RESEARCH BULLETIN 47
SEPTEMBER 1984

BALLOON LOGGING WITH THE PENDULUM-SWING SYSTEM: FACTORS AFFECTING LIFT

ELDON D. OLSEN
BRIAN L. TUOR
MARVIN R. PYLES

FOREST RESEARCH LAB

COLLEGE OF FORESTRY
OREGON STATE UNIVERSITY

The Forest Research Laboratory of Oregon State University was established by the Oregon Legislature to conduct research leading to expanded forest yields, increased use of forest products, and accelerated economic development of the State. Its scientists conduct this research in laboratories and forests administered by the University and cooperating agencies and industries throughout Oregon. Research results are made available to potential users through the University's educational programs and through Laboratory publications such as this, which are directed as appropriate to forest landowners and managers, manufacturers and users of forest products, leaders of government and industry, the scientific community, and the general public.

As a research bulletin, this publication is one of a series that comprehensively and in detail discusses a long complex study or summarizes available information on a topic.

The Authors

Eldon D. Olsen is associate professor, Brian L. Tuor is instructor, and Marvin R. Pyles is assistant professor in the Department of Forest Engineering, College of Forestry, Oregon State University, Corvallis.

Disclaimer

To Order Copies:

Copies of this and other Forest Research Laboratory publications are available from:

Forestry Business Office
College of Forestry
Oregon State University
Corvallis, Oregon 97331

Please include author(s), title, and publication number if known.

BALLOON LOGGING WITH THE PENDULUM-SWING SYSTEM: FACTORS AFFECTING LIFT

ELDON D. OLSEN
BRIAN L. TUOR
MARVIN R. PYLES

CONTENTS

INTRODUCTION

This Bulletin discusses the various factors affecting load capacity when a tethered (moored) balloon is used for logging. Such a system is now in the prototype stage. In this new system, lift for the load of logs is provided by the balloon and the load is swung to the landing in a pendulum-like movement. The pendulum-swing system differs from conventional balloon systems in which the load is always suspended directly under the balloon.

Both balloon systems are designed for logging in mountainous areas with few roads. Balloon systems can operate over longer yarding distances (1,500 feet or more) and on steeper slopes (40 percent or greater) than can most ground-based and cable systems, although costs per thousand board feet are higher. Other advantages of balloon logging include:

1. Reduction in land area lost to roads and, hence, in road construction costs;
2. Minimization of soil disturbance and subsequent erosion because logs are fully suspended, rather than dragged on the ground;
3. Reduction of log breakage during yarding; and
4. Increased ability to harvest isolated patches of windthrown and insect-infested timber.

The advantages claimed for the pendulum-swing over the conventional balloon system are that the balloon is more stable, the yarding cycle is faster, the running lines are smaller, and the horsepower required is less. The disadvantages are that the pendulum-swing system requires a larger balloon to achieve equivalent payloads and that the system is more complex to set up.

Load or lifting capacity in such a system is affected not only by the balloon itself but also by the tensions occurring in the lines that tether it and move the carriage from which the logs are suspended. These factors can only be grasped by understanding how the pendulum-swing system operates and how it is rigged.

PENDULUM-SWING BALLOON SYSTEM

The pendulum-swing balloon system is illustrated in Figure 1. It was originally proposed by J. L. Bell[1] in 1974 as an alternative to other balloon logging systems then in use. Major components proposed by Bell were a natural-shaped balloon with a capacity of 1.1 million cubic feet, three or more guylines, and a conventional yarder (power source for line-spooling drums) with a 50-ft tower.

The helium-filled balloon is held in a relatively fixed position 1,000 to 1,500 ft above the ground by means of three or more guylines, at least one of which is attached to a winch capable of spooling the entire length of the guyline. This winch allows the balloon to be repositioned by changing the guyline length. The remaining guylines are anchored to stumps or other suitable objects on or near the perimeter of the harvesting unit. Tower height is not critical provided that the lines spool properly during yarding. Downhill yarding is preferred because of the assistance provided by gravity in swinging the load.

Engineering analysis (Tuor 1983) shows that the pendulum-swing system with inverted Tyler rigging (Figure 1 inset) behaves similarly to a carriage suspended from a single line attached to a balloon-mounted winch. The Tyler system is preferred to the originally proposed suspended winch because the former is lighter and is powered from the yarder. The lift or pendulum line, which is anchored at one end and spooled onto a yarder drum at the other, passes through the carriage and over the balloon sheave (a pulley suspended beneath the balloon). The pendulum line transfers the balloon lift to the load as the carriage travels down that line in what appears to the observer as a pendulum-swing movement with the balloon as the pivot. Carriage position can be raised or lowered by changing the length of the pendulum line. The carriage is moved back and forth by the main and haulback lines, both of which are attached to the carriage at one end and spooled onto yarder drums at the other. The haulback line is directed back toward the yarder by means of fixed corner blocks. Loads are suspended from the carriage by chokers.

---

[1] U.S. Pat. No. 3807577.

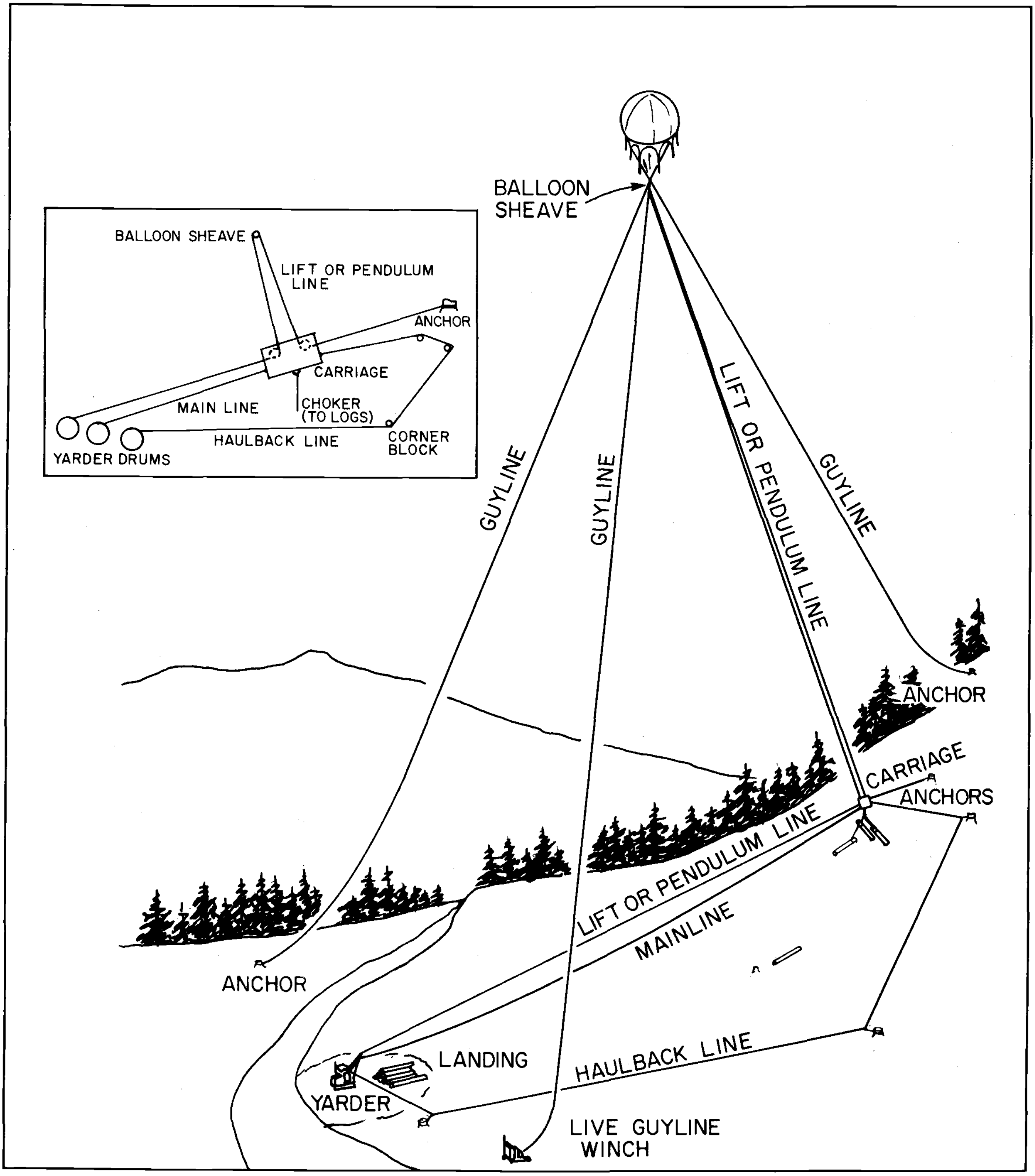

FIGURE 1.

PENDULUM-SWING BALLOON LOGGING SYSTEM. INSET--INVERTED TYLER RIGGING.

TYPICAL YARDING SCHEDULE

How the system works can best be demonstrated by describing a typical yarding sequence. At the beginning of the cycle, the carriage is at the landing. The yarder operator begins by shortening the pendulum line. Since this line is anchored at the end and suspended from the balloon sheave, the carriage is raised into the air. Simultaneous spooling-in of the haulback line and spooling-out of the main line takes the carriage away from the landing toward the point of load pickup. When the carriage reaches the point where a load is to be attached, the foreman or rigging slinger signals the yarder operator to stop outhaul and lower the carriage to the ground by lengthening the pendulum line. The main and haulback lines may also have to be adjusted to place the carriage properly. After attaching the logs to the chokers, the foreman or rigging slinger signals the yarder operator to lift the turn free of the ground by shortening the pendulum line. As soon as the turn is sufficiently clear of the ground, the yarder operator begins spooling-in the main line and spooling-out the haulback line so that the turn swings toward the landing in a safe and controlled manner. As the turn approaches the landing, the operator slackens both the haulback and the pendulum lines and allows the turn to come into the landing area as in a conventional highlead or skyline operation. The turn is then unhooked and the carriage sent back out to the woods to begin another cycle.

FACTORS AFFECTING LIFT

Lift is the vertical force that can be applied to the logs and carriage at a point directly over the logs. The load-lifting capability of a conventional balloon system is relatively easy to establish because the load is always suspended directly under the balloon. Thus, the load that can be lifted from the ground equals the available lift at the base of the balloon less any tensions exerted by the main and haulback lines.

Determining the load-lifting capability of the pendulum-swing system, on the other hand, is more complex. In this system, the lift or pendulum line not only supports the load but also interacts with the other lines. Thus, the pendulum line tension is either greater or less than the load lift, depending on the interaction of the haulback and main lines. The haulback line, unlike the main line, usually assists the pendulum line in supporting the load. In general, the load lift is greater than the pendulum line tension whenever the load is upslope near the top of the setting, but the reverse tends to be true when the load is downslope near the landing. Whenever the combined upward force of all the line tensions is equal to or greater than the load weight, the load will be suspended in the air.

The following factors each have a major influence on the load that can be lifted:

1. Balloon position in the air in relation to load position on the ground;
2. Weight of the guylines and pendulum line;
3. Guyline angles in relation to angle of pendulum line;
4. Dynamic effect of load swinging;
5. Static and dynamic effects of wind forces;
6. Effect of operating lines (main and haulback) in either assisting or counteracting the pendulum line lift.

Each of these factors will be discussed in detail in the following subsections. The discussion will be drawn from four studies conducted by the Department of Forest Engineering at Oregon State University: Beary (1983), Ammeson (1984), Avery (1984), and Tuor (1984).

Comprehension of the discussion requires an understanding of the coordinates used to analyze the pendulum-swing system. These coordinates are from Avery's (1984) computer model for calculating lift potential beneath the balloon and are illustrated in Figure 2. X refers to the distance in feet from the left edge of the setting at guyline anchor 1. Y refers to the horizontal distance from the truck road. Z refers to the vertical elevation above the truck road. In Figure 2, the X coordinate for the landing is halfway between guyline anchors 1 and 2. Note that the lowest value used in the model is 10 ft.

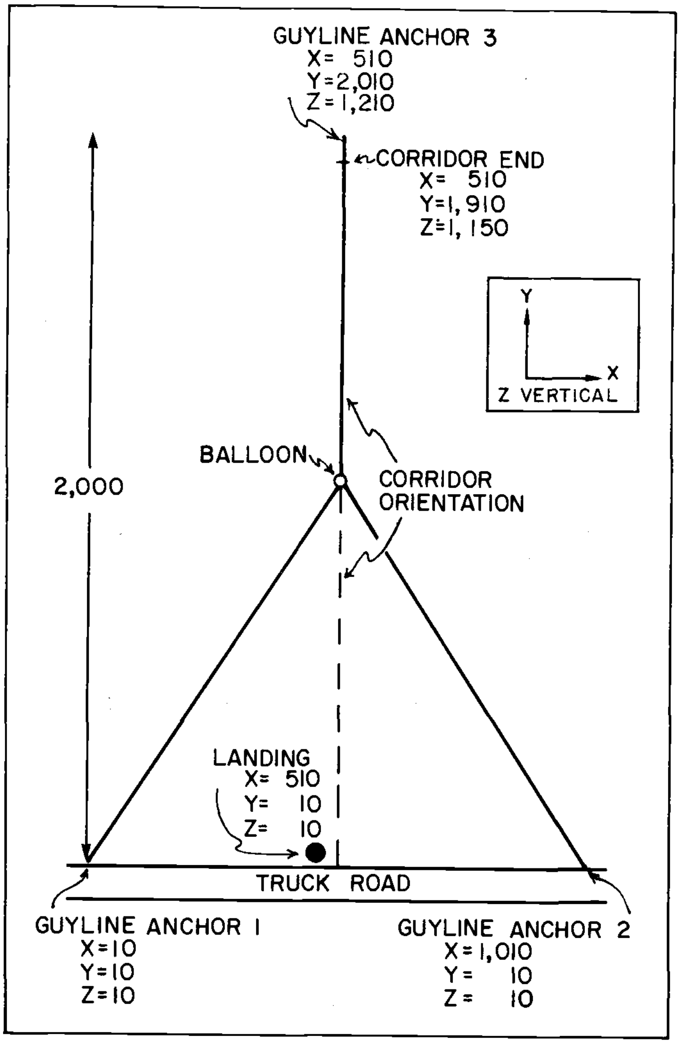

FIGURE 2.

ORIENTATION OF GUYLINE ANCHORS, CORRIDOR, AND BALLOON AS USED TO ANALYZE PENDULUM-SWING SYSTEM. DIMENSIONS ARE IN FEET.

BALLOON AND LOAD POSITIONS

Relative position of the balloon and the load--the first factor influencing available lift--is affected by the shortening of the pendulum line when the load is picked up and by balloon elevation. These determinants have been evaluated by Avery (1984), who developed the above-mentioned iterative model for determining lift potential of a balloon system in static equilibrium. In this model, tensions in the lines are calculated by a series of equations that allow for the catenary (sag) effects involved. The model assumes a single pendulum line suspended from a winch under a balloon stabilized by two or more guylines and is therefore an approximation of the inverted Tyler system.

EFFECT OF SHORTENING THE PENDULUM LINE

Shortening the pendulum line changes the relative positions of the load and the balloon and thus affects lift. When the load is initially hooked to the pendulum line, the line is slack. As the pendulum line is shortened, it becomes taut and more and more lift is applied to the load. (Eventually, the line can be shortened so much that sag is virtually eliminated.)

If the lifting capacity of the balloon is insufficient to suspend the load, shortening the pendulum line will move the balloon instead of the load. In that case, the balloon will tend to move directly over the load.

Avery's (1984) analysis of line shortening was restricted to conditions resulting in a balloon movement of less than 20 ft; it is believed that greater movement would slow the turn cycle. Such a restriction in balloon movement also contributes to greater line control and overall stability of the system.

EFFECT OF BALLOON ELEVATION

The elevation of the balloon above the load also affects lift. Figure 3 illustrates the

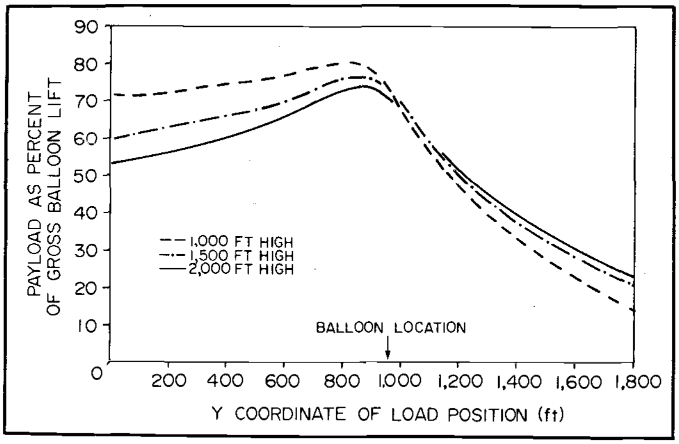

FIGURE 3.

LOAD-LIFTING CAPABILITY AT VARIOUS LOAD LOCATIONS AS BALLOON HEIGHT IS VARIED. GROSS BALLOON LIFT IS 47,000 LB AT THE BASE OF THE BALLOON. BALLOON COORDINATES ARE X = 510 FT AND Y = 980 FT; SLOPE OF THE SETTING IS 60 PERCENT.

effect of balloon elevation on lift available at various load locations. Landing and guyline anchor positions are as specified in Figure 2. Load-lifting capabilities at various points on the slope are shown for balloon elevations of 1,000, 1,500, and 2,000 ft. At points upslope from the balloon, load-lifting capability increases slightly as balloon elevation increases. However, as the load moves toward the landing, higher balloon elevations result in decreased lift. This decrease is due to the increasing length of the pendulum line. Ammeson (1984) has shown that the same general relationships exist regardless of the balloon's position along the Y coordinate.

LINE WEIGHT

The second factor affecting available lift is the size and weight of the guylines and pendulum line. This factor was also evaluated by Avery (1984) in his model for determining lift potential. Figure 4 illustrates load-lifting capability at various load locations for two sizes and weights of line. The lower curve represents lift capability if all guylines and the pendulum line are 1-1/4-inch wire rope (weight, 2.89 lb/ft). The upper curve represents lift capability if the guylines are 1-5/8-inch Kevlar® (weight, 0.67 lb/ft) and the pendulum line is 1-inch wire rope. In both types of rigging, each guyline is capable of counteracting the entire gross balloon lift of 47,000 lb without exceeding one-third of its breaking strength. Landing and guyline anchor positions are as specified in Figure 2. Note that the load-lifting capability is much greater for the balloon system rigged with Kevlar® guylines than for the system rigged with wire rope guylines. Note also that, for the system with Kevlar® guylines, available lift is nearly 40 percent greater when the load is directly under the balloon than it is when the load is near either end of the corridor.

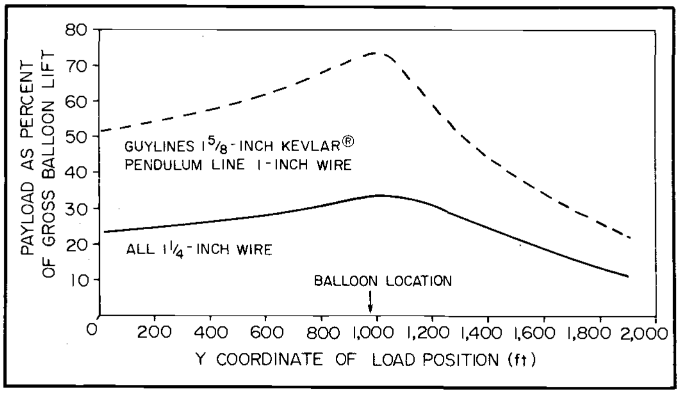

FIGURE 4.

LOAD-LIFTING CAPABILITY AT VARIOUS LOAD LOCATIONS ACCORDING TO SIZE AND WEIGHT OF LINES USED. GROSS BALLOON LIFT IS 47,000 LB AT THE BASE OF THE BALLOON. INITIAL BALLOON COORDINATES ARE X = 510 FT, Y = 980 FT, AND Z = 2,092 FT OR 1,500 FT ABOVE THE 60 PERCENT SLOPE.

PENDULUM AND GUYLINE ANGLES

The third factor affecting available lift is the angles that the pendulum line and opposing guylines make with the horizontal while the load is being lifted. This factor was evaluated by Avery (1984) in his computer model, although the fundamental behavior involved was not recognized until Tuor (1984) conducted field studies.

Figure 5 is a highly simplified diagram of the relationship between load-lifting capa-

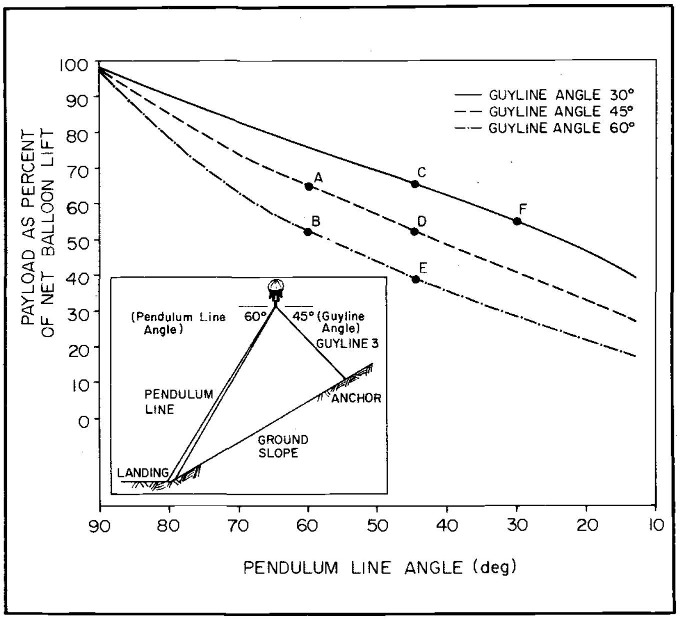

FIGURE 5.

LOAD-LIFTING CAPABILITY AS A FUNCTION OF THE ANGLES THAT THE PENDULUM LINE AND OPPOSING GUYLINES MAKE WITH THE HORIZONTAL. POINTS A, B, C, D, E, AND F ARE DEFINED IN TEXT. SLOPE IS 60 PERCENT. INSET--RIGGING CONFIGURATION FOR POINT A.

bility (payload) and angles of the pendulum line and opposing guylines (Tuor 1984). Note that load-lifting capability decreases as the angle of the pendulum line decreases, i.e., as the pickup point moves away from the balloon. Note also that the angle of the opposing guylines influences what the balloon system will support at any given angle of the pendulum line. As the angle of the opposing guylines decreases, the load-lifting capability of the pendulum line increases, regardless of pendulum line angle. This relationship is perhaps the most important concept to grasp in understanding the lift capability of the pendulum-swing system.

Points B, D, and F on Figure 5 indicate lifting capability when the angles of the pendulum line and opposing guylines are equal. In these cases, half of the balloon's net lift is exerted on the pendulum line as lifting capability and the other half is exerted on the guyline anchor. (The points on the figure represent experimental data and thus vary slightly from the 50-percent value one would expect for lift.)

Point E on Figure 5 indicates lifting capability when the guyline angle is greater than the pendulum line angle. In this particular case, payload capacity is less than 40 percent of net balloon lift. Point C, on the other hand, indicates lifting capability when the pendulum line angle is greater than the guyline angle. In the case depicted here, payload capacity is almost 70 percent of net balloon lift.

Point A on Figure 5 indicates lifting capability when a load is being placed on the landing. (The rigging configuration during this operation is schematically illustrated in the inset to Figure 5; guylines 1 and 2 and the haulback line are assumed to be slack and to exert a negligible effect on lift.) In this particular case, lifting capability of the pendulum line is less than 70 percent of net balloon lift.

Maintaining adequate lift while the load is being placed on the landing is crucial to the success of the pendulum-swing system. In an actual operation with a corridor 65 ft wide and 2,000 ft long on a 60 percent slope, the balloon would be repositioned several times with the guyline winch. Each position would probably be closer to the landing than the corridor midpoint shown in Figure 2. Although such forward positions limit the balloon's lifting capacity upslope of the midpoint, the haulback line can assist with lift in such cases. Moving the balloon farther up the slope severely limits the load that can be supported near the landing, and the haulback line cannot effectively compensate.

LOAD SWINGING

The fourth factor influencing available lift is the effect of swinging the load. This mathematically complex action was studied by Beary (1983), who monitored changes in line tensions and balloon position during the pendulum-swing phase of balloon logging. His field studies revealed additional limits on load lift during the actual swing.

In a pendulum-swing system, load swinging causes a fluctuation in the tensions of the various lines. Figure 6 illustrates the fluctuations in such a system during the free swing of a 1,000-lb weight through several periods. The graph shows that the pendulum line tensions exceed the suspended load during part of the free swing. Note that when the load begins to swing, tension in the pendulum line first sharply decreases and then sharply increases. This "spiking" is characteristic of pendulum lines during load swinging. The initial drop occurs partly because the load undergoes a free fall and a rotation at the instant it begins to swing. The load rotates because its center of mass

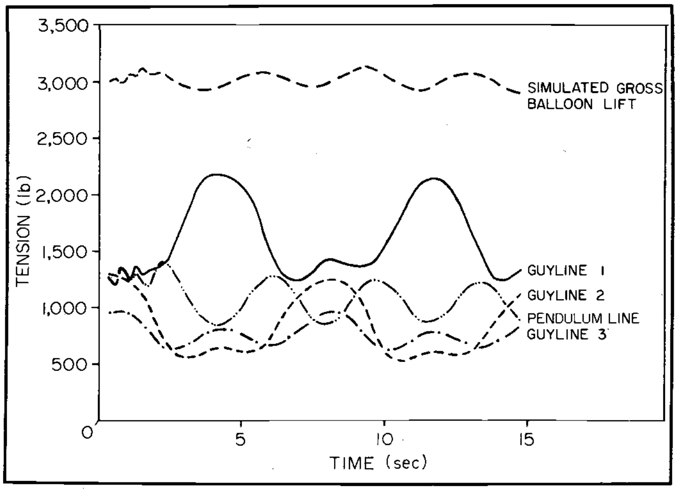

FIGURE 6.

TIME PLOT OF LINE TENSIONS PRODUCED BY THE FREE SWING OF A 1,000-LB WEIGHT.

must align itself with the pendulum line. Once alignment is complete, the load's trajectory follows an arc. The other factor contributing to the initial drop is the removal of the horizontal tension in the haulback line as the swing begins.

Instead of a free swing, a full-scale field operation would use a controlled swing, whose maximum velocity would be only about 1/4 that of a free swing. The centrifugal force of a controlled swing would also be less--1/16 that of a free swing. Fortunately, maximum centrifugal force would occur when the load is directly under the balloon, the point where maximum lift from the balloon is available.

In a field operation, a free swing would occur only if the haulback line failed. In this case, the load would probably be dropped onto the ground by lengthening the pendulum line. But if safety or the value of the timber prohibited such a course, a free swing could be attempted. The maximum tension during such a free swing would be

$$T = 2W(1 - \cos\theta) + W$$

where T = maximum tension, in lb
W = load weight, in lb
θ = angle of the pendulum line with the vertical at the beginning of the swing, in degrees

In an extreme case where $W = 10{,}000$ lb and $\theta = 45°$, T would be 15,858 lb. Wind drag, line drag, and sheave resistance were ignored in this analysis. These factors would slow the velocity even further, resulting in less swing-induced tension and greater available lift.

WIND

The fifth factor influencing available lift is the effects of wind. These effects can be considered from two perspectives--static and dynamic. Static effects are computed on the assumption that a balloon has a constant reaction to a steady wind and that resulting line tensions and lift will be constant. Dynamic effects are computed from measurements of a balloon's actual oscillation in a steady wind and of the oscillating line tensions and lift that result.

STATIC EFFECTS

Avery's (1984) computer model was used to determine the static effects of wind on lift at various load positions. Two assumptions were made for the purpose of the analysis:

1. Wind force is constant in direction and magnitude;
2. Wind force is applied at the junction of the vertical lines (i.e., at the base of the balloon).

Drag resulting from wind forces on a natural-shaped balloon was determined from the physics equation:

$$\text{Drag (in lb)} = C_D\ 1/2\ \rho v^2 V^{2/3}$$

where C_D or drag coefficient = 0.3
ρ or air density = 0.002378 slugs/ft^3
v = wind speed (in ft/sec)
V = volume of balloon (1,100,000 ft^3)

For the analysis, 15-mph winds were assumed to be blowing in the +X (left to right), +Y (front to back), or -Y (back to front) directions and the orientation of the guylines and corridor to be as in Figure 2. According to the drag equation, a 15-mph wind exerts 1,840 lb of force at the junction of the vertical lines. The static effect of such winds on lift is shown in Table 1. Note that the effect depends on the direction of the wind. Because the load swings in the Y direction, winds from that direction have a greater effect on lift than do those from the X direction.

Only when wind direction is perpendicular to the swing path is the balloon position changed drastically. Depending on load position, the balloon is then moved as much as 50 feet in the direction the wind is blowing, as shown in Table 2. This movement seriously affects the system only when the wind is gusting. A sudden slackening or tightening of the pendulum line during hooking or unhooking may result in excessive stress to the balloon system as well as a dangerous, unpredictable movement of the load. Operations can be continued under these conditions, but workers must be cleared from the area while the load is suspended or being landed. In addition, the load must be raised higher in the air. And when no load is being suspended, extra slack must be allowed in the pendulum line so that balloon movements will not move the carriage.

TABLE 1.

EFFECT OF WIND AND WIND DIRECTION ON NET BALLOON LIFT.

Load position[1]		Maximum lift			
Y coord. (ft)	Z coord. (ft)	No wind	15 mph (+X)	15 mph (+Y)	15 mph (-Y)
		lb			
1,910	1,150	11,528	11,527	10,264	12,795
1,410	850	21,943	21,912	19,674	24,208
910	550	34,975	33,963	35,886	33,593
410	250	28,305	27,230	29,533	27,077
10	10	25,304	24,302	26,414	24,195

[1] X coord. of load = 510 ft for all load positions.

TABLE 2.

EFFECT OF WIND ON BALLOON POSITION.

Load position, Y coord. (ft)	Balloon position, X coord.	
	No wind	15 mph (+X)
	ft	
1,910	510	510.61
1,410	510	512.86
910	510	562.90
410	510	560.38
10	510	559.30

DYNAMIC EFFECTS

The dynamic effects of wind on the pendulum-swing system were observed by Tuor (1984) during field trials with a 37,000-ft^3 prototype balloon. Figure 7 is a typical plot of line tensions as affected by wind. In this instance, a 7-mph wind is blowing toward the loading point near guyline anchor 1. (Guyline 1, not shown on the graph, has gone slack because the pendulum line has been shortened.) Horizontal wind drag on the balloon is about 42 lb. Note that at least two of the lines are always reacting to the balloon's oscillations in the wind. In this case, the greatest variation in tension is in guyline 3: maximum tension is 140 percent of mean tension. In guyline 2, maximum tension is 125 percent of mean tension. Net load lift also varies with balloon movement in the wind.

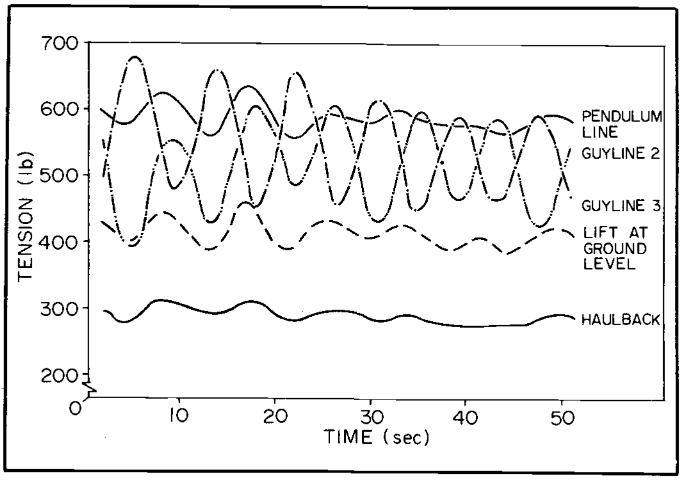

FIGURE 7.

DYNAMIC EFFECT OF A 7-MPH WIND ON LINE TENSIONS IN A PENDULUM-SWING SYSTEM.

HAULBACK AND MAIN LINES

The sixth factor influencing available lift is the effect of the haulback and main lines in either assisting or counteracting the pendulum line. Avery's (1984) model was used to analyze how a taut haulback line increases lift and how a taut main line exerts a downward force. Although a simple vector analysis can be performed anywhere along the slope to show the forces exerted on these lines, the actual effect is more complex because the lines sag and drag on the ground.

Figure 8 illustrates how lift is affected by haulback line angle at various pendulum line angles. Note that, for any pendulum line angle, lift is greater when the haulback line

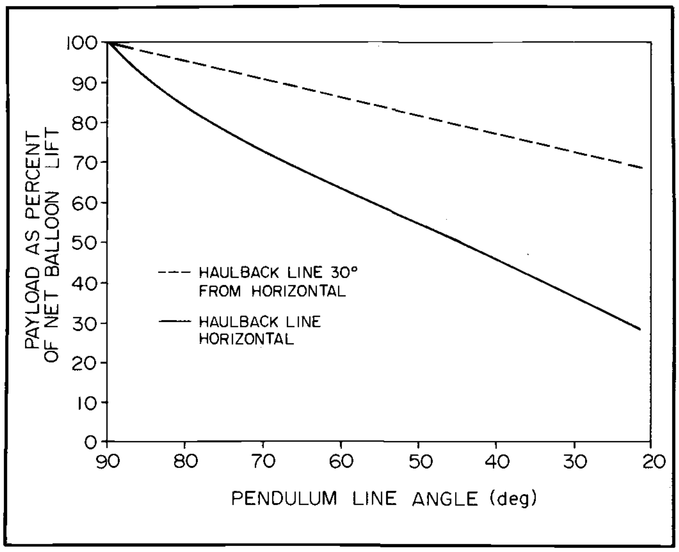

FIGURE 8.

THEORETICAL EFFECT OF HAULBACK LINE ANGLE ON PAYLOAD AT VARIOUS PENDULUM LINE ANGLES. SLOPE IS 60 PERCENT.

is at a 30° angle from the horizontal (i.e., at some distance from the corner block at the rear of the setting) than when it is horizontal (i.e., near the rear corner block).

The haulback line exerts lift while the load is first being suspended. As the swing progresses and the load moves directly under the balloon, lift from the haulback line decreases and lift from the pendulum line increases.

As the load passes under the balloon, the main line begins to exert a negative influence on lift. This line assists gravity (the pendulum swing) in moving the load to the landing. It exerts its maximum influence by holding the load on the ground while the pendulum line is slackened.

MAXIMUM PAYLOAD

Maximum payload is determined by the interaction of the six previously discussed factors with the balloon's lifting capacity. The payload contours in Figure 9 illustrate the complexity of the interactions of all the lines--guylines, pendulum line, haulback and main lines. The maximum payload that can be moved is limited by the smallest contour through which the load must pass. Furthermore, the dynamic effects of the pendulum swing and the wind further reduce this maximum static lift. A carriage weighing about 8,000 lb is needed to lower the lines to the ground (Ammeson 1984). After this dead weight is deducted from the contours shown in Figure 9, the net payload of logs is considerably reduced. For the configuration shown here, average net payload for a swing would be about 10,400 lb.

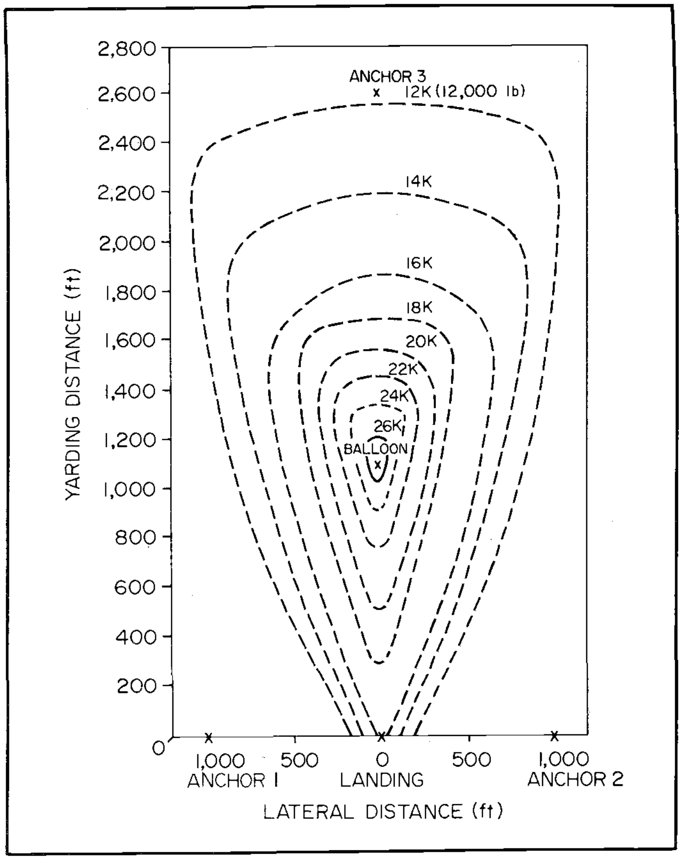

FIGURE 9.

PAYLOAD CONTOURS FOR LOGGING A 60 PERCENT SLOPE WITH A BALLOON TETHERED 1,500 FT ABOVE THE UNIT, 1,100 FT FROM THE LANDING.

OPERATIONAL CONSIDERATIONS

During initial implementation of a full-scale operation, the tension in every line in the pendulum-swing system should be checked to ensure that safe working limits have not been exceeded. Sometimes, line sizes must be increased so that a desired payload can be attained. Any increase in line size must, however, be carefully considered because of the additional weight and also the decreased length of line that can be spooled onto the drums.

In skyline operations, a rule-of-thumb recommended by the USDA Forest Service is a ratio of 3:1 for ultimate breaking strength tension to safe working tension. This safety factor allows for both a deterioration in line condition during use and for sudden stresses to the system. Because of the stability of the pendulum-swing system, this same ratio was used in the present analysis.

Because the balloon can exert considerable twisting motion, extra precautions are necessary to prevent strand unraveling or separation. Long splices must be appropriately exaggerated. Swivels should be inserted where appropriate.

This analysis assumed constant atmospheric conditions. Changes in air pressure, temperature, and humidity can, however, be expected, and these changes will affect gross lift. Moisture clinging to the balloon will add dead weight. And helium leakage through the balloon fabric will occur.

CONCLUSION

This Bulletin outlines the six factors that affect lift of a pendulum-swing balloon system and how they interact. The static load-lifting capabilities of any particular system can be precisely determined with Avery's (1984) model for computing static lift. However, the dynamic effect of load swinging, gusting wind, acceleration, and drag can only be crudely estimated from the behavior of prototype systems. Full-scale field tests or extensive analog simulations will be required for precise predictions of dynamic lift.

ANNOTATED REFERENCES

AMMESON, JAMES. 1984. Economic analysis of the pendulum balloon logging systems. Master of Forestry Paper, College of Forestry, Oregon State University, Corvallis.

> This paper compares the productivity and costs of pendulum-swing and conventional (Yo-Yo) balloon logging systems. Time studies were made during summer 1983 on a balloon logging sale in the Coast Range of southern Oregon. From these observations estimates were made of the conventional system's productivity and costs. For the pendulum-swing system, engineering calculations were made to determine expected line speeds, and Avery's computer model (see below) was used to predict productivity. Incremental cost analysis was used to establish the economic limitations of the system.

AVERY, ROBERT B. 1984. Mathematical model for determining the position and line tensions for a tethered logging balloon. Master of Science Thesis, Oregon State University, Corvallis.

> This paper describes the development and use of a computer model to determine the static loading of the pendulum-swing balloon system. An iterative search technique based on catenary equations was developed to find the equilibrium position of the balloon. This model was used to specify important design factors including line sizes, balloon heights, guyline anchor positions, and landing locations. The model was also used to answer questions about wind effect, line materials, and system limitations, and to verify the reasonableness of field data from other studies.

BEARY, GREGORY L. 1983. Dynamic characteristics of the pendulum balloon system swing. Master of Forestry Paper, College of Forestry, Oregon State University, Corvallis.

> This paper describes the results of field tests with a small-scale pendulum-swing system during the summer of 1983 in the McDonald Forest north of Corvallis. Under investigation were reactions in the system's lines when a load was swung. The study indicated when the maximum forces in the lines would occur during the swinging of the load.

TUOR, BRIAN. 1984. Field test to determine the static forces on the pendulum swing balloon logging system. Master of Forestry Paper in preparation, College of Forestry, Oregon State University, Corvallis.

This paper reports preliminary engineering analysis on the pendulum-swing system. It also describes an analysis of measurements taken in summer 1982 during a field test of a 37,000-ft^3 balloon used as a prototype model under static conditions. This study established important information about guyline anchor positions, wind effect, and load-lifting capabilities. When used as guylines, synthetic rope was found to be a desirable substitute for wire rope (steel cable).

OLSEN, E.D., B.L. TUOR, and M.R. PYLES. 1984. BALLOON LOGGING WITH THE PENDULUM-SWING SYSTEM: FACTORS AFFECTING LIFT. Forest Research Laboratory, Oregon State University, Corvallis. Research Bulletin 47. 14 p.

From mathematical models of line tensions and field data on prototypes, the factors affecting the load-lifting capacity of a tethered balloon used for logging were evaluated. In this system, a pendulum-like swing is used to bring the logs to the landing. The six factors affecting lift are relative position of balloon and load, weight of guylines and pendulum line, guyline angles in relation to angle of pendulum line, dynamic effect of load swinging, static and dynamic effects of wind, and effect of operating lines in assisting or counteracting the pendulum line.

OLSEN, E.D., B.L. TUOR, and M.R. PYLES. 1984. BALLOON LOGGING WITH THE PENDULUM-SWING SYSTEM: FACTORS AFFECTING LIFT. Forest Research Laboratory, Oregon State University, Corvallis. Research Bulletin 47. 14 p.

From mathematical models of line tensions and field data on prototypes, the factors affecting the load-lifting capacity of a tethered balloon used for logging were evaluated. In this system, a pendulum-like swing is used to bring the logs to the landing. The six factors affecting lift are relative position of balloon and load, weight of guylines and pendulum line, guyline angles in relation to angle of pendulum line, dynamic effect of load swinging, static and dynamic effects of wind, and effect of operating lines in assisting or counteracting the pendulum line.