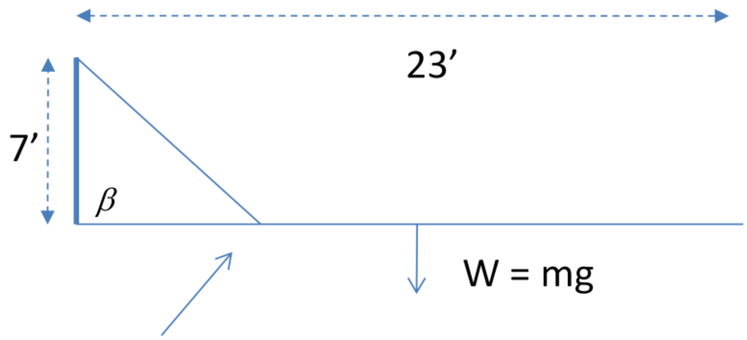
Subject: Design of My TX-472 Tower Raising Fixture **Date:** September 11, 2011
Reference: **Author:** Jeff Crawford

Part I – Geometry of the Problem

The necessary calculations to determine the stresses associated with a tower raising fixture for a TX-472 crank-up tower are performed here. The tower weighs 1,040 pounds and for purposes of our calculations here, is assumed to be equivalent to a uniformly loaded column 23 feet in length. The standard attachment point, designated "M", is 7 feet from the base.

There are two parts to this calculation: determination of the actual force at the top of the tower raising fixture and the stress requirements resulting from this. First, the statics problem of cable forces required to raise the tower must be solved. This will determine the maximum cable tension along the course of tower travel as it is being elevated into a vertical position. One easily recognizable boundary condition is that associated with the tower when it is flat on the ground; the sum of the moments at the tower base should equal zero. This is a good check on the general solution for all angles $0 \le \theta \le 90^o$.



Position "M"

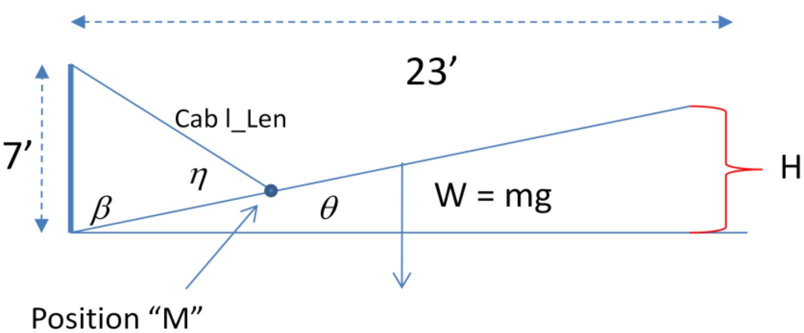
Refer to the diagrams below for definitions.
The center of the tower mass is always half-way along its 23-foot length, or in other words 11.5 ft up from the bottom.

Because the tower is telescoping it is not actually a uniform length of mass equal to 23 feet, but for the purposes of our calculations here, is more than sufficient as mentioned previously.

Figure 1

$$x\_base = \sqrt{23^2 - H^2} \qquad \beta = 90 - \theta \qquad T\_center = \frac{1}{2} x\_base$$

$$cbl\_len = \sqrt{7^2 + M^2 - 2 \times 7 \times M \cos(\beta)} \qquad \theta = \sin^{-1}(H/23)$$



The factor "7" in Figure 2 comes from the fact that the tower raising fixture is assumed to be 7 feet in height.

Figure 2

With these relationships established, we now sum moments around the base of the tower raising fixture.

1) Due to $W = mg$

$mg\cos(\theta)$ is the portion of W that is perpendicular to the lever arm formed by the tower back to the base of the tower raising fixture. The lever arm for W for all angles is fixed at 11.5 ft because this is the tower's centroid.

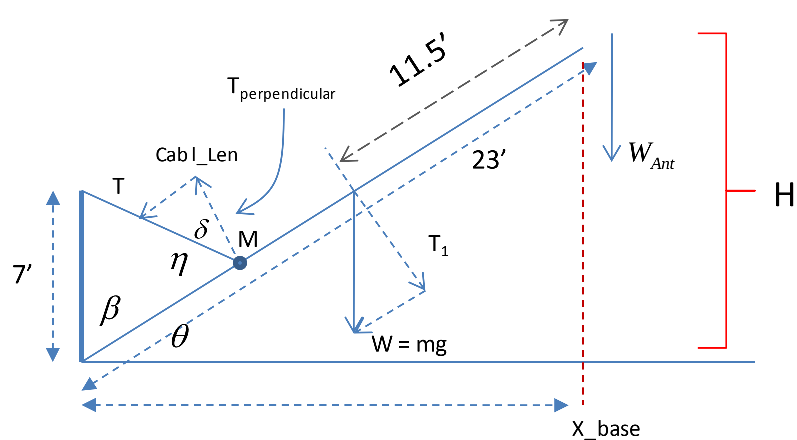


Figure 3

$$Torque_1 = T_1 \times 11.5 = mg\cos(\theta) \times 11.5$$

2) Due to the Cable Tension "T"

$$\frac{T_{perpendicular}}{T} = \cos(90-\eta) = \cos(\delta)$$

$$T_{perpendicular} = T \times \cos(\delta) \qquad \delta = 90-\eta$$

$T_{perpendicular}$ acts through a lever arm of length "M" $$Torque_2 = M \times T_{perpendicular} = M \times T\cos(\delta)$$

We can equate these two contributors to torque at the base and solve for "T", the tension in the cable.

$$11.5 \times mg\cos(\theta) = M \times T\cos(\delta) \qquad T = \frac{11.5 \times mg\cos(\theta)}{M\cos(\delta)}$$

If the addition of a weight at one foot above the tower's top is made to account for an antenna load, the formula for T is augmented in the following manner:

$$11.5 \times mg\cos(\theta) + W_{antenna}\cos(\theta) \times 24.5 = M \times T\cos(\delta)$$

$$T = \frac{11.5 \times mg\cos(\theta) + W_{antenna}\cos(\theta) \times 24.5}{M\cos(\delta)} = \frac{\cos(\theta)\{11.5 \times mg + W_{antenna} \times 24.5\}}{M\cos(\delta)}$$

We can verify the worst case results by reviewing the cable tension when the tower is resting entirely on the ground. In this scenario only a portion of the cable tension acts to counter the effects of gravity, W = mg, due to the angle formed by the cable to the tower.

Position "M"	Associated Angle β	Equilibrium Tension, lbs	Tension With Ant = 100 lbs
7	45	2416	2911.2
8	41.18	2270.2	2735.3
9	37.875	2164.5	2607.9
10	35	2085.5	2512.8

The calculations to the right are for a gin-pole height of 7 feet attached 7 feet up the tower from the tower base.

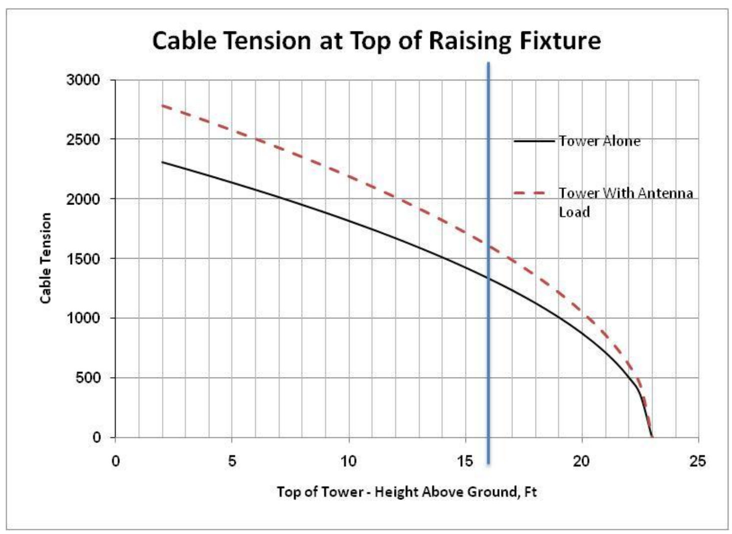


Figure 4

*Summary – **Part I***

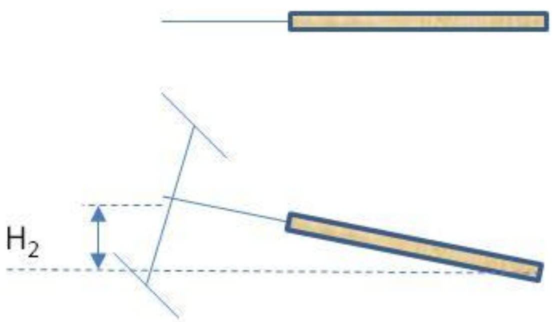
Making the gin pole longer or the point of cable attachment farther toward the top of the tower reduces cable strain, but in so doing (lengthening the gin pole), the stress at the base of the gin pole can grow much larger. For this reason, and in consideration of cable and winch strengths that are available, a position "M" of 7 to 8 feet appears to be most suitable. The graph to the right includes the effect of a 100 pound antenna load 1-foot above the tower's top.

Part II

In the actual installation procedure, the 16 foot mast and M2 rotator will be mounted on the tower at ground level. Once the tower is raised sufficiently, the Cushcraft XM-240 antenna will be mounted. Elevating the tower slightly higher, the C31XR antenna could be mounted, followed by raising the tower to its completely vertical position. Therefore, there are actually three segments to the tension curve as a function of tower height.

Description	Weight	Location With Respect to Top of Tower	Tower Height When Applicable
M2 OR-2800PX rotator	42 lbs	-4 ft	0
16 ft Reinforced mast	85 lbs	+4 ft	0
Cushcraft XM240; 23 ft boom	55 lbs	+9 ft	➢ 8.64 ft
Force12 C31XR; 31 ft boom	82 lbs	+1 ft	➢ 11.83 ft

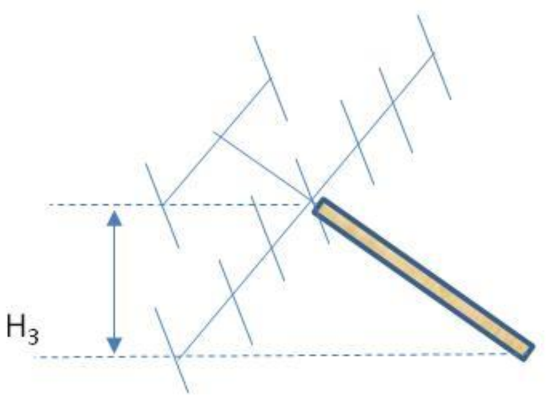
*** assumes the rotator is mounted 4 feet down inside the tower



The Details

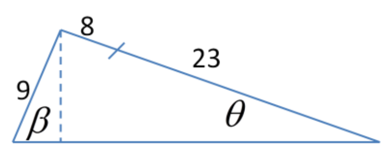
In the figures to the left, the top indicates the position of the tower when lying flat on the ground. The equivalent weight, when positioned one foot above the tower top (i.e. 24.5 feet) is equal to:

$$42(23.5-4)+85(23.5+4)=24.5W_1$$
$$W_1=128.84\,lbs$$



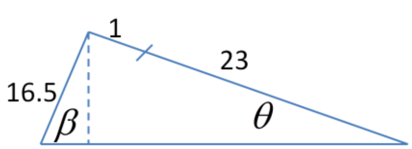
The second figure shows the 2-element Cushcraft XM-240 atop the 16 foot mast. Determining the equivalent weight when positioned one foot above the tower's top shows:

$$55(23.5+9)+85(23.5+4)+42(23.5-4)=24.5W_2$$
$$W_2=201.8\,lbs$$



$$\tan(\theta)=9/31 \qquad \theta=16.189^o$$
$$\sin(\beta)=H_1/9$$
$$H_2=8.64\ ft$$

H_3 is calculated in much the same way, this time however, the mast is only 1 foot long for the C31XR and half its boom length, 16.5, determines the other leg of the triangle.



$$\tan(\theta)=16.5/23 \qquad \theta=35.655^o$$
$$\sin(\beta)=H_3/16.5$$
$$H_3=13.41\ ft$$

$$55(9+23.5)+85(23.5+4)+82(24.5)+42(23.5-4)=24.5W_3$$
$$W_3=283.8\,lbs$$

Summarizing:

Position of Tower Top	Included in Weight (Weight, Position)	Equiv Weight 1 Ft Above Top
0	Mast [85,+4] Rotator [42, -4]	128.84
8.64	Mast [85,+4] Rotator [42, -4] Cushcraft XM-240 [55, +9]	201.8
13.41	Mast [85,+4] Rotator [42, -4] Cushcraft XM-240 [55, +9] Force12 C31XR [82, +1]	283.8

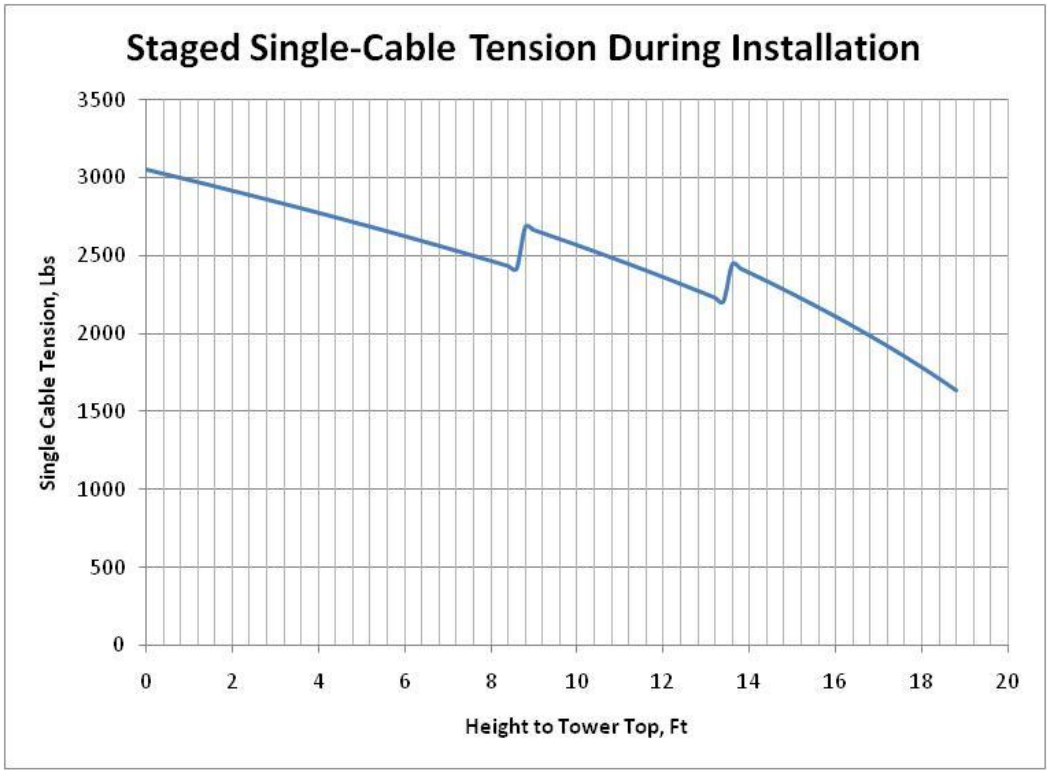
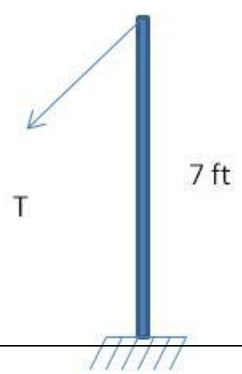


Figure 3

Figure 3 reveals two facts. If the tower's top can be raised to 6 feet above ground through some other means, such as an engine hoist in my case, the single-cable tension, and the force imparted to the top of the raising fixture, can be reduced substantially, in this case to ~ 2,500 lbs. Figure 3 shows that if the tower is tipped only 1 foot from true, the restoring force is around 700 lbs.

Part III



In the following calculations the feasibility of designing a raising fixture not attached to the tower base itself, but instead using one single vertical steel member, is investigated.

The maximum shear is, in fact, equal to $T\sin(angle)$

where the "angle is between the vertical post and the cable T.

The maximum bending moment at the point of attachment is $T\sin(\theta)\times M\Big|_{M=7}$

If we make the assumption that the steel used is of grade 36 kips, the maximum allowable bending stress is 24 ksi (assuming $F_b = 0.66\ F_y$ for a safety factor), the required section modulus is

$$S = \frac{7T\sin(\theta)}{24ksi} = \frac{7\times 3\times \sin(50^o)\times 12}{24} = 8.04$$ using T = 3,000. To provide some conservatism to this calculation, we determine S for T = 4 kips.

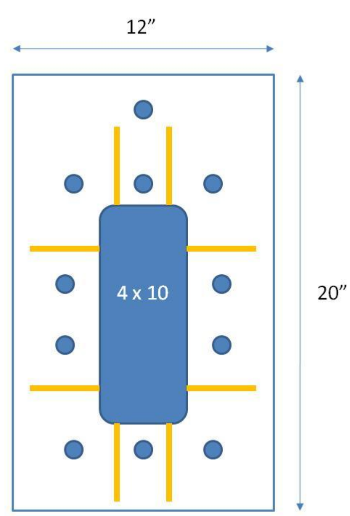
$$S = \frac{7T\sin(\theta)}{24ksi} = \frac{7\times 4\times \sin(50^o)\times 12}{24} = 10.72$$

The following rectangular beams could be used. "S" is the section modulus.

Single Column			Double-Columns		
8 x 3 x 0.3125	S = 11.2	Weight = 148.5	5x3x0.375	2S = 11.78	2W = 241.8
8x4x0.25	S = 11.3	Weight = 133.1	6x2x0.3125	2S = 10.68	2W = 207.6
10x2x0.25	S = 11.1	Weight = 133.1	6x3x0.25	2S = 11.96	2W = 194.74
10x4x0.1875	S = 12.3	Weight = 119.6			
10x4x0.25	S = 15.9	Weight = 156.9			

This does not include a) a base plate of approximate dimensions 12" x 16" or b) additional steel reinforcement where the rectangular tube is connected to the base plate.

If available, the two options above highlighted in green appear to be the optimum given the design parameters. The 10x4x0.1875 is selected due to its smaller weight, but more importantly, its width of 4 inches will provide greater immunity to lateral forces should they occur (for some reason).



If I am forced to buy a 21 ft or 24 ft length of rectangular tubing by the vendor, then the double-column arrangement may be best from an overall cost/wasted material perspective.

The minimum AISC bolt-to-bolt spacing recommended spacing is 2.666 times the bolt diameter.

Bolt Diameter	Minimum Edge Distance	Minimum 2.666 d
5/8	0.875	1.67
¾	1	2
7/8	1.125	2.33
1	1.25	2.67

Part IV

Due to the availability of materials and the accompany excesses required for purchasing same, it was decided to largely duplicate the raising fixture as sold by US Towers. The vertical column member is 2" x 6" x 7 1/3' , 0.25 inch wall and the side supports are each 1"x1"x ~ 3.5 ft, 0.25 inch wall. The sheaves on the tower need to be 3.25" in diameter, while one on the raising fixture itself is 3.25" and the other 5.25".

Further research into sheaves and their associated costs lead me to go the route of using a chain hoist and come-along.