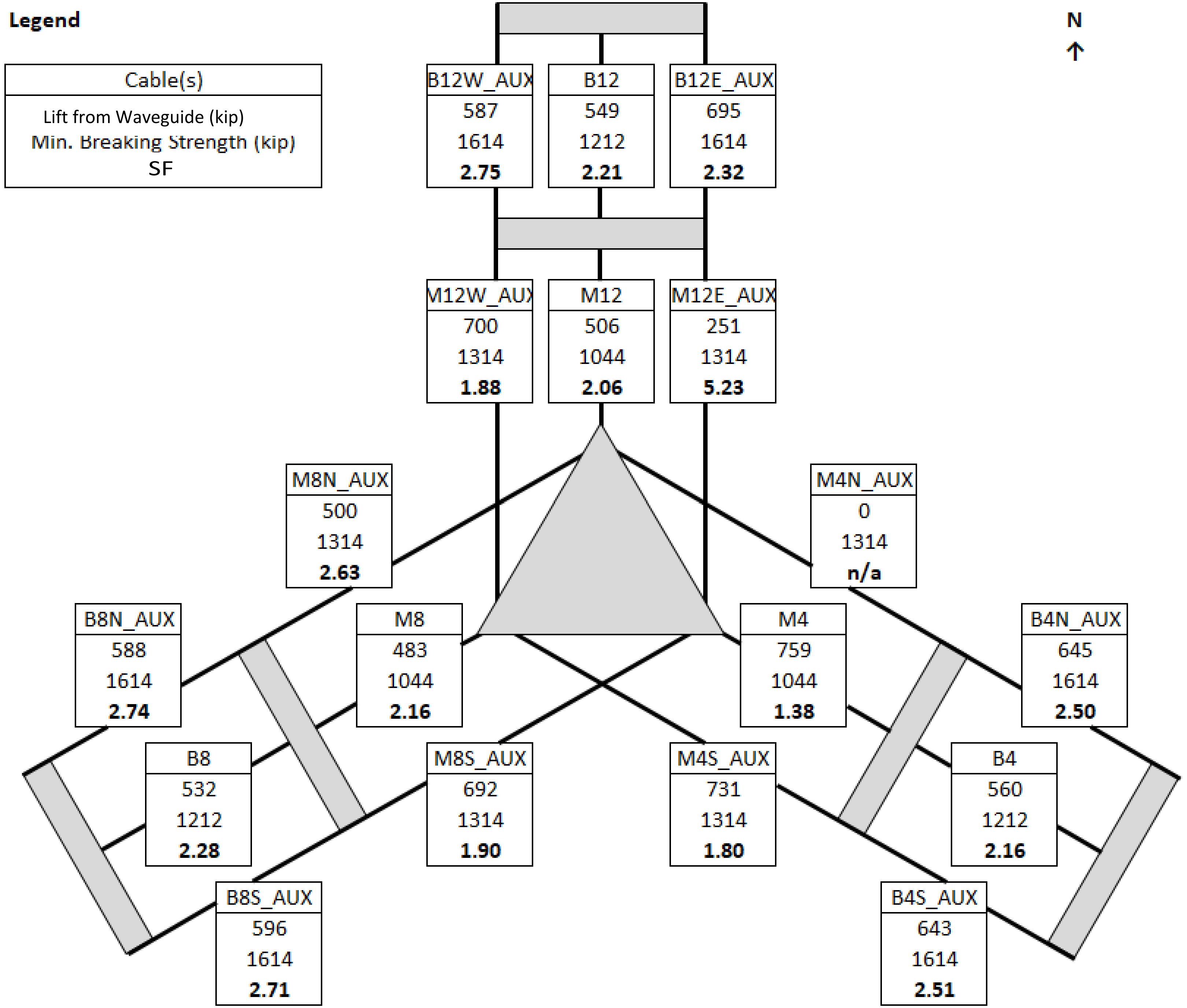
N ↑



Cable Safety Factors

If Lifting Platform from Waveguide System

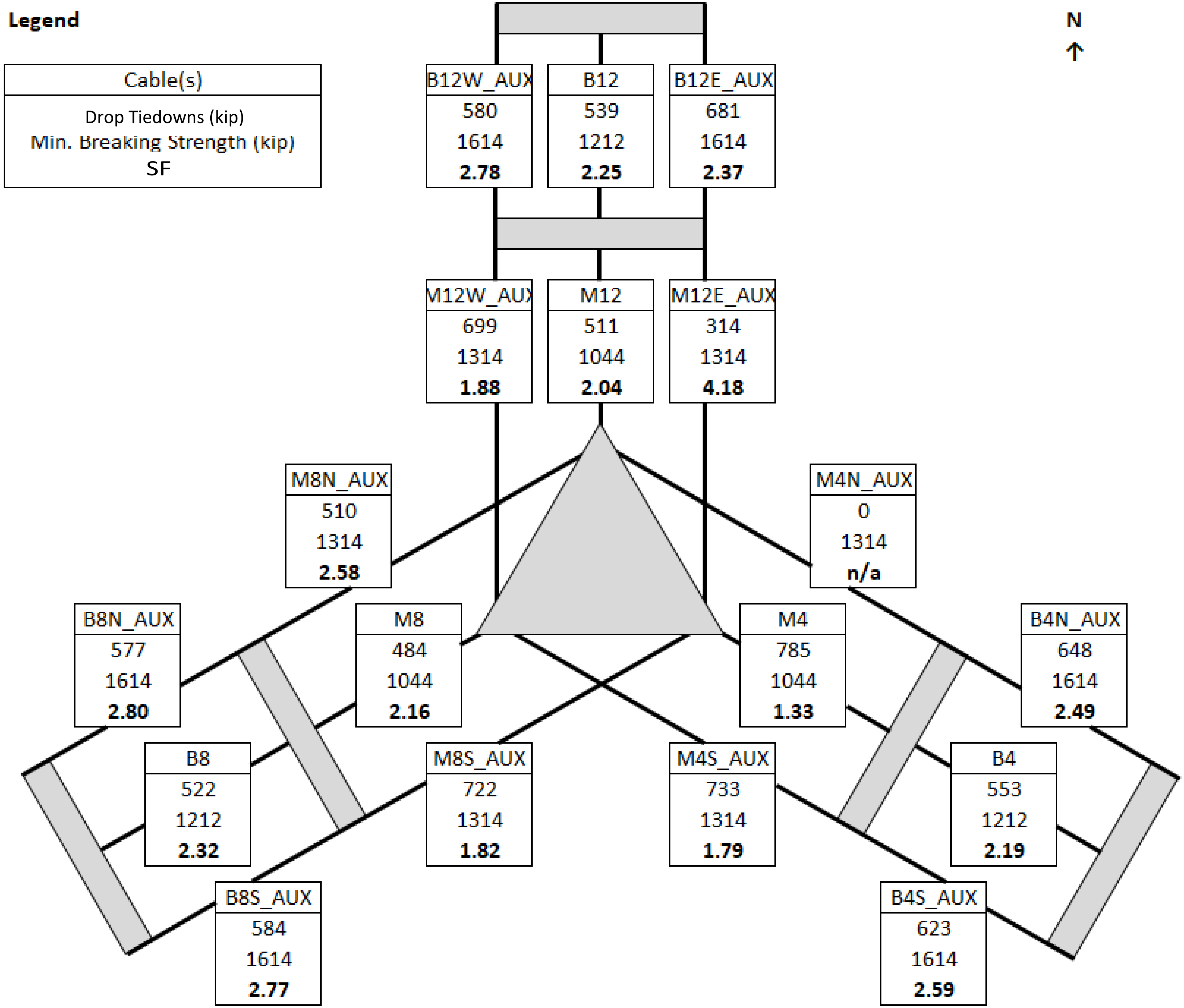
(starting from current condition)



Cable Safety Factors

If Dropping Tiedowns

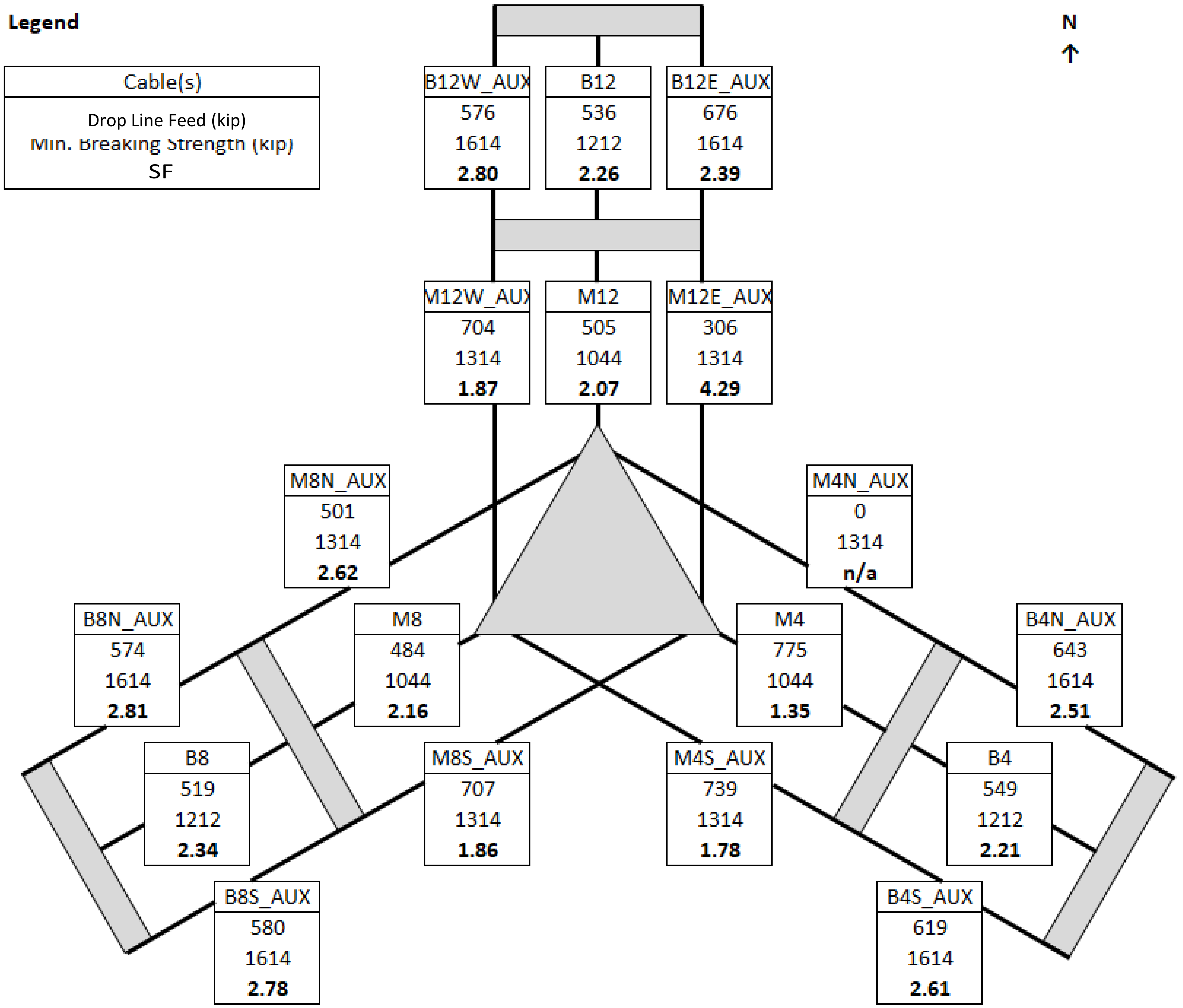
(starting from current condition)



Cable Safety Factors

If Dropping Line Feed

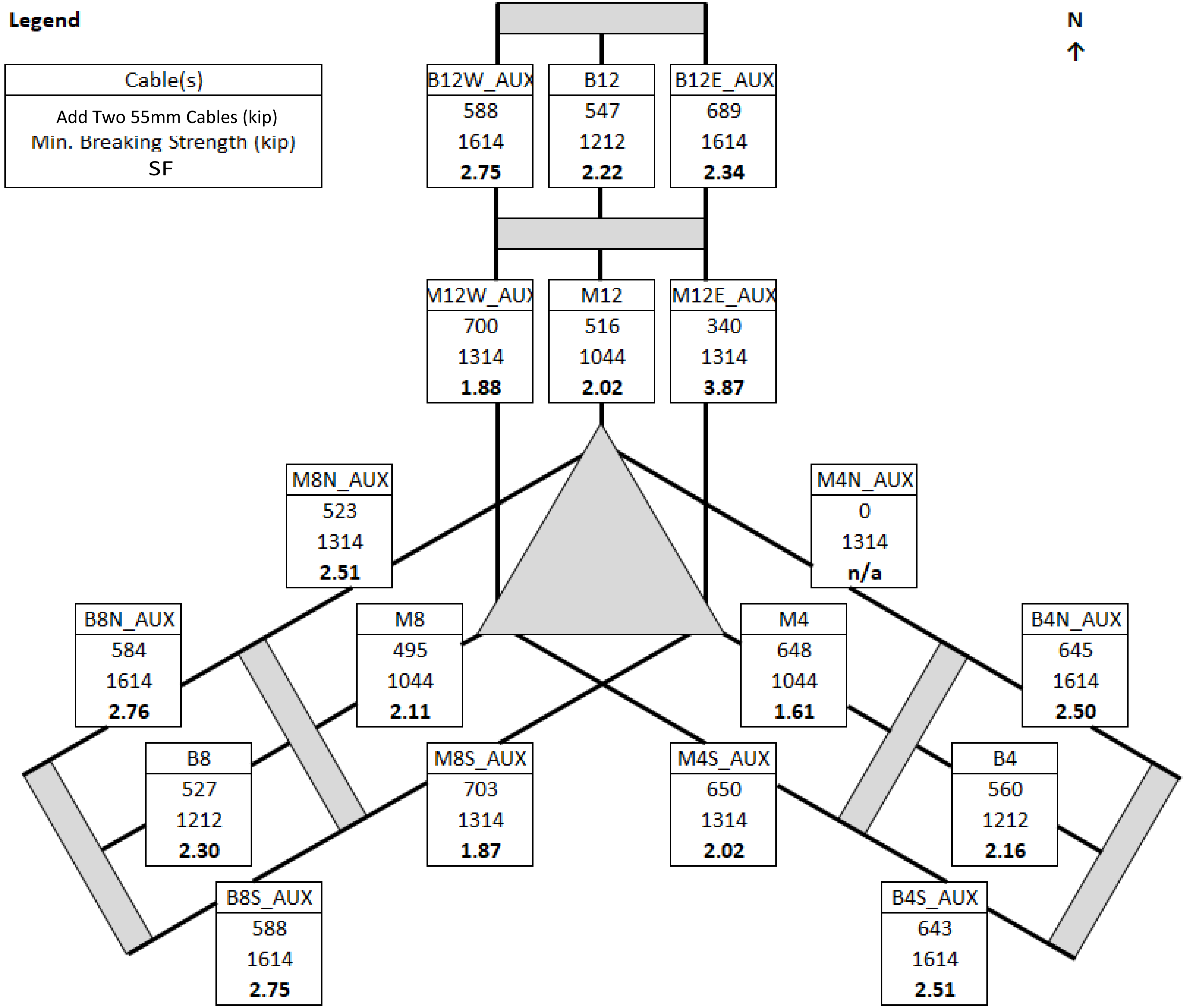
(starting from current condition)



Cable Safety Factors

If Adding Two 55mm Cables where M4-4 was, Tensioned to 50% Breaking Strength

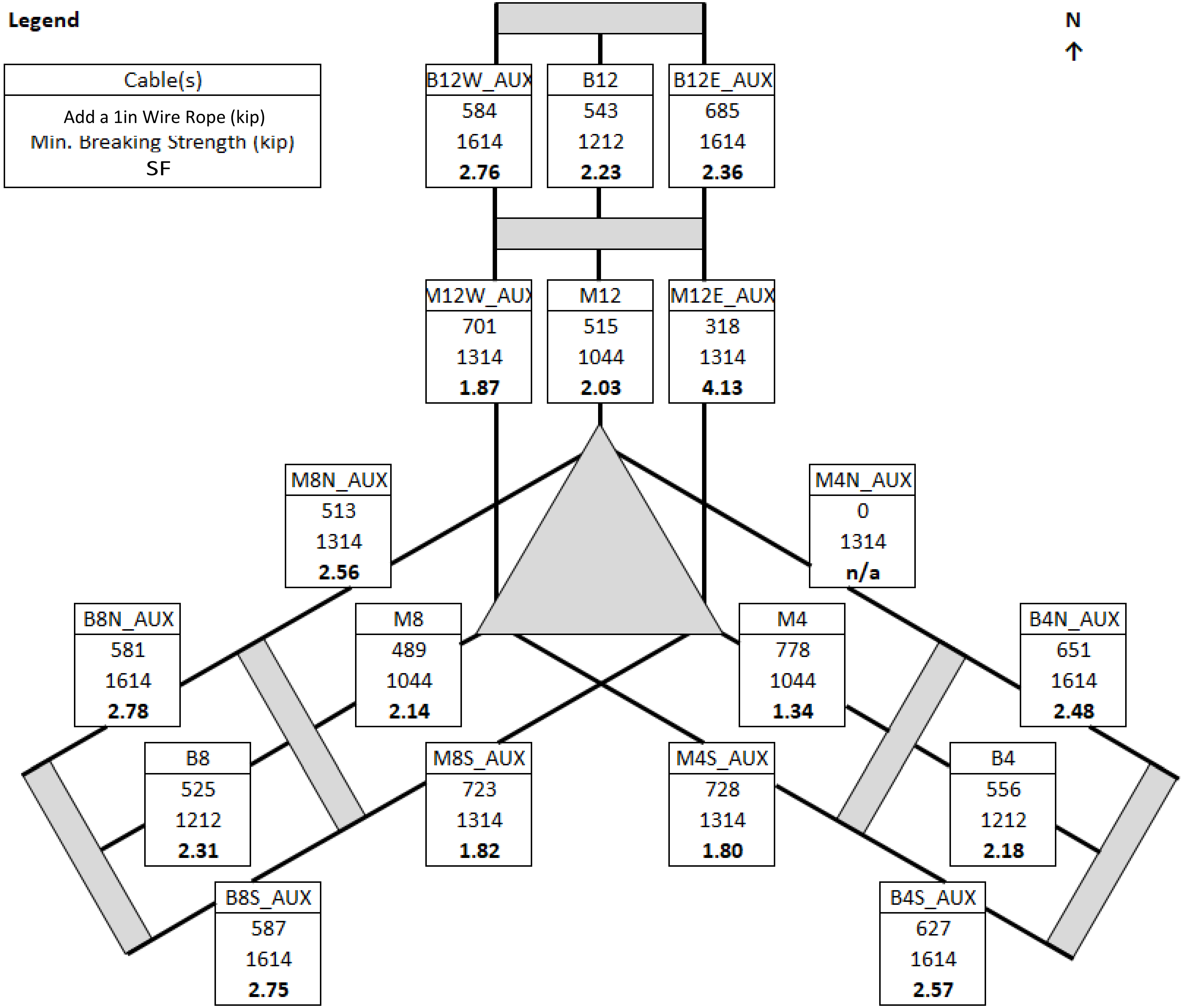
(starting from current condition)



Cable Safety Factors

If Adding a 1in Wire Rope where M4-4 was, Tensioned to Breaking Strength

(starting from current condition)



Cable Safety Factors

Starting From Current Condition

Cable(s)	Before Second Cable Failure	Current Condition	If Dejacking all Backstays by 18"	If Moving Gregorian Out	If Moving Line Feed In	If Dropping Counterweight	If Cutting M4-4	If Dropping Gregorian	If Dropping 100kip Uniformly from Platform	If Reconnection on M4N_AUX and Re-Tensionning to 300kip	If Lifting Platform From Waveguide Cables	If dropping Tiedowns	If dropping Line Feed	If adding 2 x 55mm cables where M4-4 was, tensionned to 50% breaking strength	If adding a 1in wire rope where M4-4 was, tensionned to breaking strength
M4	1.61	1.32	1.37	1.38	1.33	1.36	1.33	1.43	1.39	1.47	1.38	1.33	1.35	1.61	1.34
M4N_AUX	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.40	n/a	n/a	n/a	n/a	n/a
M4S_AUX	2.15	1.79	1.96	1.61	1.77	1.74	1.78	2.07	1.84	1.80	1.80	1.79	1.78	2.02	1.80
M8	2.10	2.14	2.19	1.99	2.12	2.13	2.14	2.54	2.26	2.13	2.16	2.16	2.16	2.11	2.14
M8N_AUX	2.47	2.57	2.84	2.84	2.59	2.67	2.57	2.59	2.64	2.41	2.63	2.58	2.62	2.51	2.56
M8S_AUX	1.78	1.81	2.01	2.07	1.83	1.90	1.83	1.80	1.86	1.91	1.90	1.82	1.86	1.87	1.82
M12	2.02	2.03	2.07	2.07	2.03	2.08	2.03	2.24	2.13	2.09	2.06	2.04	2.07	2.02	2.03
M12E_AUX	3.31	4.16	4.76	4.89	4.22	4.42	4.27	4.16	4.33	2.88	5.23	4.18	4.29	3.87	4.13
M12W_AUX	1.88	1.87	2.08	1.70	1.85	1.83	1.88	2.16	1.93	1.95	1.88	1.88	1.87	1.88	1.87
B4	2.13	2.18	2.45	2.19	2.18	2.21	2.19	2.35	2.26	2.16	2.16	2.19	2.21	2.16	2.18
B4N_AUX	2.46	2.48	2.81	2.51	2.48	2.52	2.49	2.66	2.57	2.43	2.50	2.49	2.51	2.50	2.48
B4S_AUX	2.46	2.58	2.95	2.58	2.58	2.61	2.59	2.80	2.67	2.59	2.51	2.59	2.61	2.51	2.57
B8	2.27	2.31	2.55	2.31	2.31	2.34	2.32	2.52	2.40	2.30	2.28	2.32	2.34	2.30	2.31
B8N_AUX	2.73	2.78	3.15	2.77	2.78	2.81	2.79	3.03	2.89	2.76	2.74	2.80	2.81	2.76	2.78
B8S_AUX	2.70	2.75	3.13	2.76	2.75	2.79	2.76	2.99	2.85	2.76	2.71	2.77	2.78	2.75	2.75
B12	2.18	2.23	2.51	2.24	2.23	2.27	2.24	2.42	2.32	2.20	2.21	2.25	2.26	2.22	2.23
B12E_AUX	2.30	2.36	2.66	2.38	2.36	2.39	2.37	2.53	2.44	2.31	2.32	2.37	2.39	2.34	2.36
B12W_AUX	2.71	2.77	3.19	2.76	2.77	2.80	2.78	3.03	2.88	2.75	2.75	2.78	2.80	2.75	2.76