NASA/CR–20250010465

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December 2025

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Concepts and Design Trends for Tall Plug-and-Play Telescoping Mast Lunar Solar Arrays

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Prepared for Langley Research Center
under Contract 80LARC23DA003

December 2025

Available from:

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Abstract

At the lunar South Pole, elevated rotating solar arrays can receive nearly continuous sunlight exposure for power generation despite the Sun remaining low on the horizon throughout the year. In addition, taller masts will enable longer lines-of-sight for electromagnetic devices requiring that capability. However, the structural masts required to raise these arrays increase significantly in mass and stowed volume as array height grows. Traditional mast design approaches, when applied to tall masts in the Moon's reduced gravity, result in extremely slender structures with height-to-diameter ratios that exceed current engineering state-of-the-art. In this study the emphasis is on the design of tall telescoping support masts to deal with the slenderness issue. The reader is referred to References 1, 2, and 3 for the design of the solar array blankets.

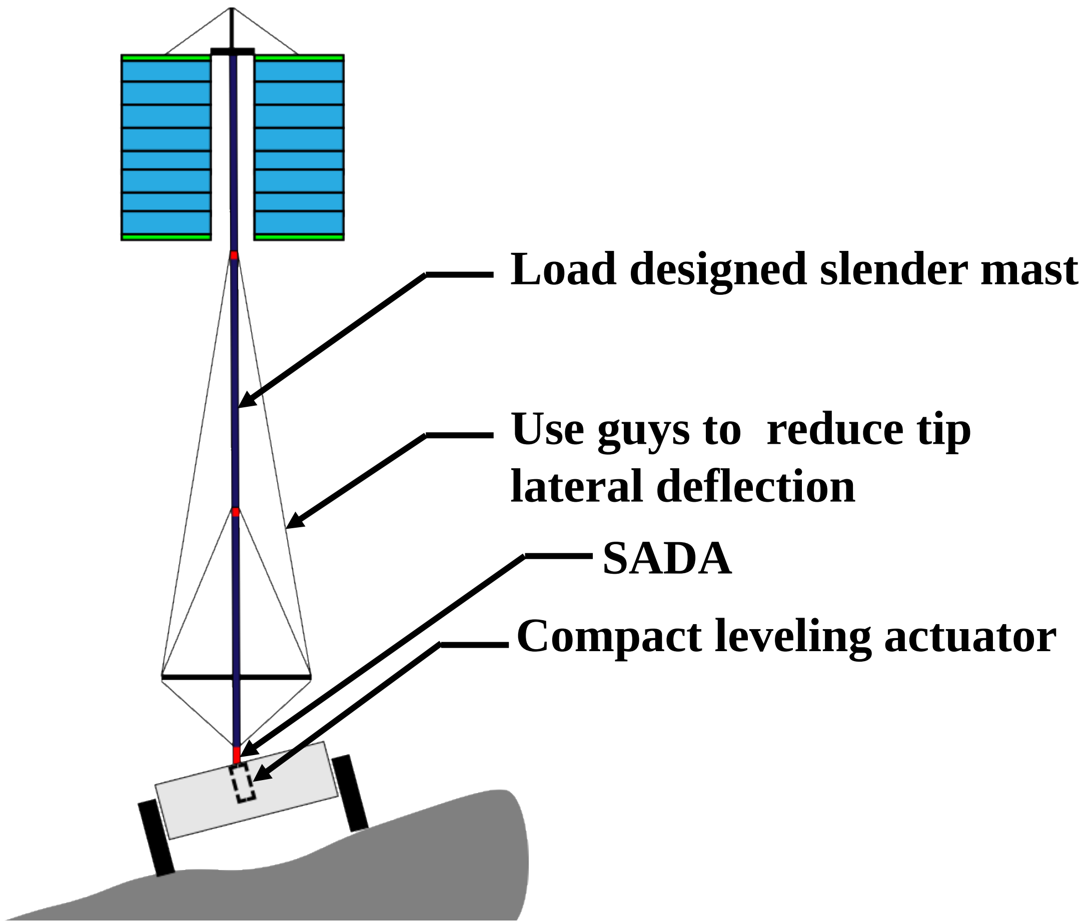
This study proposes two potential design strategies to achieve robust, tall, lightweight, and stowage-efficient masts. The first simply increases mast diameter through higher design factors of safety, while the second employs integrated guy-stiffening to enhance structural performance thereby improving robustness. Both approaches use telescoping tubular mast designs that eliminate the need for bulky deployment canisters, maximizing mass and volume efficiency.

In addition, a recently developed compact base-mounted actuator is incorporated in the design to provide leveling capability, enabling a "Plug-and-Play" (P&P) vertical solar array system that provides a highly versatile and modular capability. Preliminary design studies and parametric analyses are presented to demonstrate early design trends. A major objective of this paper is to provide a design methodology that can be used in future system trade studies. To validate and refine these novel concepts, experimental testing will be required to establish confidence in their application.

Two Plug & Play Concepts Considered to Address High Slenderness Issue

(Shown on 15^o slope)

a. Integrated guy stiffened slender mast



b. Un-guyed larger diameter mast

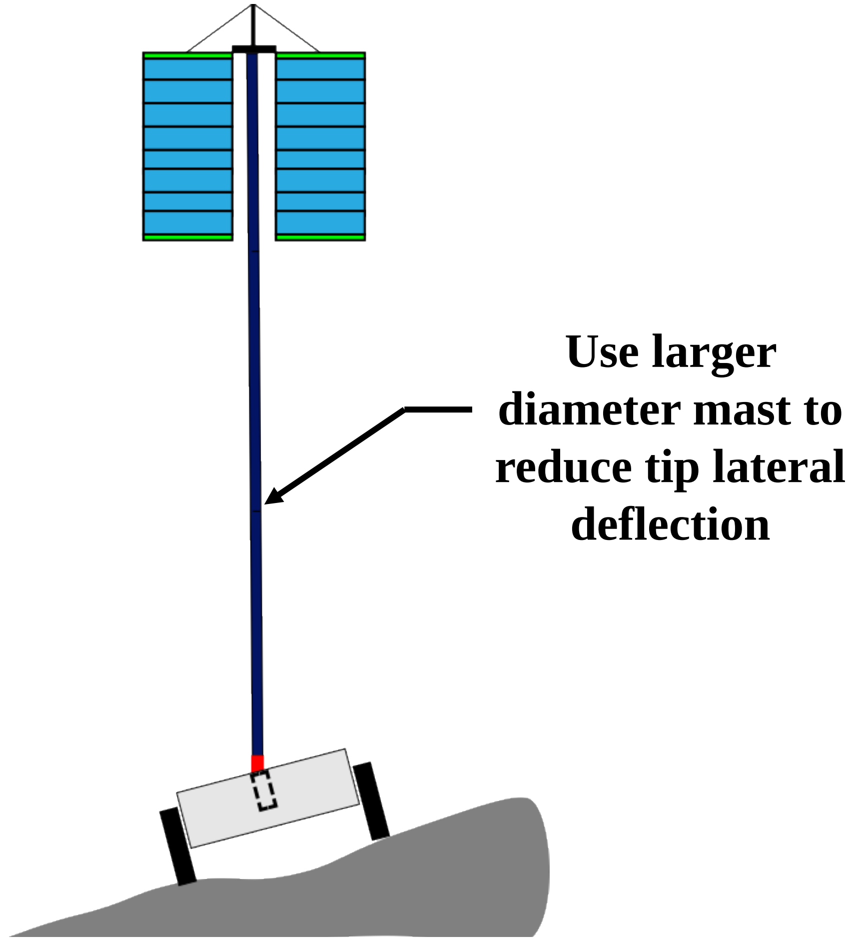


Figure 1

Two Plug & Play Concepts Considered to Address High Slenderness Issue

Using Traditional Earth based design methods, low lunar g loads result in high slenderness ratio tall mast designs that are beyond the current state-of-the-art

Structural Challenges:

- **Euler-load-designed tall lunar masts are very slender and susceptible to large tip deflections**
- **Euler-load-designed tall lunar masts must consider additional design constraints, such as imperfections, to improve robustness**
- **New concepts and design methods are necessary for tall mass and volume efficient lunar solar arrays**

Two concepts considered to address slenderness and leveling issue shown in Figure 1

a. **Use integrated guys and compact leveling actuator to simplify system leveling control**

b. **Increase mast diameter to provide necessary mast dimensional stability**

Figure 1 Text

Key Plug & Play (P&P) Synergistic Features

1. **Telescoping mast eliminates deployment canister, e.g. CTA[1,2]**
   - **Telescoping enable:**
     - **High modulus materials**
     - **Tapered tubes**
     - **Thick walls**
   - **Unfurlable masts have low, modulus, constant diameter, and thin walls**
2. **Compact actuator[5] orients mast up to 15° slope & enables & enables plug and play (P&P) concept**
3. **P&P solar array module enables versatile packaging and applications**
4. **STAC "*<u>S</u>equential <u>T</u>ip-<u>A</u>dditive <u>C</u>onstruction*" telescoping mast enables robust deployment and sequentially deployed guys**
5. **Guy tensioning springs compensate for dimensional errors**

Figure 2

Key Plug & Play (P&P) Synergistic Features

As detailed in References 1 and 2, adopting a telescoping mast design removes the necessity for a bulky deployment canister, thereby reducing both launch stowage volume and overall system mass. Furthermore, using fully formed telescopic segments makes it possible to employ high modulus composite materials (20 to 30 msi), unlike unfurlable mast concepts, which are limited to approximately 5 msi due to stowage deformation requirements. Additionally, the thickness of telescopic sections is not restricted and can be adjusted as needed to achieve compact storage and required structural performance.

The telescoping tubular mast is also compatible with the compact leveling actuator described in Reference 5 and illustrated notionally in Figure 1. The integration of this actuator represents a significant advancement, enabling a truly modular and highly versatile Plug & Play solar array, as will be elaborated upon subsequently.

Another key feature proposed for the P&P telescoping mast is its sequential deployment mechanism. The lowest section deploys first, followed by each subsequent adjacent section. This sequence allows stabilizing guys to be tensioned progressively, ensuring a rigid mast throughout deployment. Innovative error-compensating springs are incorporated to maintain correct guy tension during the entire process.

Figure 2 Text

Basic P&P Tall Telescoping Mast Design Strategy

1. **Design telescoping mast to support tip compression load with a FS ≥ 3 against Euler buckling without guys**
2. **Analyze the following two approaches**
   a) **Add sequentially deployed integrated guys to dimensionally control the tip displacement of the resulting slender mast to an acceptable value**
   b) **Increase mast diameter to dimensionally control the tip displacement of the mast to an acceptable value**
3. **Conduct trade study of mast mass, volume, and complexity, to determine the preferred approach**

Figure 3

Basic P&P Tall Telescoping Mast Design Strategy

The design strategy for the P&P telescoping mast focuses on ensuring that the unguyed structure can withstand compressive loads from the elevated solar array assembly as well as from any additional electromagnetic instruments. Previous studies demonstrate that applying Euler buckling safety factors of around 1.5 in the lunar low-gravity environment leads to extremely slender mast designs that are highly sensitive to initial lateral imperfections, often resulting in excessive tip deflections. To address this, the current approach involves an iterative process, beginning with a safety factor of 3 and increasing it as needed until both structural performance and packaging requirements are satisfied.

The first key requirement is that the lowest telescoping segment must have a diameter large enough to stow all inner segments needed for the target mast height. The second requirement is achieving sufficient bending stiffness to prevent excessive lateral tip deflection under the applied tip mass. To meet this criterion, the design process involves three steps: (1) adjust the baseline mast diameter to accommodate nested tubing, (2) enhance stiffness either by integrating guying supports (Figure 1-a) or by increasing the diameter of an unguyed mast (Figure 1-b), and (3) evaluate the trade-offs between mass, stowage volume, and system complexity to identify the preferred solution.

This paper presents preliminary analyses of the two structural configurations illustrated in Figure 1. The intent is to identify design trends, confirm feasibility, and outline directions for future development. For tractability, these analyses assume that the telescoping mast has a constant tube diameter, neglecting its inherent taper. This approximation allows closed-form solutions to readily capture early design insights. More advanced studies, including finite element analyses of tapered mast geometries, will ultimately be needed to provide higher-fidelity results, but such efforts are beyond the scope of this paper.

Figure 3 Text

Tubular Mast Design Nomenclature*

a – Mast tip initial deflection
aovd – a/d
AR - Blanket aspect ratio
bd - Solar cell blanket areal density, kg/m^2
d – Mast diameter
Et – Tube modulus of elasticity, Pa
FS - FS on Euler buckling of mast
g – Gravity, m/sec^2
gf - Gravitational factor ~ (1/6 Moon, 1/3 Mars)
gr - Graphite-epoxy
H - Height of mast, m
HovD – Slenderness of mast
N – Number of telescoping sections
δ – Mast latera tip deflection
δovd - δ/d
θ – Mast initial tilt angle, degrees
ρ – Mast material density, kg/m^3

dPPL – Diameter of mast due to PPL, m
dHovd – Diameter of mast due to Hovd, m
JF - Factor to account for joint mass or volume
HovdPPL – Mast slenderness due to PPL
HovdHovd - Mast slenderness due to Hovd
k – Later stiffness of the mast tip, N/m, or lb/in
kPPL – k due to PPL
kHovd k due to PPL
MPL - Mass of payload at top of mast, kg
MPPL – Mast mass due to PPL, kg
MHovd – Mast mass due to Hovd, kg
PL - Module power level, Watts
PPL - Tower compressive tip load due to MPL, N
SADA- Solar array drive assembly
VHovd – Mast volume due to Hovd
VPPL – Mast volume due to PPL
tm - Thickness of telescoping tube, m

***Reference 3**

Figure 4

Tubular Mast Design Nomenclature

The nomenclature used the tubular mast analysis and design is presented in Figure 4 and is the same as that used in Reference 3. All units used are metric, except that the mast tip lateral stiffness, is converted to English units, lb/in, in the charts for clarity.

Figure 4 Text

Solar Array & Tubular Mast Parameters & Design Equations Used For Subsequent Parametric Charts

Solar Array & Mast Parameters

$$PL = 50000;\ AR = 1.25;\ bd = 1;\ \Pi = 300;\ g = 9.8;\ gf = 1/6;\ Et = 207\times10^{9};\ Hovd = 50.;\ tm = 0.03\times\frac{2.54}{100};$$

$$JF = 1.3;\ \eta = 1.55 - 0.1\,AR;\ MPL = \frac{PL}{\Pi}\,bd\,\eta;\ PPL = MPL\,g\,gf;\ H = 50;\ \theta = 1;\ aovd = 0.5;$$

Load Design Equations

$$dPPL[H\_, FS\_] := \left(\frac{FS\ 8\times4\ H^2\ PPL}{\pi^2\ Et\ \pi\ tm}\right)^{1/3};$$

$$MPPL[H\_, \rho\_, FS\_] := JF\,\pi\left(\frac{FS\ 8\times4\ H^2\ PPL}{\pi^2\ Et\ \pi\ tm}\right)^{1/3} tm\,H\,\rho;$$

$$VPPL[H\_, FS\_] := \pi\left(\left(\frac{FS\ 8\times4\ H^2\ PPL}{\pi^2\ Et\ \pi\ tm}\right)^{1/3}\right)^2 \frac{1}{4}\,\frac{H}{5};$$

$$HovdPPL[H\_, FS\_] := \frac{H}{\left(\frac{FS\ 8\times4\ H^2\ PPL}{\pi^2\ Et\ \pi\ tm}\right)^{1/3}};$$

$$kPPL[H\_, \rho\_, FS\_] := \frac{Et\ 3\,\pi\left(\left(\frac{FS\ 8\times4\ H^2\ PPL}{\pi^2\ Et\ \pi\ tm}\right)^{1/3}\right)^3}{8\,H^3}\ tm\ .0058;$$

(* Convert N/m to lb/in with .0058 *)

Slenderness Design Equations

$$dHovd[H\_] := \frac{H}{Hovd};$$

$$MHovd[H\_, \rho\_] := JF\,\pi\,\frac{H}{Hovd}\,tm\,H\,\rho;$$

$$VHovd[H\_] := \pi\left(\frac{H}{Hovd}\right)^2 \frac{1}{4}\,\frac{H}{5};$$

$$HovdHovd[H\_] := .0001\,H + 50;$$

$$kHovd[H\_] := \frac{Et\ 3\,\pi}{8\ Hovd^3}\ tm\ .0058;$$

Tip Deflection Equation

$$\delta ovd[\theta\_, H\_, FS\_, aovd\_] := \left(\theta\,\frac{\pi}{180}\,\frac{H}{\left(\frac{FS\ 8\times4\ H^2\ PPL}{\pi^2\ Et\ \pi\ tm}\right)^{1/3}} + aovd\right)\left(\frac{1}{1-\frac{1}{FS}}\right);$$

Figure 5

Solar Array & Tubular Mast Parameters & Design Equations Used For Subsequent Parametric Charts

The Equations used to generate the mast parametric design charts are presented in Figure 5. The solar array and mast parameters used to generate the mast design charts are shown at the top of Figure 5. All the "**Load Design Equations**" presented in Figure 5 are based on the tube diameter, **dPPL**, that is obtained from the traditional Euler buckling constraint equation for a vertical cantilevered column as shown in the equations below.

$$\mathbf{PPL} = \frac{\pi^2\ \mathbf{Et\ It}}{\mathbf{FS\ 4\ H^2}} = \frac{\pi^2\ \mathbf{Et}\ \pi\ \frac{\mathbf{dppl}^3}{8}\ \mathbf{tm}}{\mathbf{FS\ 4\ H^2}} \quad \Rightarrow \quad \mathbf{dPPL} = \left(\frac{\mathbf{FS\ 8 \times 4\ H^2\ PPL}}{\pi^2\ \mathbf{Et}\ \pi\ \mathbf{tm}}\right)^{1/3}$$

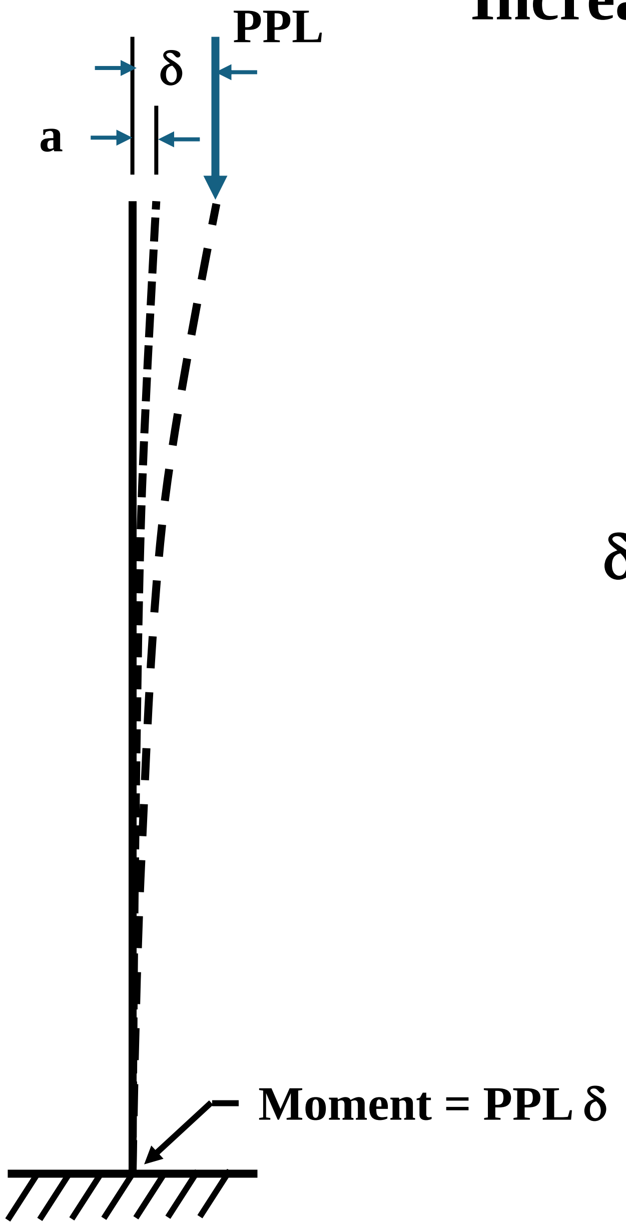
All the "**Slenderness Design Equations**" presented in Figure 5 are based on the tube diameter, **dHovd**, that is obtained from the slenderness constraint equation shown below.

$$\mathbf{dHovd} = \frac{\mathbf{H}}{\mathbf{Hovd}}$$

The slenderness diameter, **dHovd**, is obtained from the above equation by selecting a value for **Hovd**. For the examples presented in this paper, the value for **Hovd** was chosen as 50. The reason for this value is that **Hovd** = 50 is a conservative value commonly used in civil engineering structures to ensure safety robustness.

Figure 5 Text

Tip Load Induced Imperfection Deceases Rapidly with Increase in FS Because of Increasing Mast Diameter



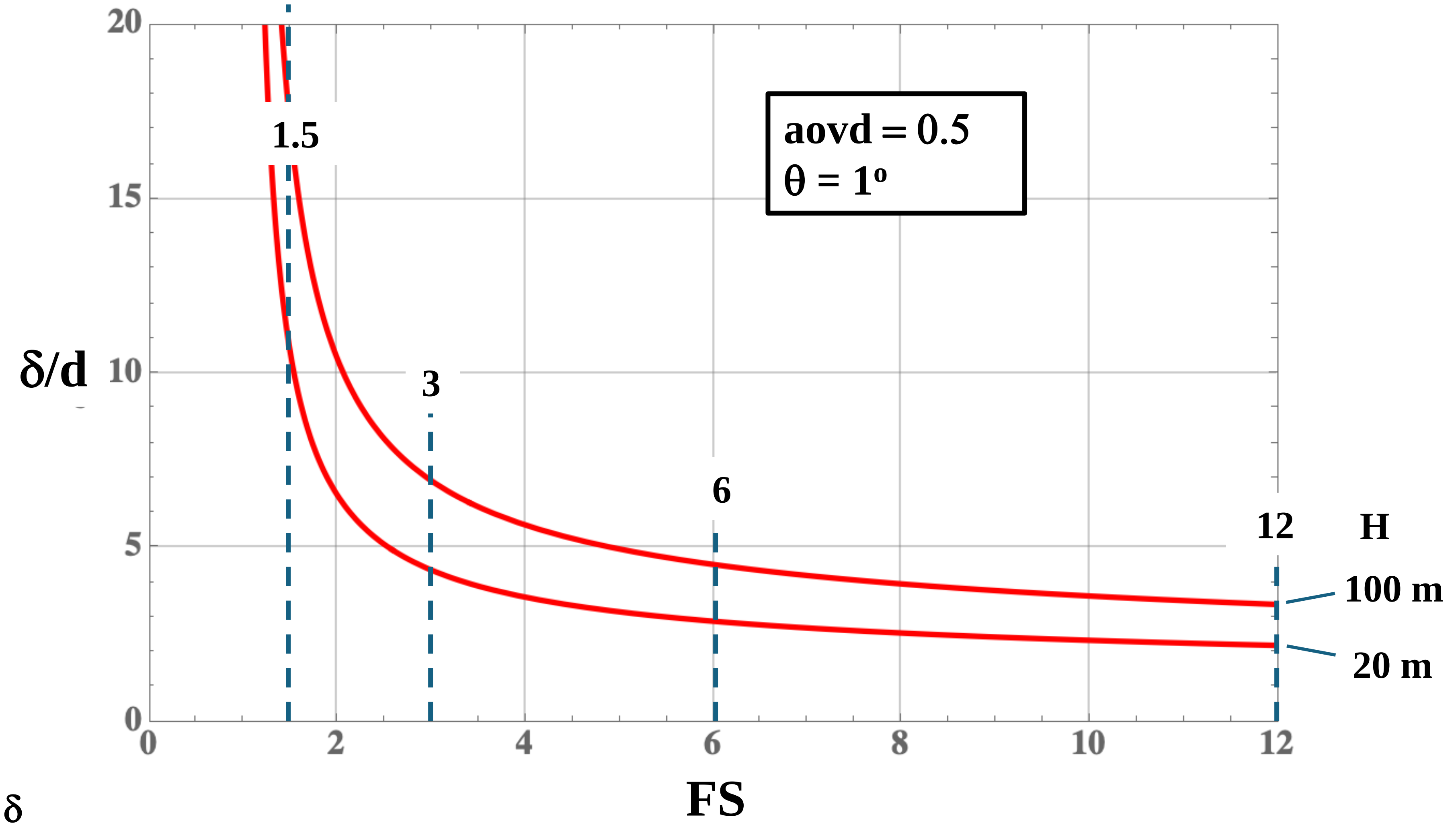


Figure 6

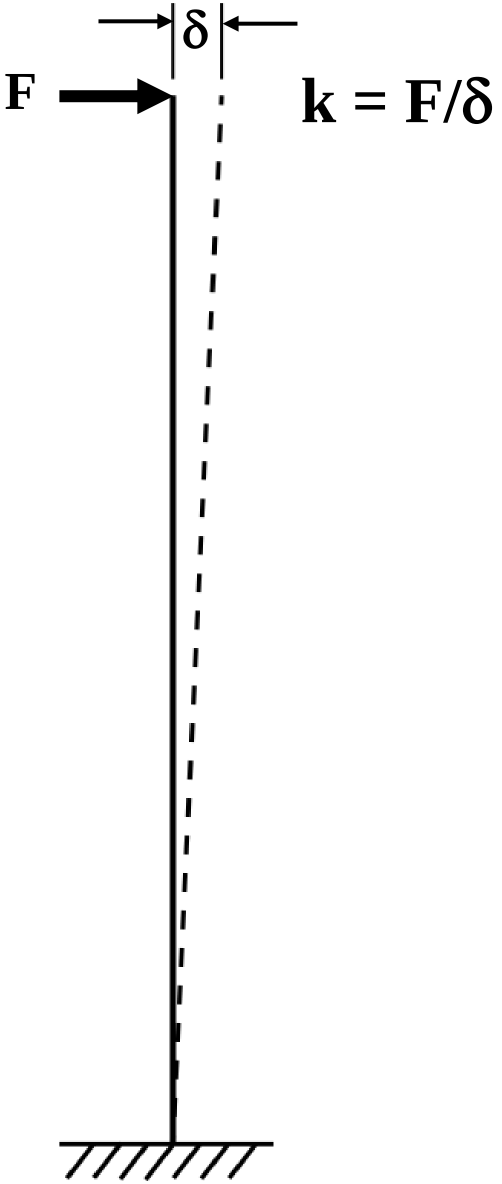
Tip Load Induced Imperfection Deceases Rapidly with Increase in FS Because of Increasing Mast Diameter

There is no known heritage requirement for choosing a slenderness value, **Hovd**. However, for the low g lunar masts, highly slender columns are susceptible to large lateral tip deflections due to small out-of-straightness imperfections as shown in figure 6. The equation used to generate Figure 6 is shown at the bottom of Figure 5. This equation is based on an imperfection amplification factor presented by Timoshenko in Reference 4. The example tip lateral imperfection parameters used to generate this figure are aovd = 0.5 and an initial angular error $\theta = 1^o$. As can be seen from Figure 6, the resulting lateral deflection due to an initial imperfection, decreases rapidly with an increase in assumed design factor-of-safety, FS. Allowable lateral tip wobble displacements during sun tracking will likely be dictated by requirements dictated by electromagnetic instruments on the mast tip.

Figure 6 Text

Lunar Mast Tip Lateral Stiffness of Decreases Rapidly With an Increase in Slenderness

(H = 50 meters)



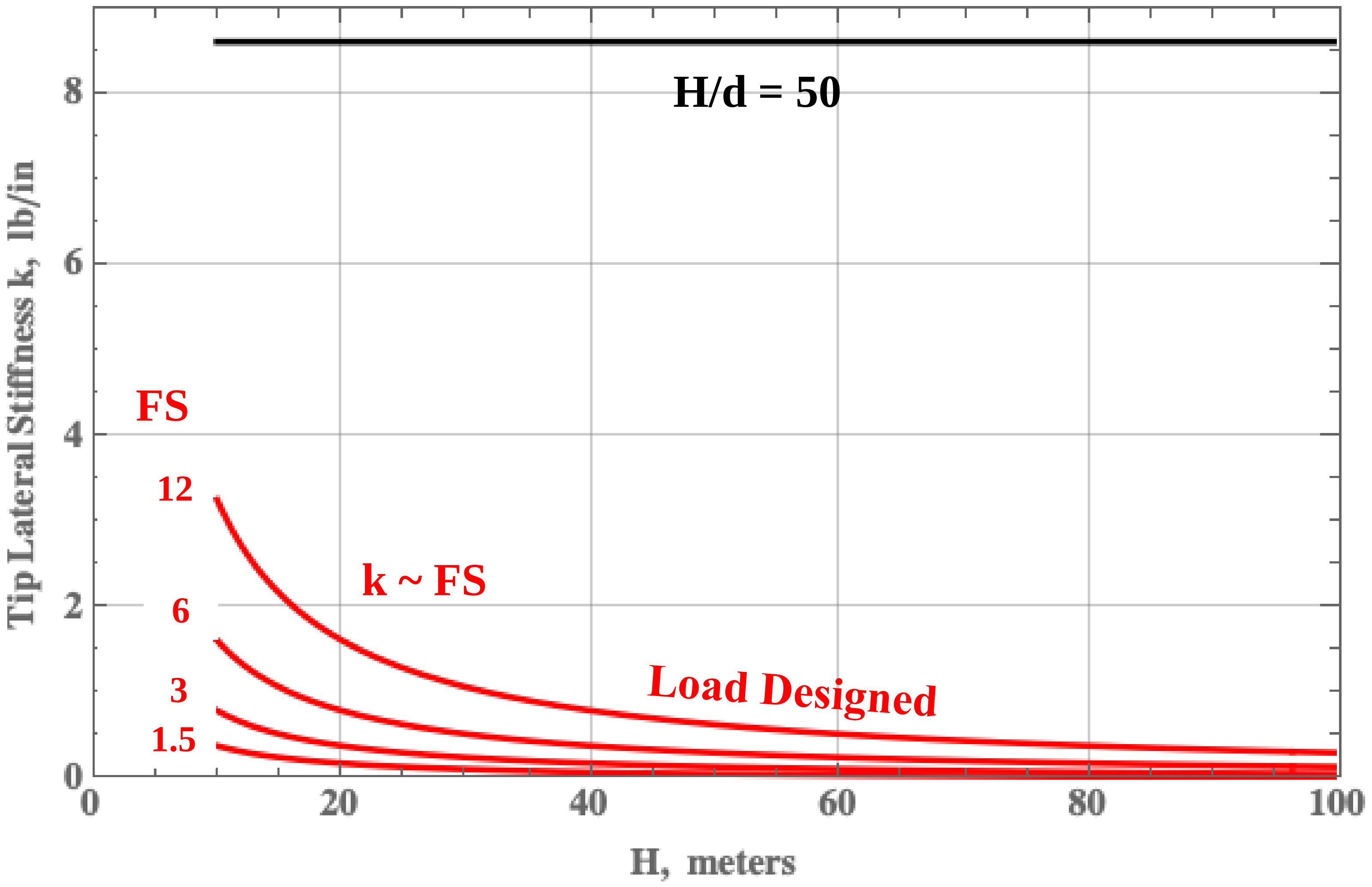


Figure 7

Lunar Mast Tip Lateral Stiffness of Decreases Rapidly With an Increase in Slenderness

Another measure of the extreme flexibility of highly slender masts is tip stiffness, k. Lunar tip mast stiffness is plotted in Figure 7 as a function of height, H. As shown in the figure, the load designed lunar mast tip stiffness decreases significantly with increase in mast height. For comparison purposes, the tip stiffness of a slenderness designed mast for a value of Hovd = 50 is also shown on the Figure. A major observation from this figure is that the lateral tip stiffness of a load designed mast using a factor-of-safety of 1.5 is over an order-of-magnitude lower than an H/d = 50 slenderness designed mast. As shown on the figure, the mast tip lateral stiffness, is linearly proportional to the factor-of-safety, FS. Although this increase in the FS results in significant improvements in lunar mast tip lateral stiffness for relatively short masts, the value of k drops dramatically for taller mast. Although no hard design requirement can be gleaned from Figures 6 and 7, these figures lend insight into why civil engineers tend to design tall columns with slenderness ratios of about 50. However, as will be shown on subsequent charts, designing for low slenderness ratios leads to significant increases in mast mass as well as stowage volume.

It should also be pointed out that because of the large reduction in stiffness with increase in mast height, structural performance and lessons learned for short lunar masts do not scale well for tall masts. A major counter intuitive observation is that because the mast's lateral tip stiffness is quite low, the use of guys will not require major authority to suppress out-of-straight deformations. A corollary observation is that low authority guys will be effective in suppressing deformations due to joint free play.

Figure 7 Text

Slenderness Ratio (H/d) of Traditional Load Designed Lunar Mast is Unacceptably High

(Example: Using Tip Load of a 50 kW Solar Array)

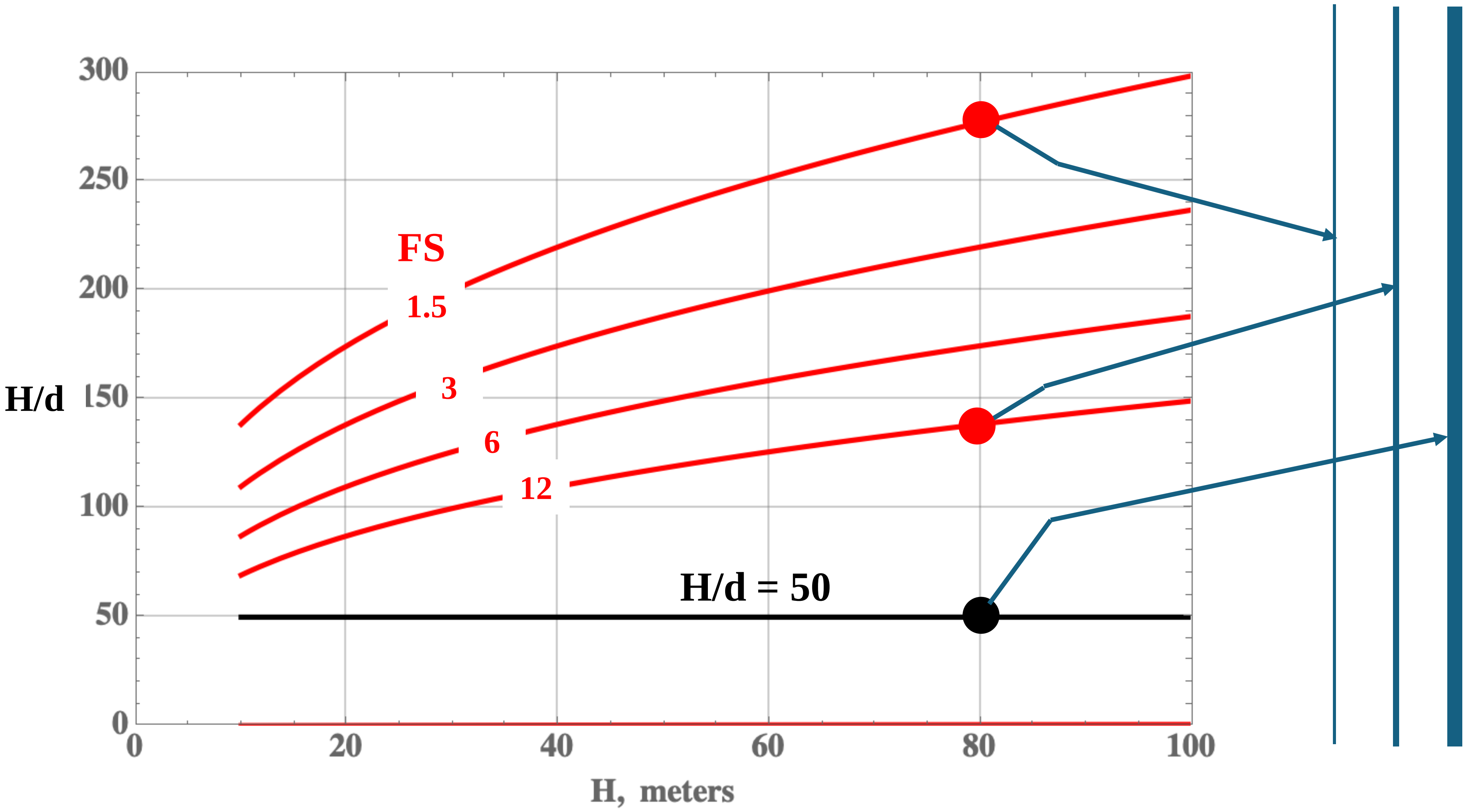


Figure 8

Slenderness Ratio (H/d) of Traditional Load Designed Lunar Mast is Unacceptably High

To provide further insight into the slenderness of tall lunar masts, their slenderness ratio, H/d, is plotted in Figure 8 for load designed masts and for a slenderness designed mast with an H/d=50. It is seen that the slenderness of load designed masts is always much higher than a mast designed to a slenderness ratio of 50. To provide further perspective, scale sketches of tubular masts with 3 different slenderness ratios are shown on the figure for a height of 80 meters. Although increasing the design factor-of-safety significantly reduces the mast slenderness ratio, H/d always remains well above the slenderness ratio of an H/d = 50 mast design.

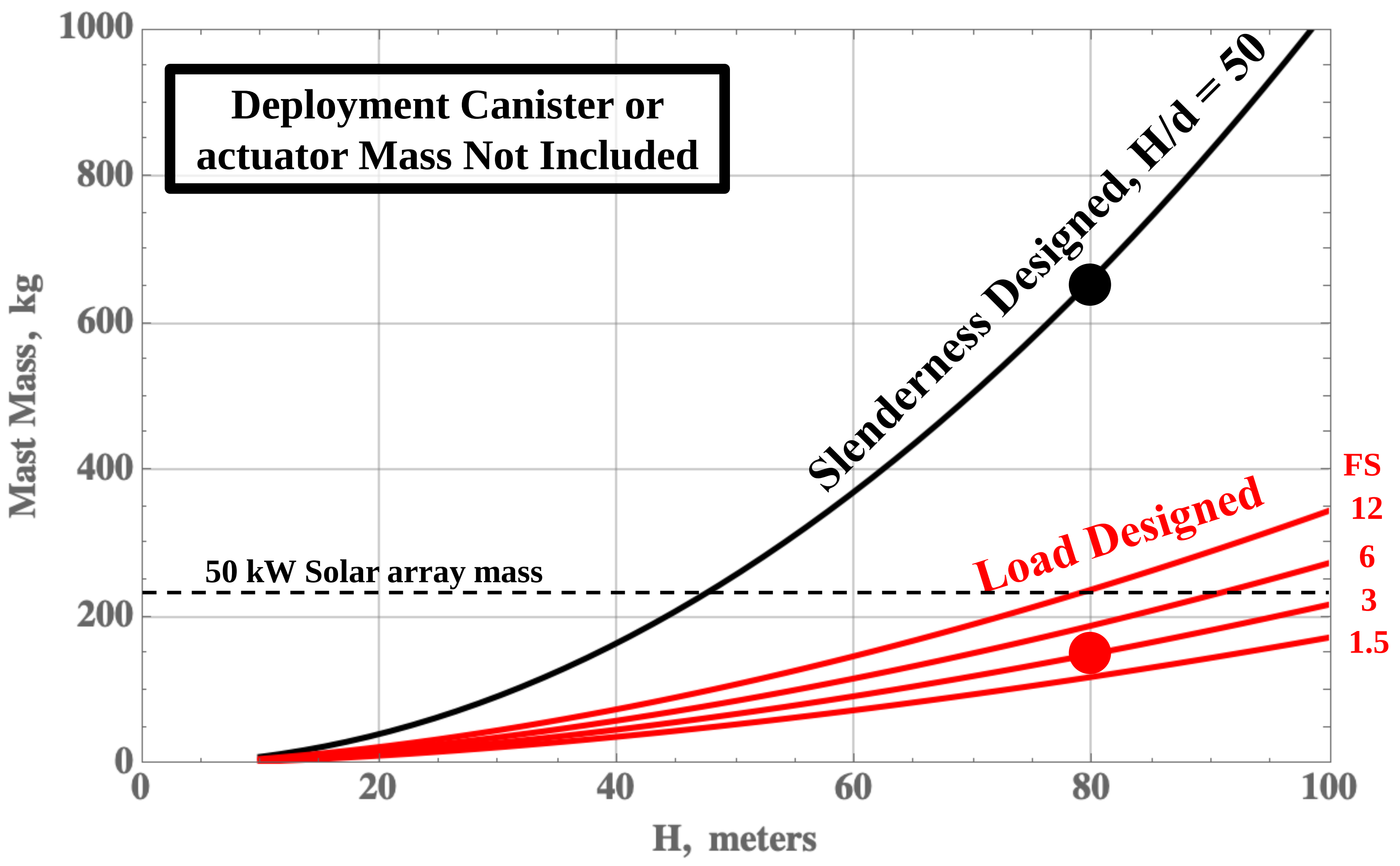
In summary, it should be noted that all the designs shown in Figure 8 will support the theoretical Euler buckling load. Thus, further studies are required to understand whether slenderness ratios with values much higher than 50 are acceptable for use in the low g lunar environment. The use of higher mast slenderness ratios will result in designs with significantly lower mass and launch stowage volume as shown on the next few charts.

Figure 8 Text

Load Designed Lunar Mast Mass is Low; However, Slenderness is Beyond SOA

(Example: Using Tip Load of a 50 kW Array (238 kg) Solar Array)*

Tip Load = 389 N (88 lb)



*Reference 3

Figure 9

Load Designed Lunar Mast Mass is Low; However, Slenderness is Beyond SOA

In Figure 9, masses are presented for load designed masts as a function of height for 4 values of factor-of-safety as well as for slenderness designed mass with a value of H/d = 50. For reference, the mass of the elevated 50 kW solar array is also presented on the chart. Although the masses of the load designed masts are much lower than the slenderness designed mast, further work is required to determine their structural adequacy.

Figure 9 Text

Stowed Volume Increases Rapidly With Increase In FS

(<u>Example</u>: Using Tip Load of a 50 kW Array (238 kg) Solar Array)*

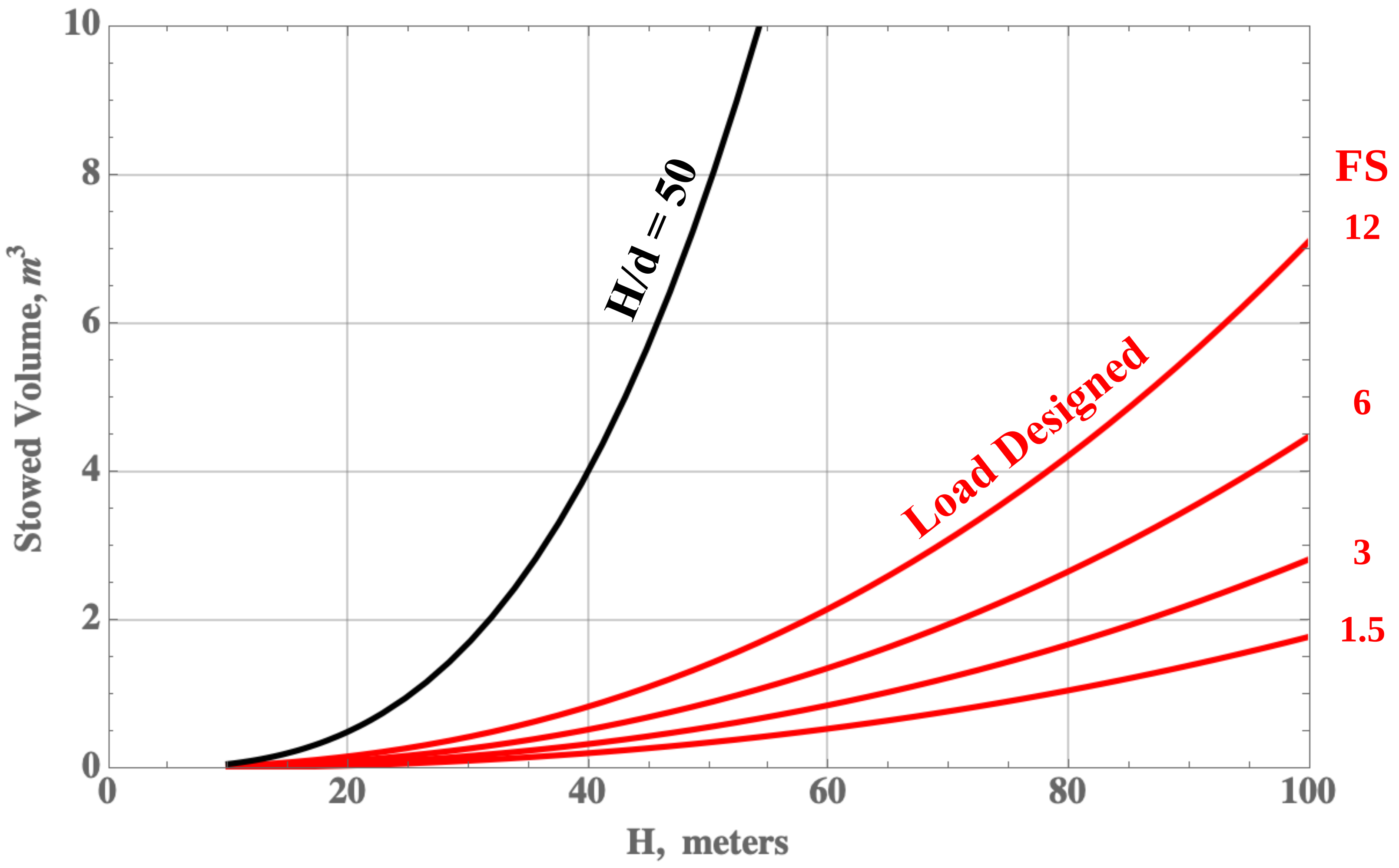


Figure 10

*Reference 4

Stowed Volume Increases Rapidly With Increase In FS

Another major factor in the design of masts for tall lunar solar arrays is the stowed volume for launch. In this study it is assumed for all heights, that all telescoping segments are 5 meters long and stowed within the diameter of the base segment. Using this assumption, the telescoping mast volumes plotted in Figure 10 as a function of height. As observed from the figure, the mast stowage volume increases dramatically with increase in mast height. As previously noted, trends observed for short masts do not scale well for taller masts.

Figure 10 Text

Lunar Mast Diameter as a Function of Factor of Safety

(Using Tip Load of 50 kW Solar Array)

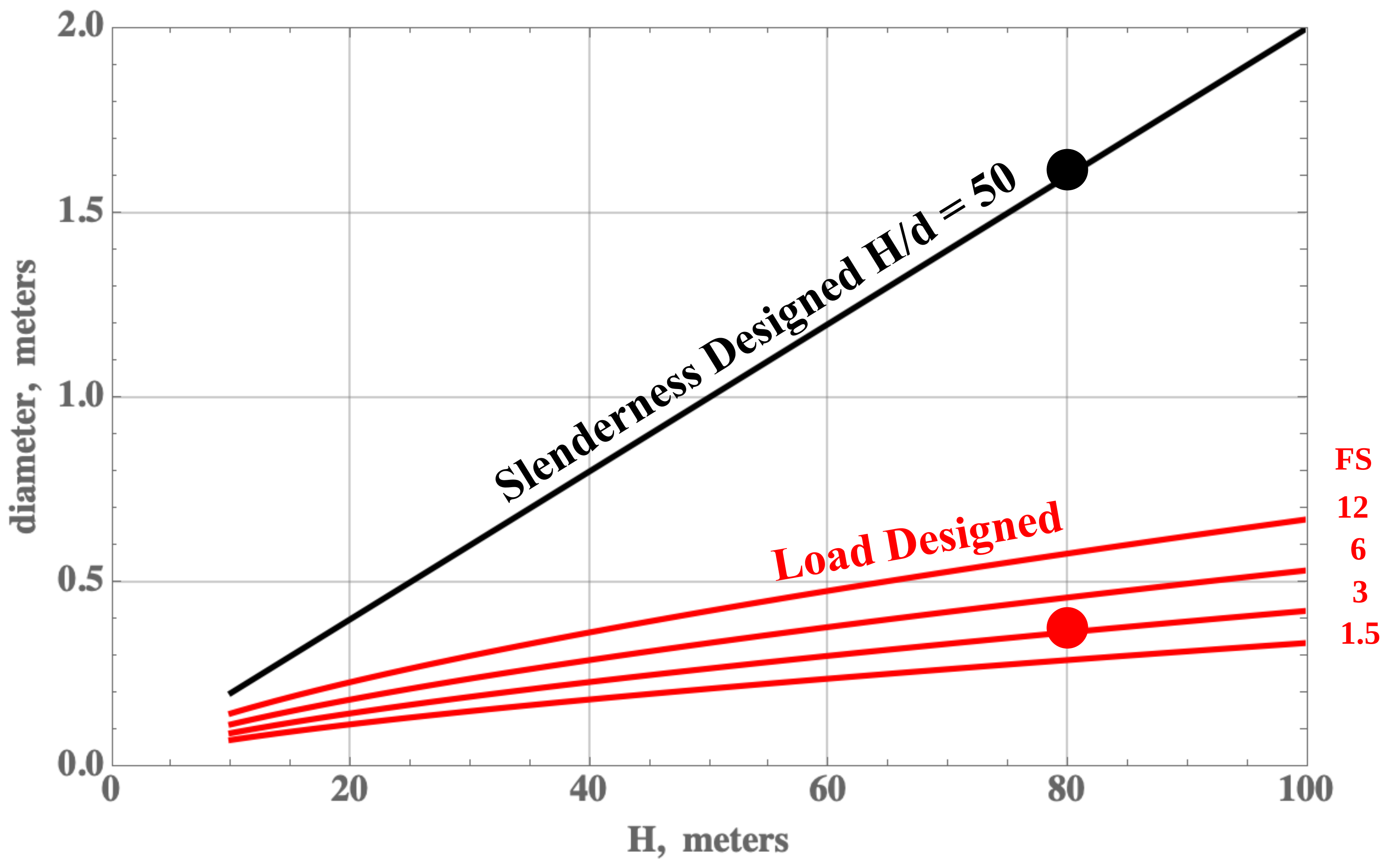


Figure 11

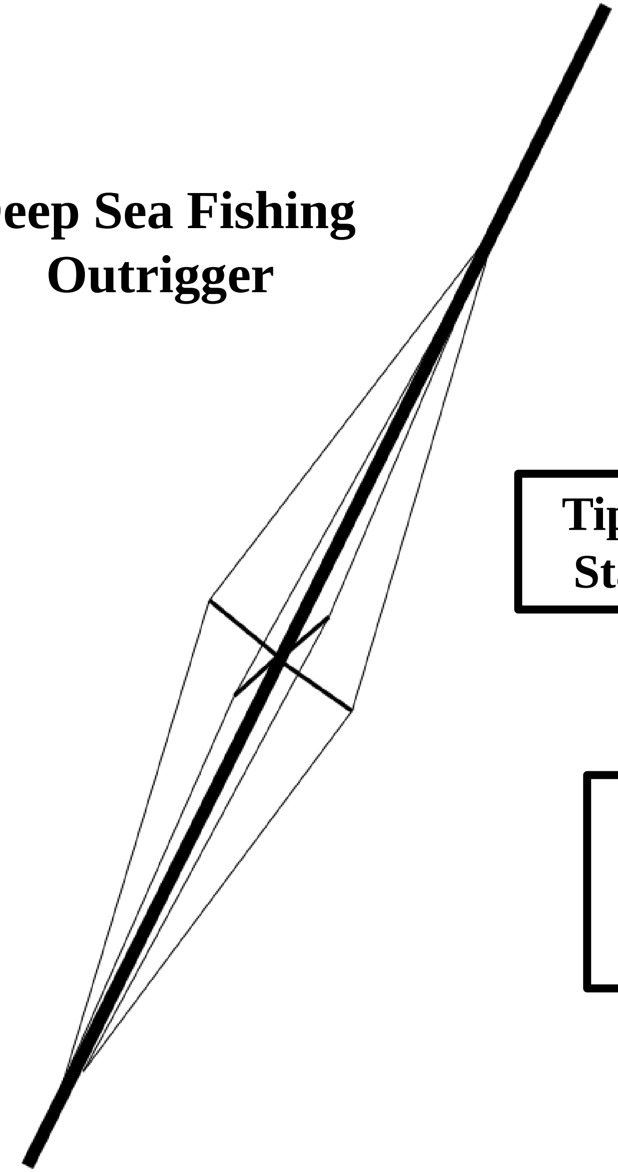
Lunar Mast Diameter as a Function of Factor of Safety

Another factor to be considered in the design of telescoping masts is to ensure that the lower most section has a large enough diameter to contain all telescoping sections. The mast diameter is plotted in Figure 11 and compared with the diameter of a slenderness designed tubular mast with an H/d = 50.

Figure 11 Text

Integrated Guys Used to Dimensionally Stabilize Slender Mast

Deep Sea Fishing Outrigger



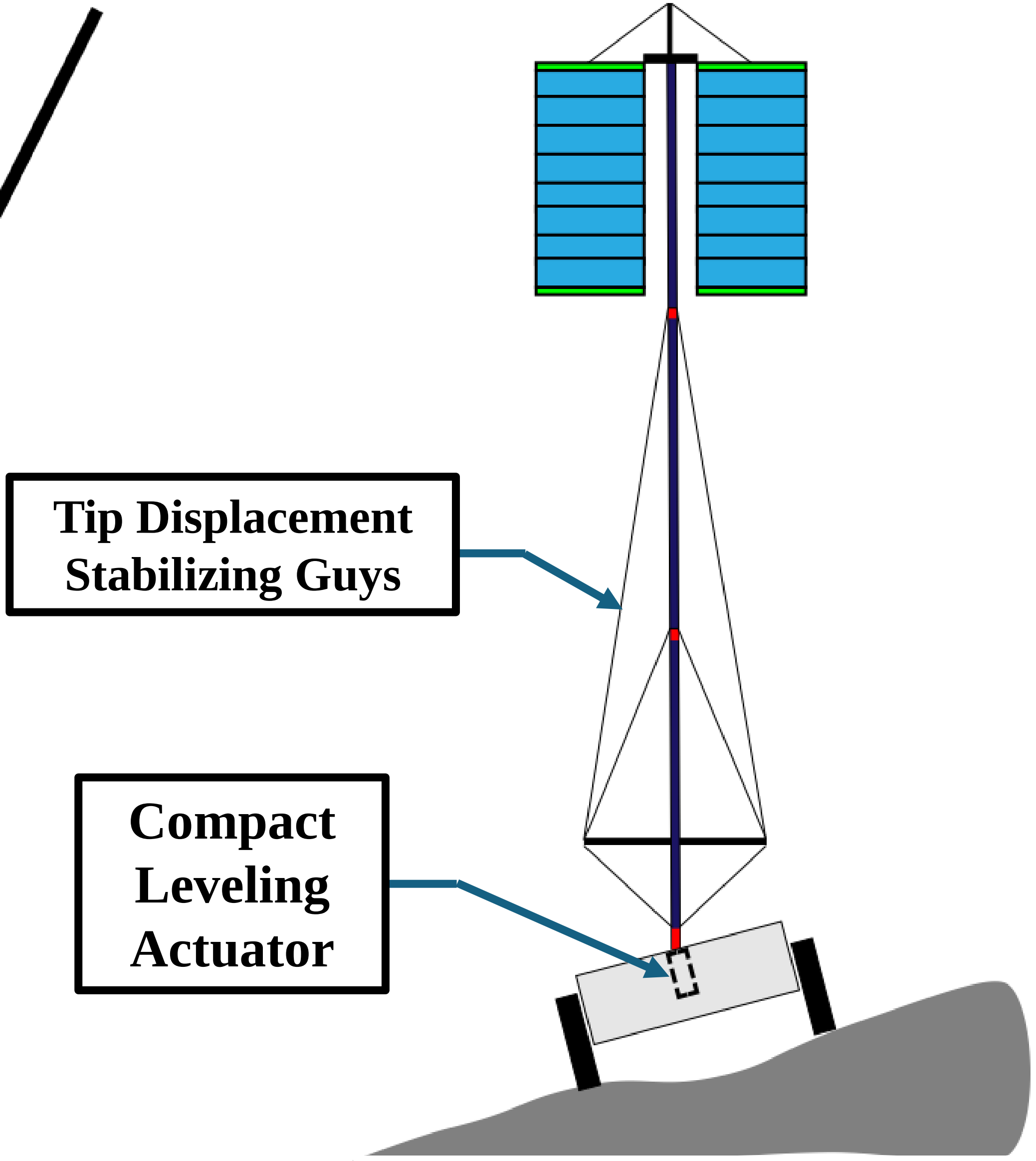


Figure 12

Integrated Guys Used to Dimensionally Stabilize Slender Mast

A second telescoping mast concept considered is shown in Figure 12. This concept makes use of integrated guys like those used on the outriggers of deep-sea fishing boats as shown on the left-hand side of the figure. The reason for using stiffening guys that converge at the base is to simplify guy tensioning and to enable a “Plug & Play” (P&P) modular solar array system. The major advantage of a P&P system is that it can be launched separately and plugged into any type of base to provide required power as well as to provide a simple approach for array replacement or upgrading. The number of guys required to stiffen the mast can be increased with increasing mast height. The other P&P enabling feature is the use an extremely compact leveling actuator as shown in the figure. This leveling actuator will be subsequently discussed in detail.

Figure 12 Text

Error Compensating Springs Used to Maintain Guy Tension

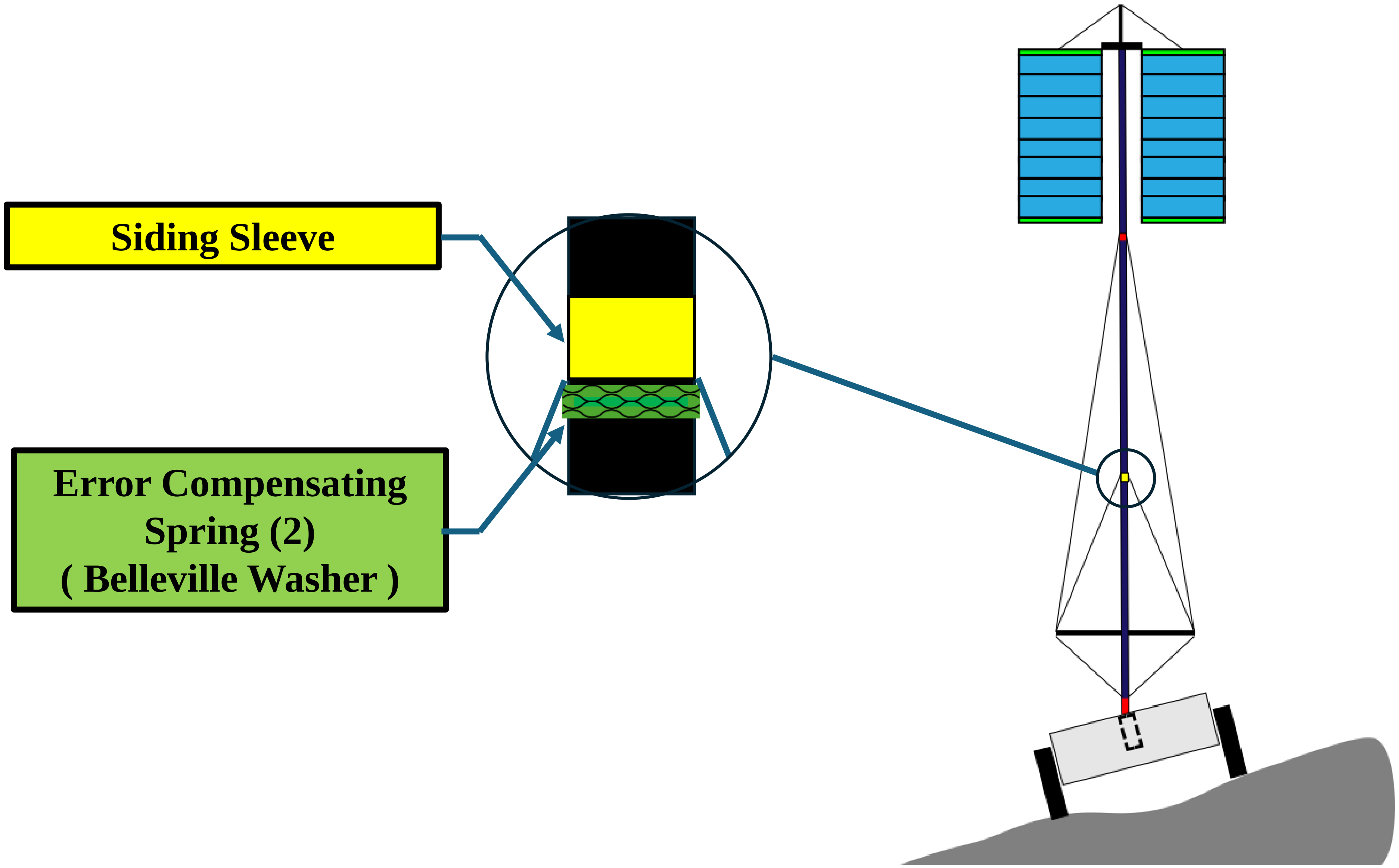


Figure 13

Error Compensating Springs Used to Maintain Guy Tension

An important feature of the P&P mast is the introduction of error compensating springs to robustly maintain the desired guy tension. This spring is notionally shown on Figure 13. The spring arrangement requires that guys are attached to a cylindrical sleeve shown in yellow that is free to slide along the tube and is forced upward by a “Belleville washer” type spring as shown in green. This spring is designed to compensate for fabrication as we as thermally induced guy dimensional errors.

Figure 13 Text

Embedded Leveling Actuator Enables P&P Capability

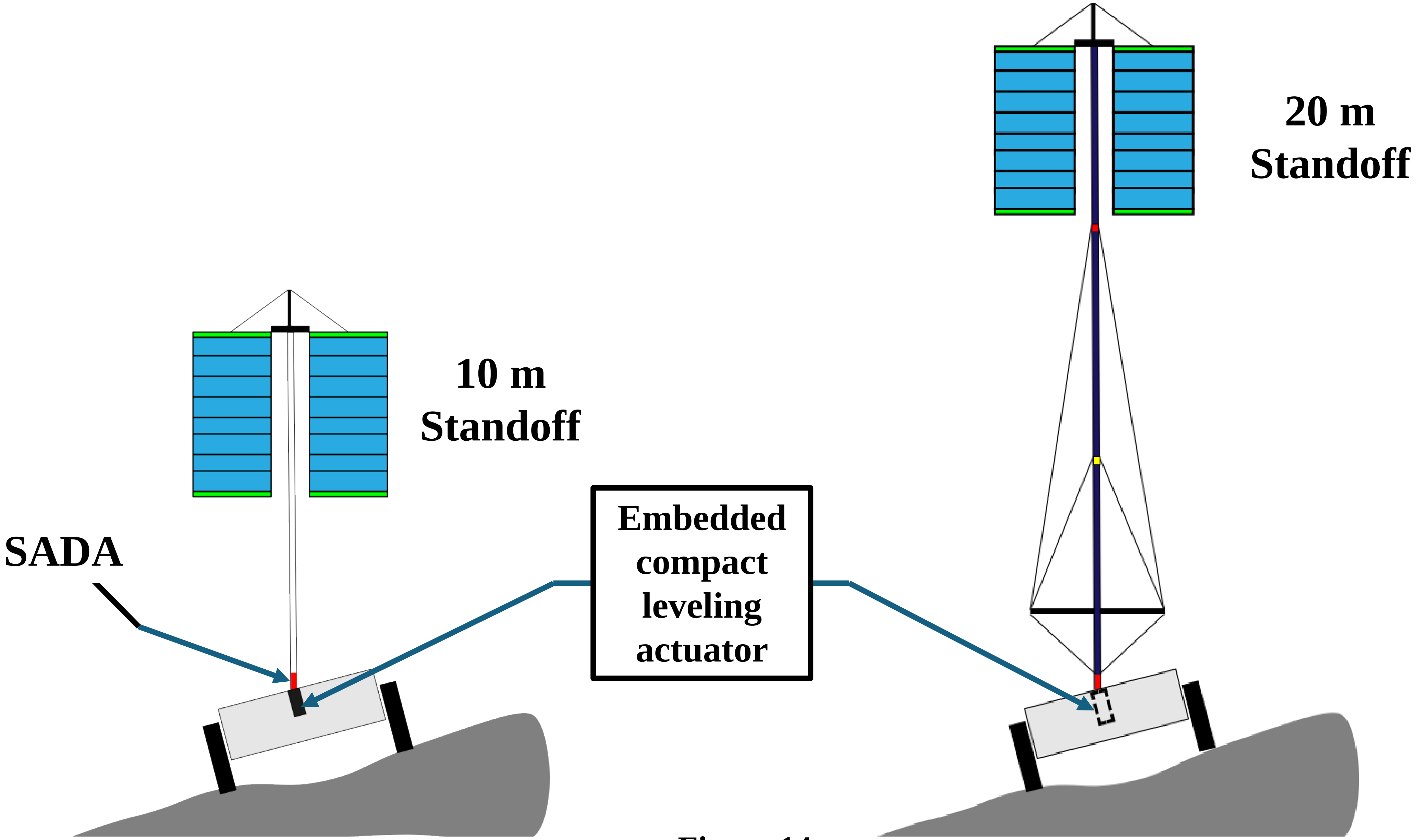


Figure 14

Embedded Leveling Actuator Enables P&P Capability

The embedded compact actuator considered is presented in Reference 5. This actuator could be used for either the unguyed array or the guyed array systems as shown in Figure 14. In addition to enabling a P&P capability, it eliminates the need for multiple leveling actuators in the selected base as well as eliminating the need for individual actuators in each guy.

Figure 14 Text

Embedded Leveling Actuator Features

Iok Wong, NASA Langley Research Center, Hampton, Virginia, VSAT Project, Reference 5

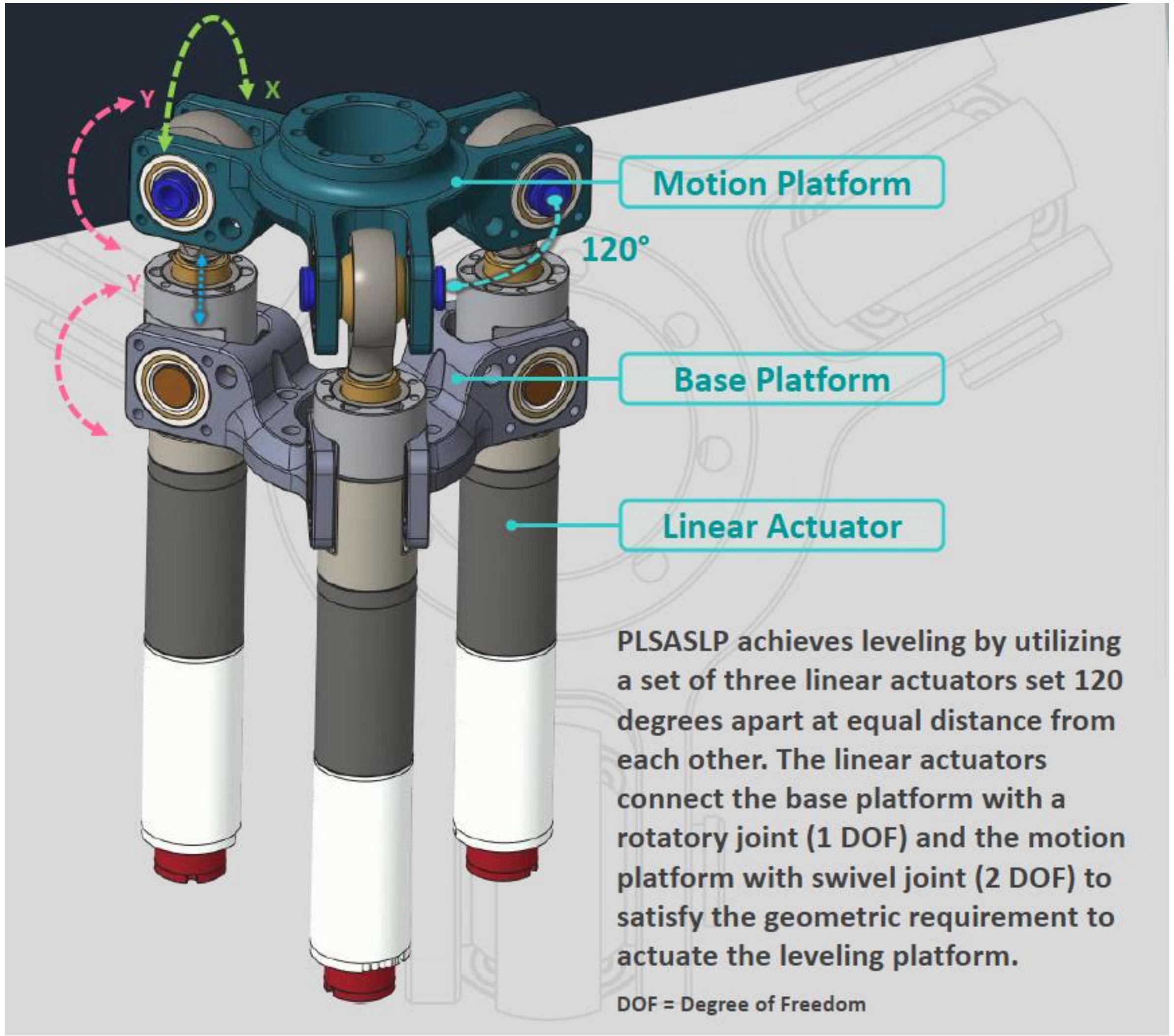


Figure 15

Embedded Leveling Actuator Features

The features of the Reference 5 compact embedded actuator are shown in Figure 15. The actuator uses 3 linear screw-jack actuators coupled with spherical bearings to provide the required leveling capability. The actuator is designed to provide a 15^{o} tilt alignment capability in a very compact form.

Figure 15 Text

(P&P) Modular Solar Arrays Versatile Launch Packaging and Applications

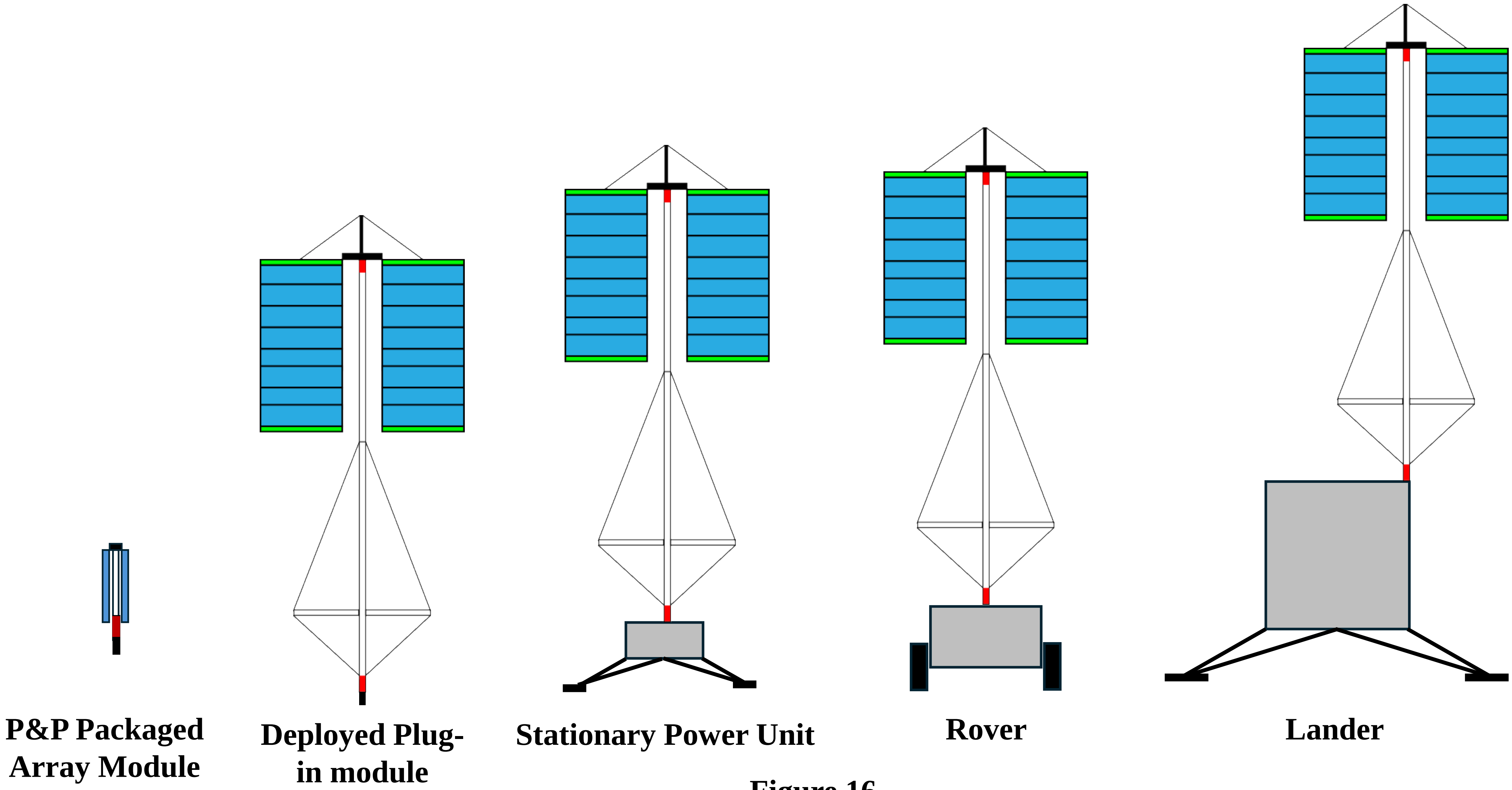


Figure 16

(P&P) Modular Solar Arrays Versatile Launch Packaging and Applications

In Figure 16 some versatile applications of Plug-and-Play (P&P) solar arrays are shown. First, since the array is P&P, the array can be stowed independent of the base providing versatile stowage, replacement, and modularity options. Next the array can be plugged into various base receivers as shown by the three right hand sketches. The array could be used with a stationary base, a rover, or could be plugged into a lander.

Figure 16 Text

Plug-and-Play (P&P) Lunar Solar Arrays Enables Modular Growth

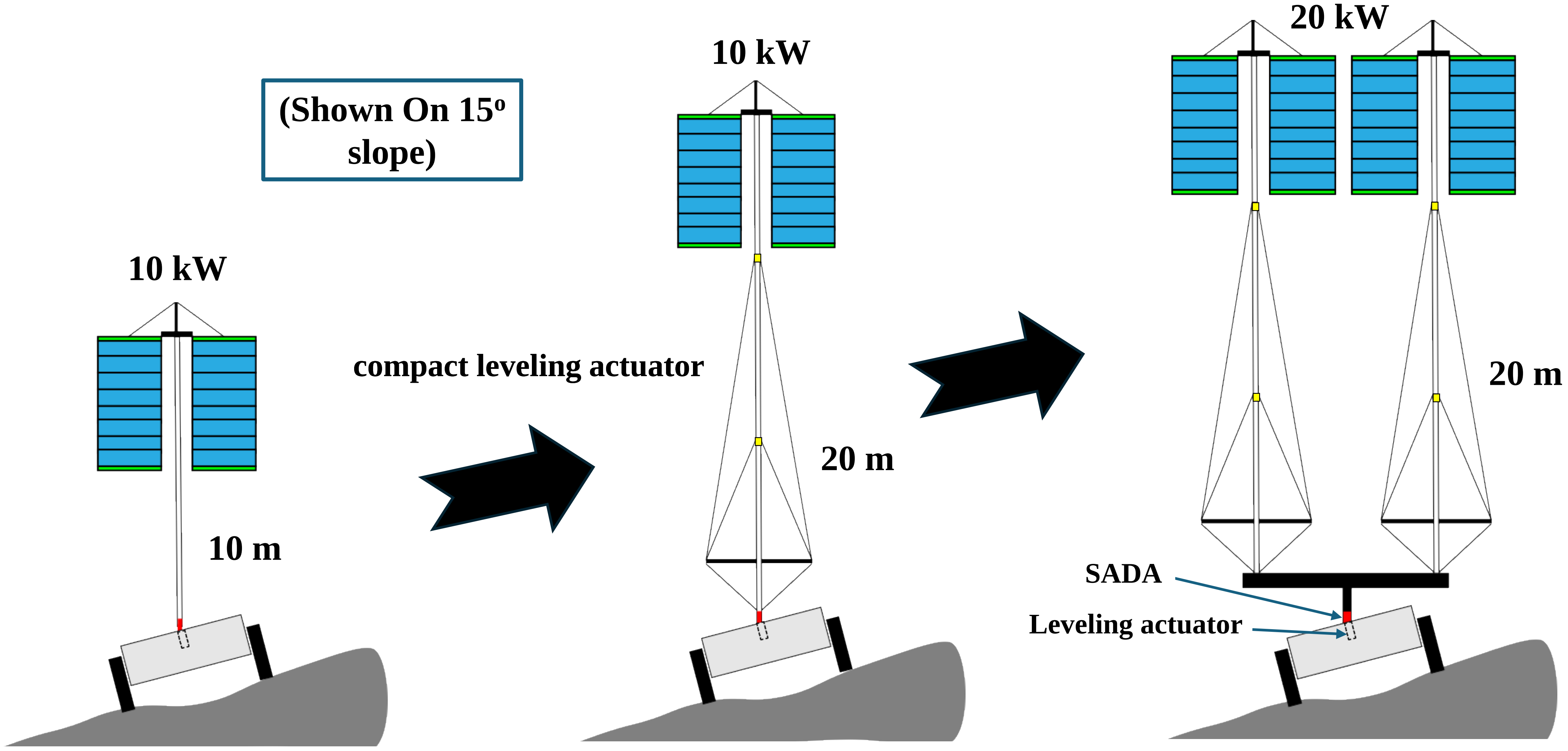


Figure 17

Plug-and-Play (P&P) Lunar Solar Arrays Enables Modular Growth

As shown in Figure 17, one compact actuator design could be used to provide leveling capability to a wide range of solar array sizes. This provides a highly modular capability that could reduce power system cost.

Figure 17 Text

Appendix A

Structural Analysis of Guy-Stiffened Mast

Appendix A. - Tip Stiffness, k, Analysis of Guy Stiffened Mast

Guy Stiffening Nomenclature

ΔBB – Deflection at B due to a load at B
ΔBC – Deflection at B due to a load at C
ΔCC – Deflection at C due to a load at C
ΔCB – Deflection at C due to a load at B. --- (Determined using Maxwell– Betti reciprocal theorem)
ΔB – Total deflection at B, (ΔB = ΔBB + ΔBC)
ΔC – Total deflection at C, (ΔC = ΔCC + ΔCB) } **(Determined using superposition**
δ1 - Axial displacement of guy member 1
δ2 - Axial displacement of guy member 2
EAG – EA of guys
F - Lateral load applied to tip of mast
h – Height of guy offset as shown in Figure A.1
Hb - h/L
H – Height of mast
k – Effective lateral spring stiffness of the tip of the mast
kUns – Tip lateral stiffness of unstiffened mast
kt – Effective lateral spring stiffness of the guys
L1, L2, θ , ϕ, - Defined in Figure A.1
L = L1+L2 – Mast stiffened length
MA – Mast root moment due to load , F, (MA = F L)
ut – Horizontal displacement at intersection of guys as shown in Figure A.1
wt - Vertical displacement at intersection of guys as shown in Figure A.1

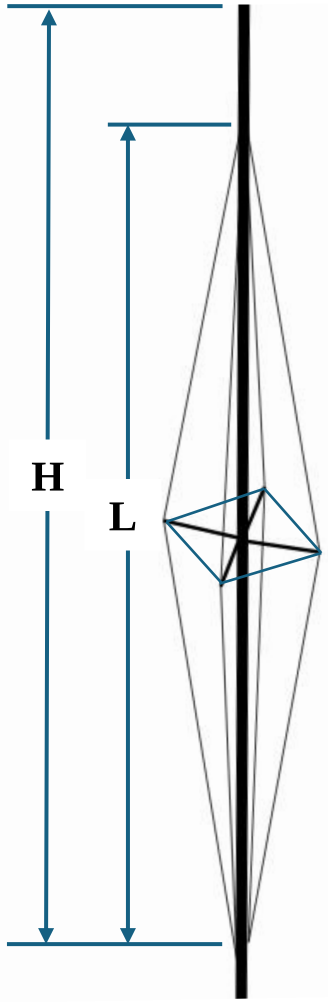
Figure A.1

Appendix A. - Effect of Outrigger Guy Tension System on Mast Tip Stiffness, k

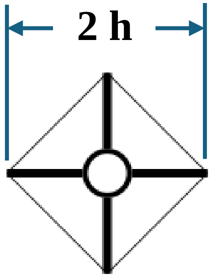
In this Appendix, an analysis is presented that enables parametric trend studies of the mast stiffening provided by the integrated guys. The nomenclature used for this analysis is shown in Figure A.1.

Figure A.1 Text

Sketches of Integrally Guy Stiffened Mast



3 or more guys provide isotropic stiffness behavior



Isometric View of a Single Set of Guys

Top View of 4 Guys

Figure A.2

Two Views of Integrally Guy Stiffened Mast

In Figure A.2, isometric and top view sketches are shown of a mast with a single set of guys. Since the guys may not extend to the full length of the mast, L denotes the stiffened length, while H is the full height of the mast. Three or more stiffeners around the central mast provide an isotropic stiffness behavior.

Figure A.2 Text

Geometry, Nomenclature, and Free Body Diagrams of Guy Stiffened Mast

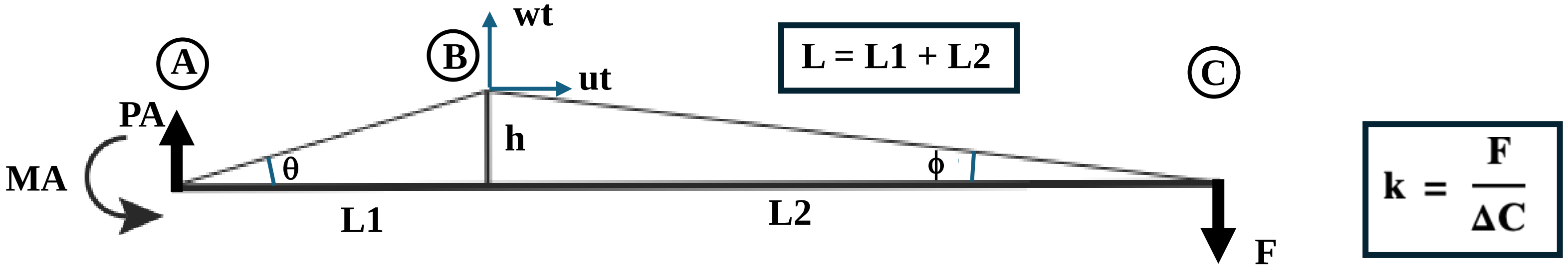


Figure A.3.a Lateral stiffness, k, of a cantilevered stiffened mast with lateral tip load, F.

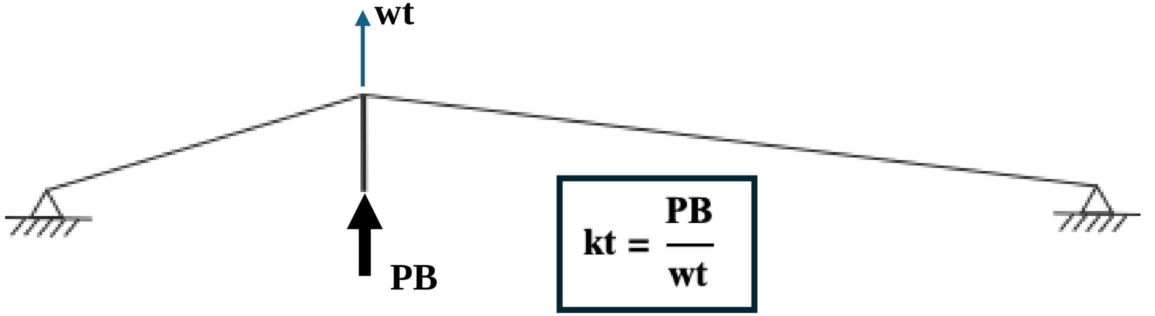


Figure A.3.b Loading applied to guys.

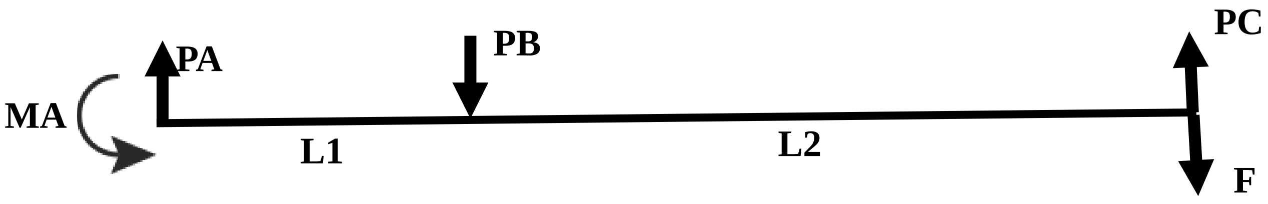


Figure A.3.c Free body diagram of loading applied to tubular mast.

Moment Equations

From $\Sigma MA = 0$ in A.3.a

$MA = F\,L$

From $\Sigma MA = 0$ Figure A.3.c

$MA - PB\,L1 - F\,L + PC\,L = 0$

Thus:

$PC = L1/L\;\;PB$

Figure A.3

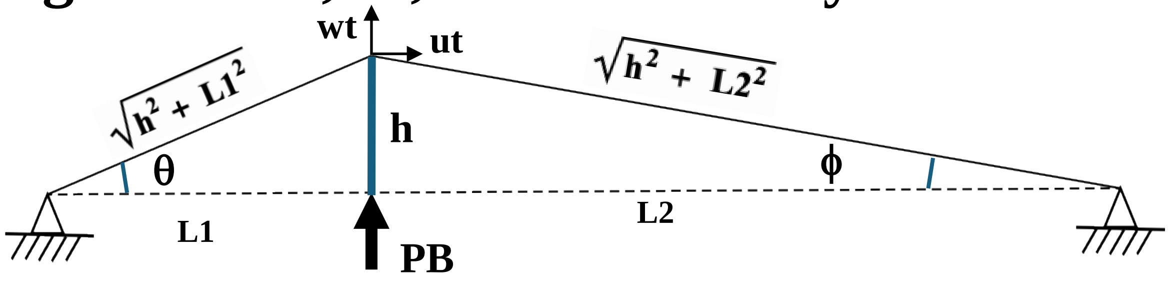
Geometry, Nomenclature, and Free Body Diagrams of Guy Stiffened Mast

The nomenclature used for this analysis is shown in Figure A.1. Since the behavior is isotropic, only one guy is analyzed, and full tip stiffness could be obtained by multiplying by a factor of 2. The mast stiffened by a single guy is shown in Figure A.3.a. A free body diagram of the loaded guy is shown in Figure A.3.b, and a free body diagram of the loaded mast is shown in Figure A.3.c.

Summation of moments around point A for Figure A.3.a and for Figure A.3.c are shown in the box labeled moment equations. Solving these two equations yields PC = L1/L PB.

Figure A.3 Text

Effective Spring Stiffness, kt, of Tension Guys in Vertical Direction



The six equations to determine δ1, δ2, wt, ut, F1, F2, are as follows:

Kinematic

$$\delta 1 = ut\ \cos\theta + wt\ \sin\theta$$

$$\delta 2 = -ut\ \cos\phi + wt\ \sin\phi$$

Equilibrium

$$F1 = \frac{PB}{1 + \frac{L2}{L1}} \frac{L2}{L1} \frac{1}{\sin\theta}$$

$$F2 = \frac{PB}{1 + \frac{L2}{L1}} \frac{1}{\sin\phi}$$

Constitutive

$$\delta 1 = F1 \frac{\sqrt{h^2 + L1^2}}{EA}$$

$$\delta 2 == F2 \frac{\sqrt{h^2 + L2^2}}{EA}$$

Where

$$\sin\theta = \frac{h}{\sqrt{h^2 + L1^2}}$$

$$\sin\phi = \frac{h}{\sqrt{h^2 + L2^2}}$$

$$\cos\theta = \frac{L1}{\sqrt{h^2 + L1^2}}$$

$$\cos\phi = \frac{L2}{\sqrt{h^2 + L2^2}}$$

And

$$kt = \frac{PB}{wt}$$

The above 6 equations are solved simultaneously to obtain the vertical stiffness of the cables, kt, as follows:

$$kt = \frac{EA\ h^2\ (L1 + L2)^2}{L1^2\ L2^2 \left(\sqrt{h^2 + L1^2} + \sqrt{h^2 + L2^2}\right) + h^2 \left(\sqrt{h^2 + L1^2}\ L2^2 + L1^2\ \sqrt{h^2 + L2^2}\right)}$$

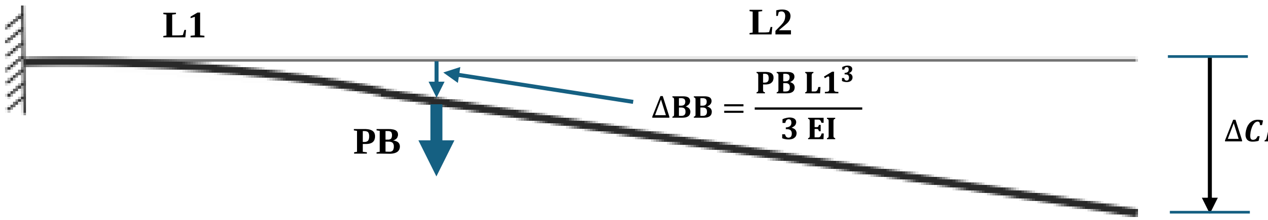
Figure A.4

Effective Spring Stiffness, kt, of Tension Guys in Vertical Direction

The tubular mast coupled with the guy stiffeners form a statically indeterminate structural system. Thus, kt must be found from a simultaneous solution of the kinematic, equilibrium, and constitutive equations. These equations are shown in Figure A.4. The resulting solution for kt is shown at the bottom of the Figure.

Figure A.4 Text

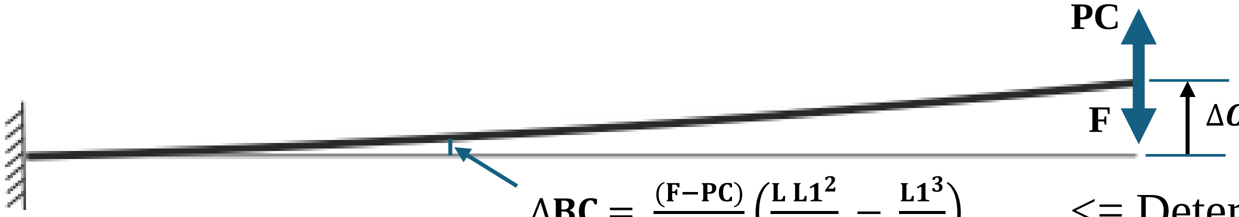
Determination of Mast Tube Deflections



$$\Delta BB = \frac{PB\,L1^3}{3\,EI}$$

$$\Delta CB = \frac{PB\,L1^3}{3\,EI} + \frac{PB\,L1^2}{2\,EI}\,L2$$

Figure A.5.a Mast deflections due to the load, PB.



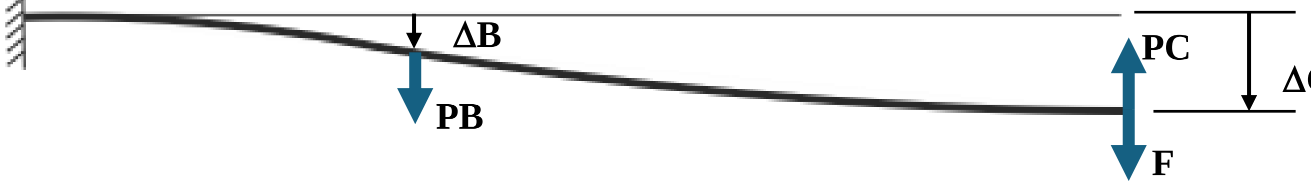
$$\Delta CC = \frac{(F - PC)\,L^3}{3\,EI}$$

$$\Delta BC = \frac{(F-PC)}{EI}\left(\frac{L\,L1^2}{2} - \frac{L1^3}{6}\right)$$

<= Determined using Maxwell-Betti Reciprocal Theorem and PC = L1/L PB

Figure A.5.b Mast deflections due to the loads, PC and F.

$$\Delta B = \Delta BB + \Delta BC = \frac{PB\,L1^3}{3\,EI} + \frac{(F-PC)}{EI}\left(\frac{L\,L1^2}{2} - \frac{L1^3}{6}\right)$$



$$\Delta C = \Delta CB + \Delta CC = \frac{PB\,L1^3}{3\,EI} + \frac{PB\,L1^2}{2\,EI}\,L2 + \frac{(F-PC)\,L^3}{3\,EI}$$

Figure A.5.c. Mast deflections due to all loads using superposition of deflections from figures A-4.a and A-4.b.

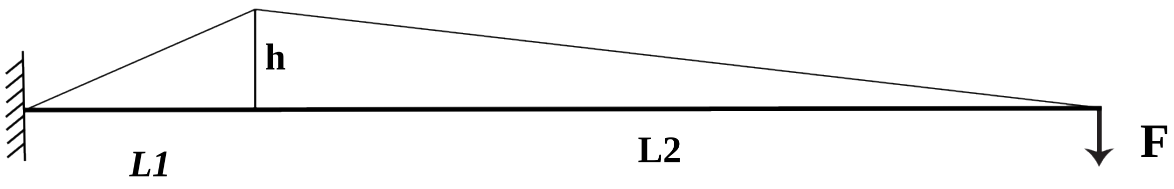
Figure A.5

Determination of Mast Tube Deflections

The deformation of the mast at point B, ΔBB, and the deflection at point C, ΔCB, due to a load at point B are shown in Figure A.5.a. The deformation of the mast at point B, ΔBC, and the deflection at point C, ΔCC, due to a load at point C are shown in Figure A.5.b. The deflection at point C was determined using Maxwell-Betti reciprocal theorem and F-PC = L1/L PB from Figure A.3.c. The total deflections at points B and C are shown in Figure A.5.c using superposition of the deformations of deformations from Figures A.5.a and A.5.b.

Figure A.5 Text

Effective Tip Lateral Spring Stiffness, k, of Guy Stiffened Mast



1. $\Delta B = \frac{PB\,(L1)^3}{3\,EI} + \frac{(F - PC)}{EI}\left(\frac{L\,L1^2}{2} - \frac{L1^3}{6}\right),$ **Defection of mast at Point B**

2. $\Delta C = PB\,\frac{(L1\,)^3}{3\,EI} + PB\,\frac{(L1)^2}{2\,EI}\,L2 + \frac{(F - PC)\,L^3}{3\,EI},$ **Defection of mast at Point C**

3. $\Delta B = \frac{L1}{L}\,\Delta C - \frac{PB}{kt},$ **Lateral deflection constraint on mast by flexible guys**

4. $PC = PB\,\frac{L1}{L},$ **Relation between PC and PB determined from equilibrium of Figure A .3.c**

5. $kt = \frac{EA\,H^2\,(L1 + L2)^2}{L1^2\,L2^2\left(\sqrt{H^2 + L1^2} + \sqrt{H^2 + L2^2}\right) + H^2\left(\sqrt{H^2 + L1^2}\,L2^2 + L1^2\,\sqrt{H^2 + L2^2}\right)},$ **Lateral stiffness of guys**

6. $k = F/\Delta C,$ **Mast tip lateral stiffness**

The lateral stiffness of the tip of the guy stiffened mast, k, is found by solving the above 6 equations simultaneously to obtain:

$$k = \frac{-EA\,Hb^2\,(-4+L1b)\,(-1+L1b)^2\,L1b^3 + 12\,EIovL^2\left((-1+L1b)^2\,L1b^2\left(\sqrt{Hb^2+(-1+L1b)^2} + \sqrt{Hb^2+L1b^2}\right) + Hb^2\left(\sqrt{Hb^2+(-1+L1b)^2}\,L1b^2 + (-1+L1b)^2\,\sqrt{Hb^2+L1b^2}\right)\right)}{\left(EA\,Hb^2\,L1b^3\left(4-3\,L1b\,(3\,(1-L1b)+2\,L1b)+L1b^2\,(3\,(1-L1b)+2\,L1b)\right) + 12\,EIovL^2\left((1-L1b)^2\,L1b^2\left(\sqrt{Hb^2+(1-L1b)^2} + \sqrt{Hb^2+L1b^2}\right) + Hb^2\left(\sqrt{Hb^2+(1-L1b)^2}\,L1b^2 + (1-L1b)^2\,\sqrt{Hb^2+L1b^2}\right)\right)\right)}$$

Figure A.6

Effective Tip Lateral Spring Stiffness, k, of Guy Stiffened Mast

The guy stiffened tubular mast shown in Figure A.6 is a statically indeterminate structural system. Accordingly, the lateral stiffness of the tip of the guy stiffened mast, k, must be found by solving the 6 equations shown in the figure simultaneously.

Figure A.6 Text

Guy Stiffened Mast Tip Stiffness Normalized WRT Unstiffened Mast

(Et = 30 msi, EG = 50 msi, t = 0.03”)

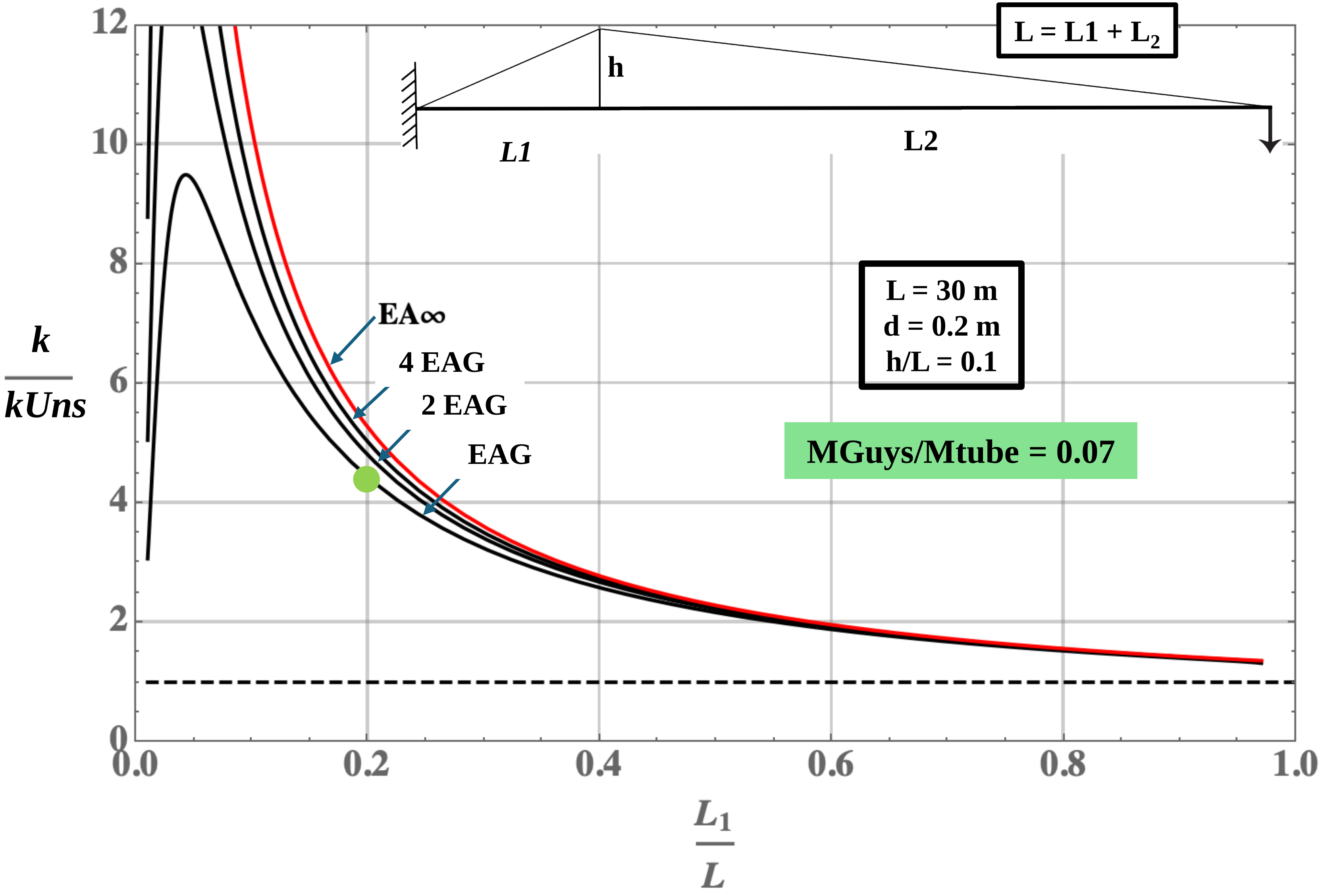


Figure A.7

Guy Stiffened Mast Tip Stiffness Normalized WRT Unstiffened Mast

To understand the general stiffening trends of the guy stiffened mast analyzed in Figure A.6, an example normalized plot of k is shown in Figure A.7 as a function of L1/L. This example plot is made for the following parameters:

Etube = 30 msi, Eguy = 50 msi, dguy = 0.14”, H = 30 meters, d = 0.25 meters, t = 0.03”, h/L = 0.1

Although Figure 7 is a point design for the above parameters, it represents a typical design trend for a tubular mast with a single set of guys. The resulting mass ratio Mguys/Mtube is 0.07 for this example. Numerous perturbations of these input parameters were conducted and verified that the design trends did not change rapidly. The major trends are that the addition of 4 guys with a mass ratio Mguys/Mtube of about 10 % provides an increase of mast tip stiffness of a factor of 4.

It should be noted that for the stiffness results shown in Figure 7, a conservative assumption was made that only one side of the guys were active in providing the stiffness, k. This assumption seems prudent until experimental results indicate otherwise. The red line in the figure is the limiting case for infinitely stiff guys. For this case tip flexibility is a result of bending of the mast central tube.

Figure A.7 Text

Appendix B

Concepts for Linear Actuation of Telescoping Masts

Appendix B. – Candidate Concepts for Linear Actuation of Telescoping Masts

Concept	Pros	Cons
➢ Synchronous approaches	Simple	Not compatible with guys
▪ Winch cable drive	Large heritage (~ 5 segments)	Large mechanical disadvantage loads
▪ Pneumatic	Simple, large Earth based heritage	No vacuum heritage
➢ Sequential approaches	Enables sequential guys	Very little heritage
▪ Stem drive	Nice heritage	Low stem actuator load capability
▪ Multiple Distributed Winches	Low cable/tape loads	No heritage
• Cable	Large heritage	Large pulleys
• Tape	Small pulleys	Little heritage
▪ Pneumatic	Simple	No vacuum heritage
▪ Internal screw drive	------------------------	No known concept
▪ External mobile screw drive	Simple mechanism	No heritage, power cables required
▪ Other?	?	?

Figure B.1

Candidate Concepts for Linear Actuation of Telescoping Masts

A major challenge in designing a tall deployable telescoping mast is the development of a reliable actuation system. Figure B.1 outlines several potential actuation approaches along with their advantages and disadvantages. The telescoping concepts can be categorized as synchronously deployable and sequentially deployable. Although by far the most prominent Earth based telescoping mast systems are synchronously deployable, this approach is not desirable for tall lunar mast applications as will be discussed subsequently.

Figure B.1 Text

Telescoping N = 4 Synchronously Deployable Cable Mast Example

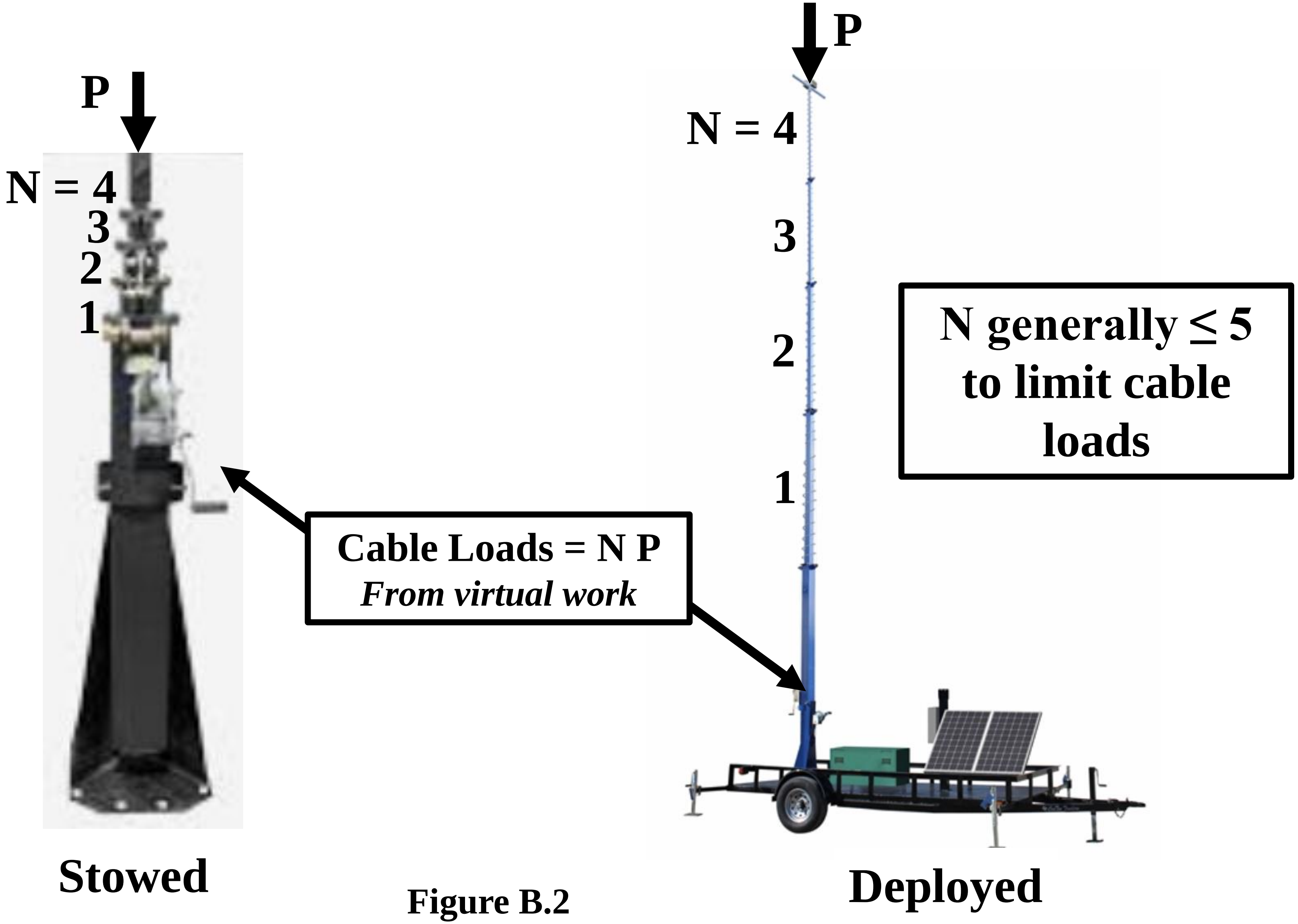


Figure B.2

Telescoping N = 4 Synchronously Deployable Cable Mast Example

On Earth, the two most common actuation systems for telescoping masts are synchronous cable and pneumatic drives. Deployment of tall telescoping masts on Earth typically involves a team of trained workers to assist in the process. Tall masts deployed on the lunar surface will probably be either autonomously deployed or assisted by a single robot. The synchronous cable drive is limited to about four or five sections because cable loads increase linearly with the number of segments, as illustrated in Figure B.2. Pneumatic actuated telescoping systems, while widely used on Earth, have yet to be demonstrated in the vacuum of space.

Figure B.2 Text

NG TTM is a Sequential Tip-Additive Construction "STAC" Mast

The Only "STAC" Concept Found & was used in deployment of Webb telescope sun shield

34-meter development article from Ref, 7

Stowed length = 2.2 meters
17 telescoping tubes
t = 0.02" to 0.04"
Diameter = 12.5" to 4.5" => H/d > 107
Mass = 58 kg

Figure B.3

NG TTM is a Sequential Tip-Additive Construction "STAC" Mast

For a guy-stiffened mast intended for autonomous deployment on the irregular lunar surface, it would be preferable for the mast to deploy the bottom section first, with each adjoining section deploying sequentially. This method enables guy wires to be progressively engaged during raising, ensuring structural stiffness throughout deployment. This construction strategy, referred to here as Sequential Tip-Additive Construction (STAC), is like how tall terrestrial masts are erected. Although STAC offers clear benefits, only one device employing this method has been developed to date; whereas all other space-deployable masts deploy the top sections first.

An example of STAC is the ASTRO Northrop Grumman (NG) telescoping tubular mast (TTM), described in References 6 and 7 and shown in Figure B.3. In the TTM, sequential deployment is driven by a long internal unfurlable STEM system. This design has proven successful, but the STEM's actuation capacity is limited to approximately 100 pounds, insufficient for applications such as deploying 50 kW solar arrays. In addition, each section of the telescoping mast must be quite short (~ 2 m) to suppress local buckling of the STEM. Such short sections would lead to an unreasonable number of sections for tall masts.

Figure B.3 Text

Multiple Winch Deployment Enables Sequential Tip-Additive Construction "STAC" Telescoping Mast With Low Tape Loads

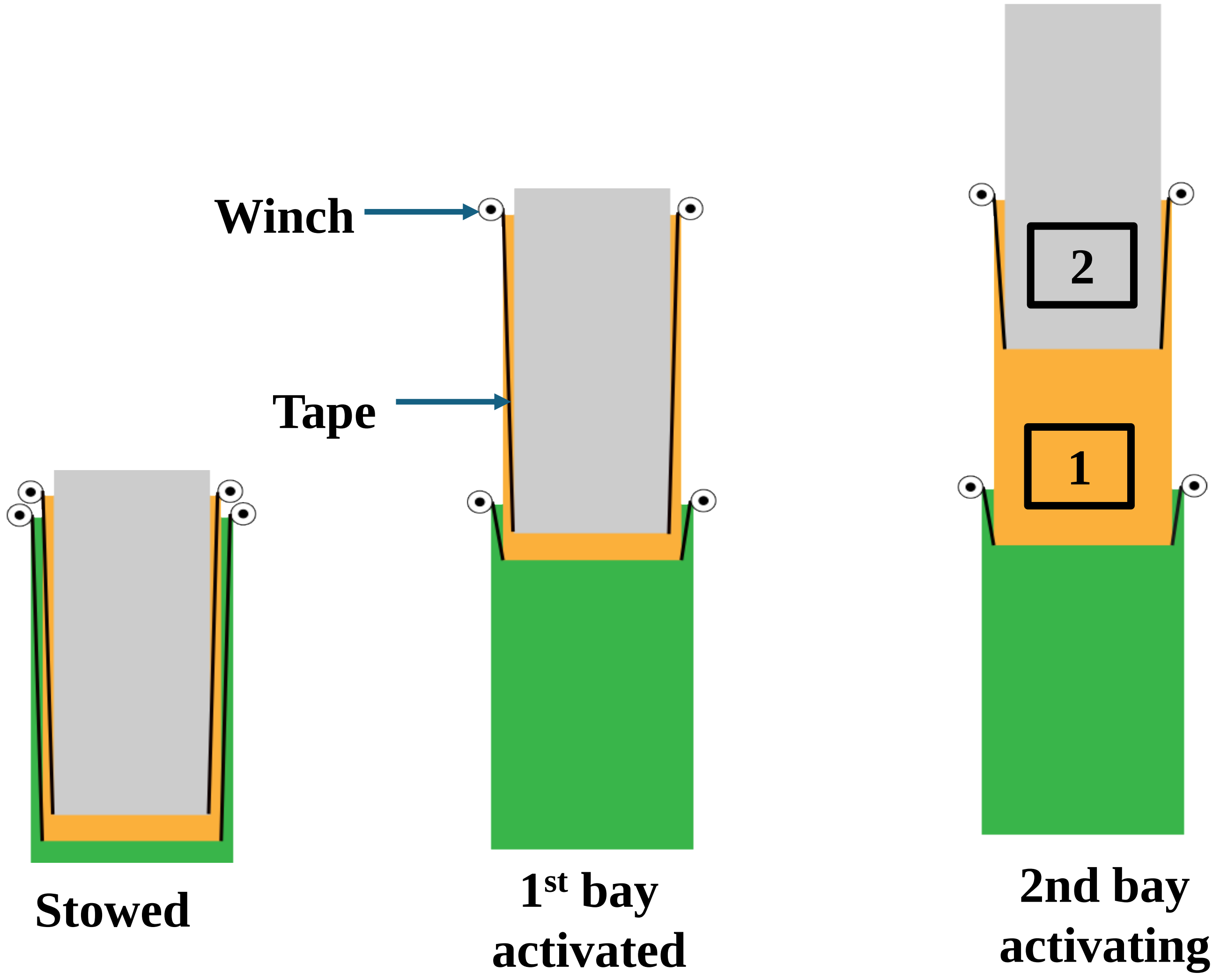


Figure B.4

Multiple Winch Deployment Enables Sequential Tip-Additive Construction "STAC" Telescoping Mast With Low Tape Loads

An alternate STAC concept involves placing winches on each mast section, as illustrated in Figure B.4. This would allow true STAC deployment while keeping individual winches small, and cable or tape loads low. Although this approach uses numerous actuators, they would offer a high degree of precision control of the telescoping sections. An additional potential benefit is by using gear motor winch drives, it would be possible to leave each deployed section under load from the cable or tape, thus, eliminating the need for a latching mechanism. In addition to simplifying mechanisms, the resulting preload could basically eliminate free-play from the telescoping joints.

Another STAC approach is pneumatic actuation. Preliminary studies show that the required pressures are low, and the amount of deployment gas is quite small. Although this approach is not yet practical because pneumatic mechanisms have not been demonstrated for vacuum environment applications, potential benefits suggest that further study is warranted.

Figure B.4 Text

Mobile Linear Actuator (MLA) Telescoping "STAC" Mast

- Concept enables taut interim guys attached to base
- Tower could be tube or truss
- Unlimited growth

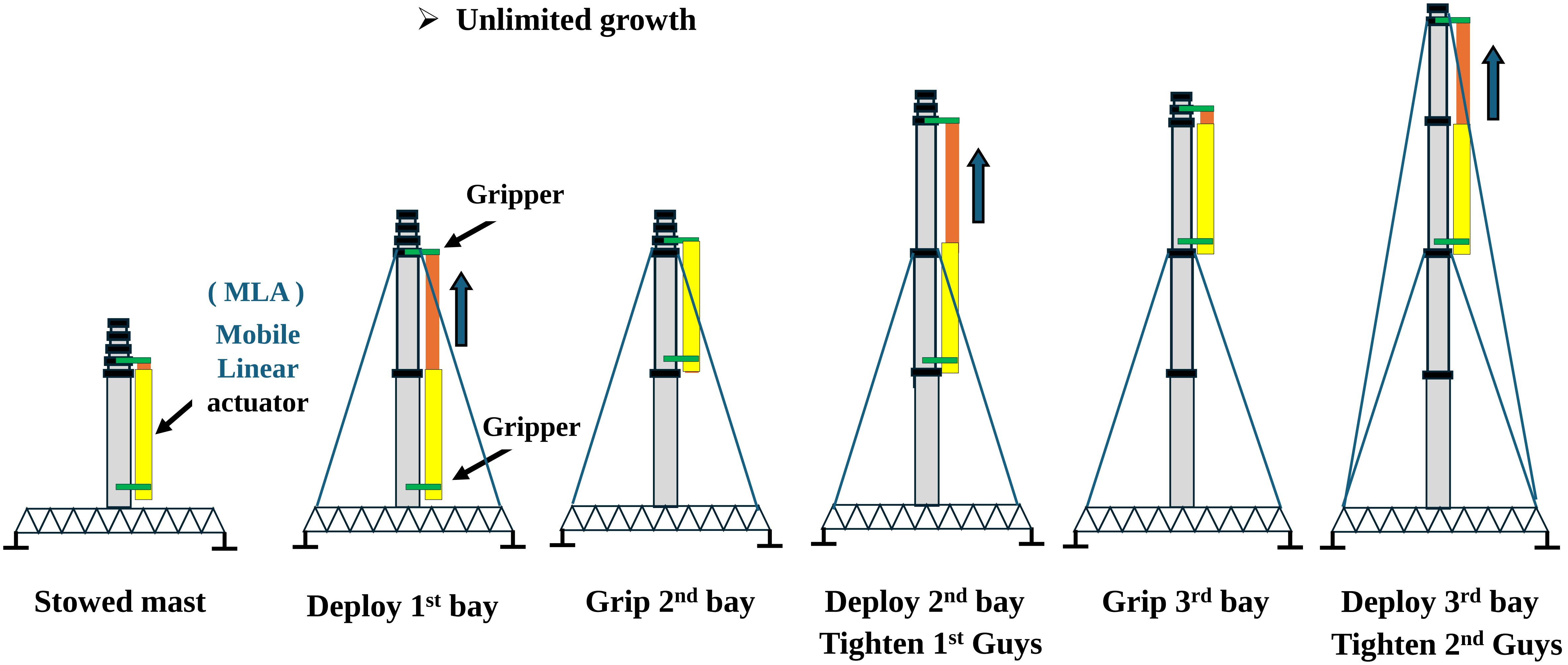


Figure B.5

Mobile Linear Actuator (MLA) Telescoping “STAC” Mast

The last option considered is to use an external robotic-style linear actuator, as shown in Figure B.5, that could sequentially extend the mast sections in a STAC approach. The concept considered is to attach an external temporary device to the packaged telescoping mast as depicted in Figure B.5. The device would be capable of pushing up the tube segments one at a time to accomplish the full deployment. This device could either be a robot that is available at the lunar base or a specific tool designed to accomplish the array deployment. It is assumed that the device has end effectors that can perform all needed grapple operations and can be also to deploy other masts. Also, the same device could be used to climb the mast for inspection, repair, and expansion. The availability of more than one of these devices at a lunar base would provide a high degree of redundancy, versatility, and reliability.

Figure B.5 Text

Tall Lunar Mast Concluding Remarks

- **Using heritage Earth-based design methods, low lunar g loads result in high slenderness ratio mast designs that are beyond the current state-of-the-art**
- **Due to the low-g loading tall lunar masts require new design methods and concepts**
- **Telescoping masts were selected for further study because they:**
  - **Eliminate bulky canister**
  - **Enable high modulus materials**
  - **Enable use of thick-wall tubes**
  - **Have efficient naturally tapered cross-section**
- **Novel Plug and Play concept proposed enables compact, modular, solar arrays**
- **Integrated guy stiffened mast concept presented to stabilize slender mast**
- **Further development required to establish feasible actuation approach for sequentially deployable telescoping mast**
- **Design strategy presented to enable future system level trade studies**

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