INTRODUCTION

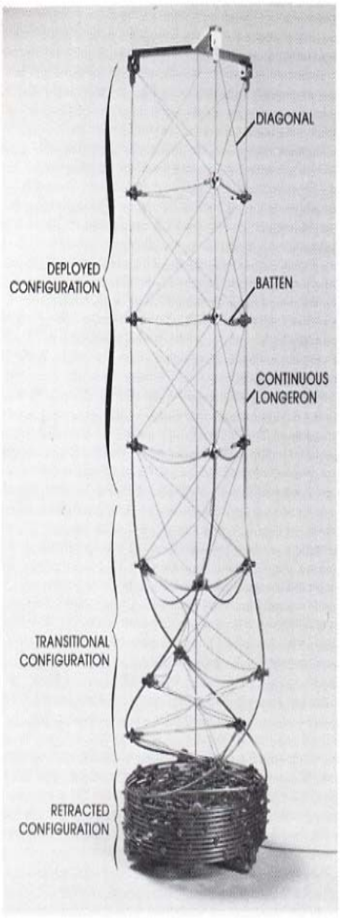

FIGURE 1
Continuous-Longeron Boom

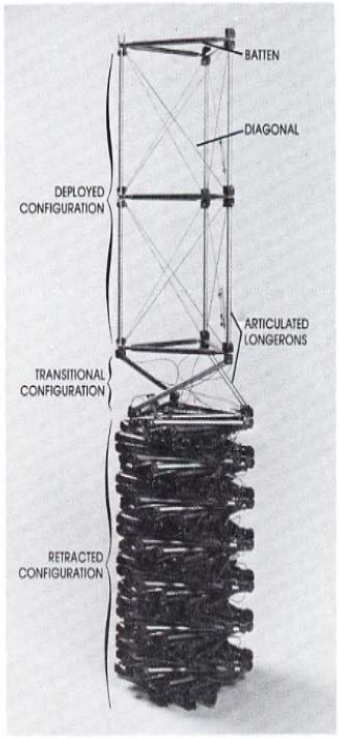

FIGURE 2
Articulated-Longeron Boom

ABLE Engineering, Inc. (ABLE) specializes in the design and manufacture of a variety of deployable lattice booms for ground, sea, air and space applications. These standard and custom-designed booms meet a broad range of structural and operational requirements. They have been made in diameters ranging from 4-40 inches and in lengths over 100 feet. These booms can be deployed either, manually, automatically or semi-automatically with high reliability and long life. When retracted, they are only a small fraction of their deployed length which, when combined with their lightweight, makes them highly portable. This paper describes and gives design information on two types of ABLE booms that are **automatically** deployed and retracted. These automated systems are especially useful in space and other hostile environments which demand stiff, strong and dimensionally stable booms that are highly portable and remotely deployable.

Typical applications for automatically deployable ABLE boom systems are to deploy and support solar-cell arrays, magnetometers, hydrophones, spectrometers, antennas, interferometers or gravity-gradient masses. Their lightweight and compact stowage volume provide the portability needed for those applications. ABLE booms are also, potentially, a very useful element for remote manipulator system in space, undersea and other unfriendly environments. Electrical conductors can be permanently attached to any of the several types of ABLE booms without impairing their capability for repeated deployment and retractions. Because of their low susceptibility to thermal distortions (see later section), ABLE booms are especially useful for applications requiring high dimensional stability in the solar radiation environment of space.

AUTOMATIC ABLE BOOMS

There are two basic types of ABLE booms. One is the “Continuous-Longeron Boom” shown in **Figure 1.** The continuous-longerons are elastically coiled when the boom is retracted. The second type is the “Articulated-Longeron Boom” shown in **Figure 2.** The corner detail of the Articulated-Longeron boom, with its extensible diagonal, permits longeron hinging for retraction and is shown in **figure 3**.

Both of these types of ABLE booms are lightweight, open lattice structures that retract into very compact cylindrical stowage volumes. The height of the stowage volume is typically 2% of the deployed boom length.

A motorized canister can be used to automatically deploy, support and retract either of these two types of booms to their partial or full lengths. **Figure 4** shows a motorized canister that was made for a 14.4-inch diameter, 105-foot long, continuous-longeron ABLE boom. The continuous-longeron boom can also self-deploy by virtue of its strain energy in its retracted configuration.

Therefore, its deployment mechanism can also consist simply of a stowage container and a payout lanyard to control its deployment rate. This “lanyard” type of deployment does not apply to the articulated boom because it cannot self-deploy.

Both types of ABLE booms and their deployment mechanism are described here along with preliminary engineering design data. Data on thermal distortions of these booms in an outer space environment are presented in a later section of this brochure.

CONTINUOUS-LONGERON ABLE BOOMS

The continuous-longeron boom is used for applications which require high dimensional stability and/or a high ratio of bending stiffness to weight. However, the stowage envelope for any particular application must be sufficiently large that the continuous longerons of the resulting boom design can be elastically coiled. The coilable boom is deployed by a canister, such as shown in **Figure 4**, when the application requires that the boom develop its full strength and stiffness at any stage of its deployment, or when the deployed portion must not rotate about the boom axis during deployment. It may be deployed by use of only a control lanyard if the application does not require the boom to have its full strength, stiffness or dimensional stability until after it is deployed to its full length. Both types of deployment mechanisms are discussed later.

Figure 1 shows the principal parts of this boom and its retraction geometry. The longerons are continuous over the boom length and are connected to the batten frames by pivot fittings. Six relatively inextensible diagonals provide shearing strength and stiffness to each bay. When the boom is twisted about its axis, tension is increased in three of the six diagonals in each bay. This causes the batton members to buckle and shorten. As twisting proceeds, the longerons rotate about their pivots and assume a helical configuration. When fully retracted, the longerons are coiled in flat helices while the batten frames stack on one another. The distortions of the boom members are always elastic. Therefore, the boom can withstand many cycles of deployment and retraction.

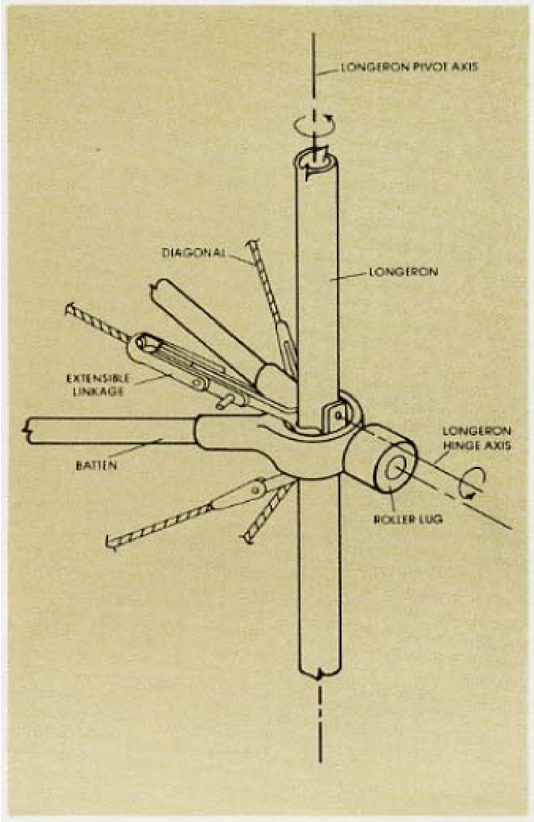

FIGURE 3
Articulated-Longeron Hinge with Cam-operated, Extensible Diagonal

The following formulas are for the more common properties of these coilable booms. They apply to booms with longerons that are solid and circular in cross section. Other cross sections may be used but the formulas must be modified accordingly. Note also that the following formulas are presented in terms of the allowable working strain ε of the longeron material because it is a critical material parameter for the coilable boom.

Bending Stiffness: $EI = 1.5\pi ER^4\varepsilon^2$

Where:

ε = maximum bending strain of longerons when completely coiled ($\varepsilon = d/2R = F/E$)

F = coiling stress of longerons
d = longeron diameter
E = Young's modulus of longeron material
R = boom radius

Shearing Stiffness: $GA = 3EA_d \sin\phi \cos^2\phi$

Where:

EA_d = extensional stiffness of one diagonal member when pretensioned to its service load

ϕ = angle between a diagonal and a batten member; typically ϕ is about 36°

Torsional Stiffness: $GJ = 0.5GAR^2$

Bending Strength: $M_{cr} = 7.44ER^3\varepsilon^4$

Note that Euler buckling of a compressed longeron limits the bending strength and that the above formula is for bending in a direction which compresses one longeron and equally tensions the other two, and for a bay length of 1.25 R. Actual bay lengths may be as low as 1.0 R.

Shearing Strength: $V_{cr} = 1.84ER^2\varepsilon^4$

Torsional Strength: $T_{cr} = 1.59ER^3\varepsilon^4$

Euler buckling of battens limits V_{cr} and T_{cr}, and in the above formulas a typical batten design is assumed; batten diameter is 0.8 times the longeron diameter.

Boom Weight: $W_B = 9\pi\rho R^2\varepsilon^2 L$

Where ρ = density of longeron material

FIGURE 4
Motorized canister for automatic deployment of booms

And L = boom length

Retracted Height: $H_B = 3 L (\varepsilon + 0.005)/\pi$

These formulas show that longeron material properties E and ε and the allowable boom radius R determine the performance that can be achieved with coilable ABLE booms. Principally, because of their high working strain, S-glass/epoxy rods with axially oriented fibers are very suitable for the longerons and battens. However, other materials can be used.

Figure 5 shows the bending stiffness, bending strength and weight versus the radius for coilable ABLE booms having solid, circular S-glass/epoxy longerons for which:

$E = 7.5 \times 10^6$ psi
$\varepsilon = 0.015$
$\rho = 0.075$ pci
Bay length = 1.25 R

The value of ε used here is a typical working strain for straight, unidirectional S-glass / epoxy rods and has resulted in highly reliable booms. Precurving the strain ε to 0.030.

By using longerons of non-circular cross section and by varying the bay length-to-radius ratio, the boom properties can be varied significantly. Therefore, the formulas and data should be used only for preliminary design purposes.

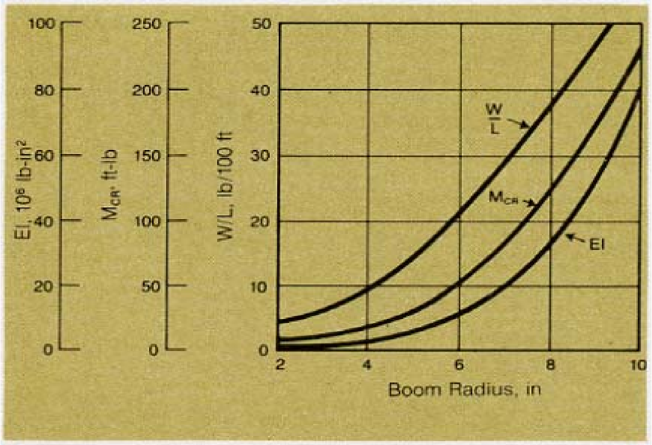

FIGURE 5
Mechanical Properties and Weights Versus Radii for S-glass/Epoxy, Continuous-Longeron ABLE Booms

ARTICULATED-LONGERON ABLE BOOMS

These systems should be used for applications which require booms of large bending stiffness or strength but for which the boom diameter is restricted; i.e., a coilable-longeron boom of a prescribed diameter may have severely limited bending stiffness and strength (as discussed earlier).

The articulated-longeron boom and its canister is shown in **Figure 2** along with a detail of its corners in **Figure 3**. The longeron, batten and diagonal members indicated in **Figure 2** comprise the principal structural components of the boom. Typically the longerons are segments of metallic or composite material tubing which are articulated at the batten frames with universal hinge fittings. Six diagonal members, typically cables, provide shearing stiffness and strength for each bay of the boom (a bay is the boom portion between adjacent batten frames). Three of the six diagonals incorporate linkages which extend when unlatched, similar to the one shown in **Figure 3**. This combination of extensible diagonals and hinged longerons permits adjacent batten frames to be rotated about the boom axis, thus collapsing the bay into the compact, retracted configuration shown in **Figure 2**. Retraction and deployment of each bay proceeds independently of the extent to which adjacent bays are deployed. Any number of bays can be interconnected to provide a boom of a desired length.

For a prescribed boom diameter and longeron material, cross-sectional dimensions can be selected to provide the necessary bending stiffness or strength. Because the longerons of this type of boom are articulated, their materials and cross-sectional dimensions are not restricted by requirements for elastic coiling. However, to insure compact retraction, the distance between their hinge points must be no greater than 0.75 times the boom diameter.

Following are formulas for the more common properties of the articulated-longeron booms:

Bending Stiffness: $EI = 1.5C_1 EA_\ell R^2$

where E = Young's modulus of longeron material
A_ℓ = Cross-sectional area of one longeron
R = boom radius measured from boom axis to longeron centerline
C_1 = a reduction factor to account for flexibilities of articulating joints; typically $C_1 = 0.75$

Shear stiffness GA and torsional stiffness GJ are as previously defined for the continuous longeron booms.

Bending Strength (minimum): $Mc_R = 1.5P_{CR}R$

where: P_{CR} = minimum strength of one longeron, whether that minimum is for Euler buckling between hinge pins, for bearing strength of joint, or for other limitations

This minimum bending strength is for one longeron loading in its weakest direction (tension or compression), and the other two longerons are each oppositely loaded to one-half the load of the critical longeron.

Shearing Strength: $V_{CR} = \sqrt{3}\, T_d \cos \phi$

where T_d = tensile strength of one diagonal

Torsional Strength: $M_T = 1.5RT_d \cos \phi$

Note that the formulas for V_{CR} and M_T are based on the assumption that diagonal strengths (rater than batten, longeron or joint strengths) are critical for pure shear or torsional loadings.

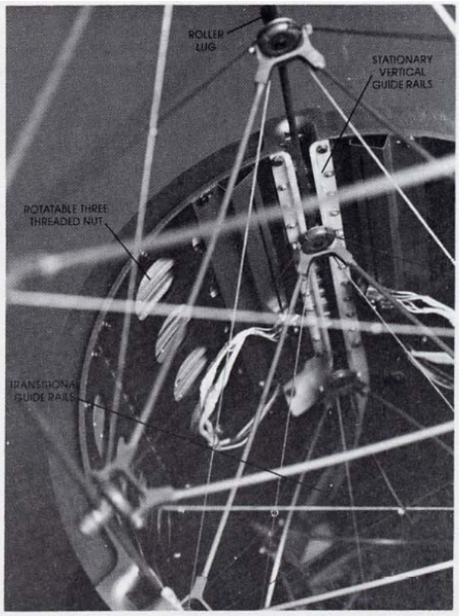

FIGURE 6
Deployment Mechanism for Continuous-or Articulated-Longeron ABLE Booms

Boom Weight: $W_B = 3C_2\rho A_\ell L$

where ρ = density of longeron material
A_ℓ = longeron cross-sectional area
L = boom length

and C_2 = an empirical coefficient, typically
C_2 = 2.5 to 3.0 for articulated booms

Retracted Height of Boom: $H_B = 0.75\, Ld/R$

where d = longeron thickness in circumferential direction

As noted earlier, automatic deployment of this type of boom is accomplished by a deployment canister, such as is shown in **Figures 4 and 6**. The principal differences between the articulated-longeron-boom canister and the one for continuous-longeron booms are in the transitional section. That is, the transition section contains cams which automatically latch and unlatch the diagonal linkages when the articulated boom deploys and retracts. Also, the transition region in the canister is somewhat shorter for the articulated boom. However, the height and weight of a canister for an articulated boom may still be estimated by the formulas presented earlier for the continuous-longeron booms.

CANISTER DEPLOYMENT MECHANISM

Figures 4 and 6 are of a canister for deploying either a continuous- or articulated- longeron ABLE boom. The retracted part of the boom stows in the stowage region indicated in **Figure 4**. Rails in the transition region guide the longerons through their transitional configurations. The deployment mechanism consists of a large, power-rotated, three-threaded nut and three pairs of stationary, vertical guide rails. **Figure 6** is a close up into the top of the canister in which some of those parts of the deployment mechanism are visible. Round roller lugs which protrude from the boom at each batten corner are engaged between the stationary guides and the threads of the nut to deploy and support the boom. When the nut is rotated by a drive motor, the boom is forced to deploy from or retract into the canister. The deployed part of the boom does not rotate in this mechanism part of the canister. Since one level of roller lugs is always engaged by the canister, the deployed portion of the boom is always supported. Therefore, the boom can be deployed to any fraction of its length and used there.

To accommodate the rotation of the stored portion of the boom, the bottom is mounted on a rotatable plate at the bottom of the canister. The height of a canister can be estimated by the formula

$$H_{can} = H_B + 3R$$

where H_B is the boom's retracted height given by the previous formula and 3R is the combined height of the transition and deployment-mechanism sections of the canister.

The canister weight can be approximated by the empirical formula

$$W_{can} = 0.04\varepsilon LR + 0.5R^2$$

where the weight is in pounds and the dimensions L (boom length) and R (boom radius) are in inches.

As can be seen from the preceding formula, the rotating-nut part of the canister becomes very heavy for booms of large radius. A lighter-weight deployment mechanism, incorporating three synchronously driven lead screws instead of the three-threaded nut, is recommended for larger-diameter canisters. The lead screws are mounted 120° apart atop the transition region of the canister, and their threads engage the boom lugs in much the same manner as do the threads of the three-threaded nut. The boom is thus forced to deploy or retract as the lead screws are synchronously rotated. The heights of canisters with lead screws is about the same as those with three-threaded nuts. However, no empirical formula has been developed for their weight.

LANYARD DEPLOYMENT MECHANISMS

When this type of mechanism is used, the boom self-deploys (as described previously) at a rate controlled by the payout rate of a restraining lanyard. This lanyard extends through the center of the boom along its axis. **Figure 7** shows this type of deployment mechanism, with the boom partially deployed. The transition region of the boom, the region between its retracted and deployed parts, propagates upward as the lanyard is payed out. The retracted part rotates as deployment proceeds. Since roller lugs are not used in the lanyard system, boom weights and outside diameters are slightly less than those for canister-deployed versions. Note that the transition region has reduced bending stiffness. Therefore, some operations are prohibited when the boom is partially deployed.

The lanyard is usually a metallic or fibrous tape and is wound on a reel. Lanyard payout rate is controlled, typically, by a viscous damper or an electric motor. When an electric motor is used, the boom can be retracted by reeling in the lanyard. The boom is twisted to initiate retraction by means of a bridle incorporated in the outboard end of the lanyard.

When the longerons are solid circular rods, the nominal self-deployment force P developed by the coilable ABLE boom is: $P = 1.178E\,\varepsilon^4 R^2$

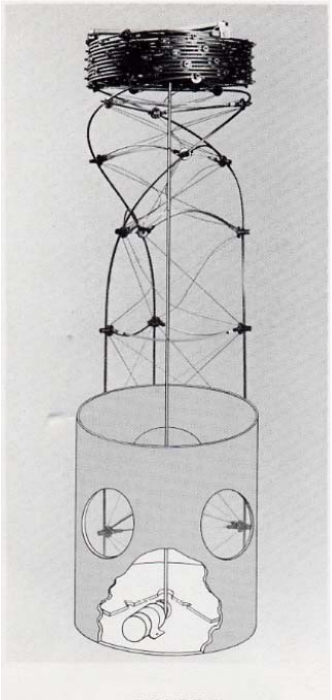

FIGURE 7
Lanyard Deployed
Continuous-Longeron Boom

Because the lanyard mechanism and stowage container design can vary widely, depending on the application's specific requirements, their weights are not standardized. However, the lanyard mechanism and containers generally weigh much less than the canisters described previously, and the stowage volume is smaller in both length and diameter.

THERMAL DISTORTIONS OF ABLE BOOMS

Because all types of ABLE booms can be made so that they undergo very little thermal twisting or bending in the environment of solar radiation, ABLE booms are especially useful for space applications that require high dimensional stability. To meet some requirements, ABLE booms are fabricated with a uniform rate of pretwist over their length. The pretwist is used primarily to preclude thermal twisting, as explained later, but it also precludes the excessive thermal bending that would occur if one longeron shadowed another. Thermal distortions of ABLE booms are also minimized by careful selection of materials.

If sun rays are parallel with one set of diagonals of an initially straight lattice boom, then that set of diagonals would have a significantly lower temperature than the intersecting set which are nearly perpendicular to the rays. Shear distortions would result in the panels surrounding those intersecting diagonals and those distortions would lead to both shearing and twisting of the overall boom. The rate of thermal twisting β′ for a boom segment has been determined[*] to be

$$\beta' = \frac{aT_oF}{3R \sin\phi \cos\phi}$$

where

a = coefficient of linear expansion for the diagonal material
T_o = diagonal temperature when oriented perpendicular to sun rays
F = a factor dependent on the orientation of the boom relative to sun rays
R = boom radius
ϕ = angle between diagonals and battens

The factor F varies cyclically with the sun's azimuth angle (angular position of radial components of sun rays). The period of F is 120° and the integral of F over the period is zero. Therefore, to nullify thermal twisting, some lattice booms are manufactured with pretwist over their length equal to an integer multiple of 120°. The result is a greatly reduced net thermal twist between the base and tip of the boom. For instance, for boom with fiberglass-rod diagonals, **Figure 8** shows the maximum possible thermal twist β_L versus length-to-radius ratio and various pretwists. **Figure 8** illustrates that β_L is very large when no pretwist is used, and that β_L, though small for pretwisted booms, increases as the ratio of boom length to boom radius increases. Note that boom bending stiffness and strength are not significantly reduced by pretwists resulting in longeron helix angles as large as 10°.

The data in Figure 8 excludes an additional source of thermal twisting that is possible for pretwisted booms. If there is a difference between the average thermal strains of the longerons and diagonals, then an additional uniform twisting or untwisting $\Delta\beta_L$ occurs:

$$\Delta\beta_L = \frac{2}{3}\left(\frac{\ell}{R}\right)^2 (\varepsilon_d - \varepsilon_l)\beta_o$$

where

ℓ = bay length
R = boom radius
ε_d = diagonal thermal strain
ε_l = longeron thermal strain
β_o = initial pretwist of total boom length

This effect is seen to be absent if $\beta_o = 0$. The effect is generally quite small when longerons and diagonals are made of materials (e.g. fiberglass rods) with low coefficients of thermal expansion and with surface properties which do not permit excessive heating. As an example, consider an ABLE boom with fiberglass longerons and diagonals ($a = 1.75 \times 10^{-6}$/°R), with an average temperature difference of 300°R between those members, and with a pretwist of 240° and ℓ/R = 1.25. Then $\Delta\beta_L$ = 0.131°.

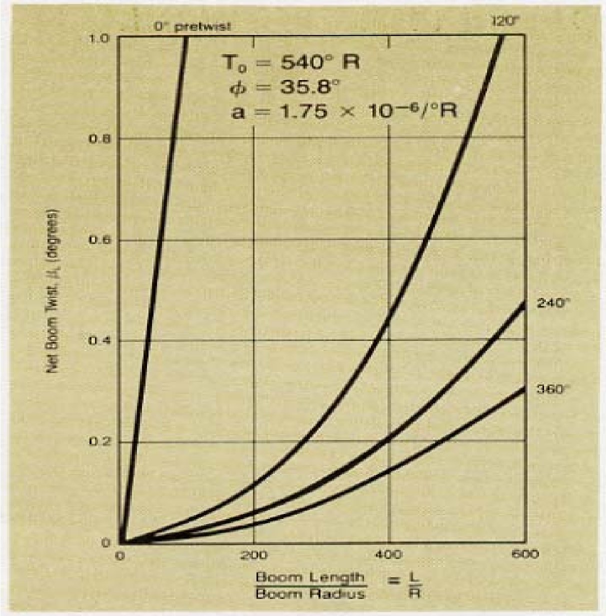

FIGURE 8
Net Thermal Twist Between Ends of ABLE Booms with Fiberglass Diagonals; Worst Sun Orientation and Various Amounts of Pretwist

Formulations also have been made for predicting thermal shearing distortions of ABLE booms, but they have not been integrated and otherwise evaluated to provide general parametric data. However, as a single-point example, the thermal-shear deflection of the tip of a 62-foot-long cantilevered boom with 120° pretwist and fiberglass diagonals was calculated to be about 0.2 inches. It is noted that shear deflections are independent of both radius and longeron thermal strains.

Also underdeveloped, are parametric data for thermal bending due to mutual shadowing among the parts of ABLE booms. However, consider the boom in the previous example. Assume its radius is 4 inches and its fiberglass longeron, batten and diagonal diameters are respectively 0.120, 0.100 and 0.032 inches. The tip deflection due to thermal bending is calculated to be 1.20 inches and the corresponding tip slope is 0.095º.

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[*] IBM Corporation: Development of a Microwave Interferometer Position Locator. NASA CR-1112188, August 1973.

All the thermal distortions in the above examples could be reduced even further by using, for instance, carbon/epoxy longerons and diagonals for which $a < 0.5 \times 10^{-6}/^{\circ}R$.

The above formulae and trends for thermal distortions apply to both articulated- and continuous- longeron ABLE booms. Either type can be uniformly pretwisted by simply making all intersecting diagonals of the same unequal lengths.

ABLE MEETS YOUR REQUIREMENTS

ABLE personnel have broad experience in engineering, manufacturing and testing these types of booms for a great diversity of applications under U.S. government contracts. This comprehensive experience will insure that the ABLE booms you receive are properly designed, manufactured and proof-tested to meet your most stringent requirements and specifications.

Because the specifications of particular applications usually dominate the design and price of automatic ABLE boom systems, no standardized price-listed systems are offered. However, upon your request, ABLE will provide preliminary design data and prices for systems to meet your requirements.