FIELD TEST TO DETERMINE THE STATIC FORCES ON THE PENDULUM SWING BALLOON LOGGING SYSTEM

by

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AN ABSTRACT OF THE PAPER OF

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Title: Field Test to Determine the Static Forces on the Pendulum Swing Balloon Logging System.

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This paper represents preliminary engineering analysis on the pendulum swing balloon system. It also describes an analysis of measurements taken in the summer of 1982, during a field test of a 37,000-foot^3 balloon used as a prototype model under static conditions. This work established the influence of important variables on the load lifting capabilities, the line tensions, and the balloon movement.

Balloon movement does not appear to be a major problem, for practical operating conditions it may be considered to be fixed in position. Line tensions were shown to conform with mathematical model predictions. The payload that the system can support at any given load position is a function of four variables: lift at the base of the balloon, the haulback line angle, the pendulum line angle, and the opposing guyline(s). Figures are used to quantitatively show the relationships. Although the paper is based on simplified mathematical models, static conditions, and a field test that wasn't an exact scale model, the results established an important understanding of the engineering fundamentals of this system.

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FIELD TEST TO DETERMINE THE
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INTRODUCTION

In 1972, a balloon logging concept was proposed and later patented by John L. Bell (patent #3807577, 1974). Officially known as the "Aerial Load Lifting and Transporting Method and System", it became known as the Pendulum Swing Balloon System. Mr. Bell approached the Forest Service to put up a timber sale on which to test the concept. The Forest Service requested that Mr. Bell provide a full engineering analysis of the system prior to committing time and money to this unique concept. In July 1981, John Bell asked the Forest Engineering Department at Oregon State University to provide an engineering and economic feasibility study.

System Description

The proposed system (Figure 1) uses a 1.1 million cubic-foot, natural-shaped helium balloon tethered in a relatively fixed position by three or more guylines. A powered winch is suspended directly beneath the balloon.

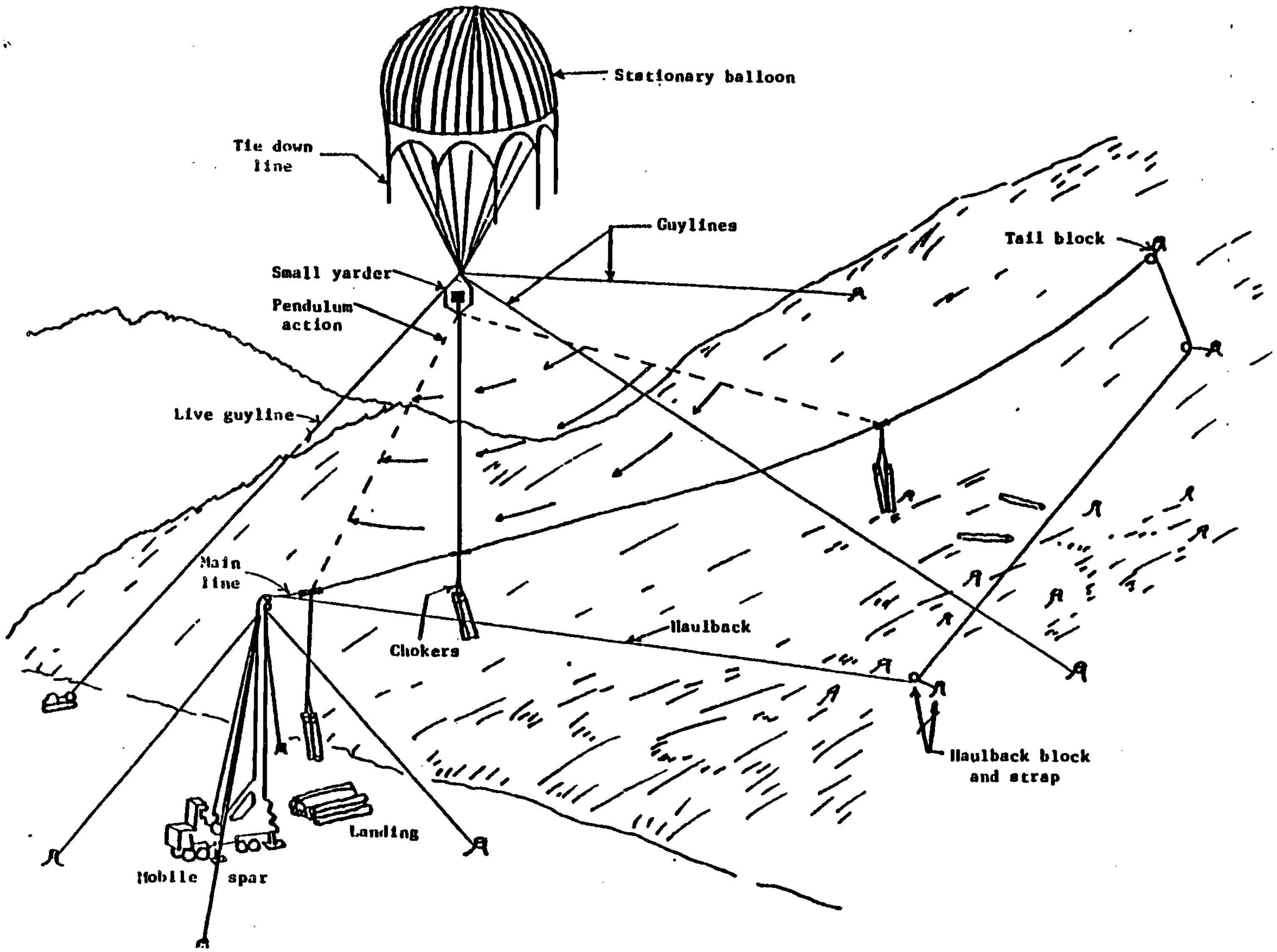


Figure 1. Pendulum Swing Balloon Logging System

A line runs from the winch to the butt-rigging of a conventional highlead logging system. The balloon provides additional lift to the highlead system and extends the feasible yarding distance. The tower height is not critical to system operation provided the lines spool properly during the yarding cycle.

Yarding Sequence

A typical yarding cycle begins with the chokers on the landing. The yarder engineer begins shortening the pendulum line to keep the chokers clear of the ground while simultaneously spooling in the haulback and spooling out the mainline to transfer the chokers to the load pick-up point. When the chokers reach the point where a load is to be attached, the rigging slinger signals the yarder engineer to stop outhaul and lower the chokers to the ground by spooling line off the pendulum line hoist. The mainline and haulback may also have to be adjusted to place the choker where desired. After attaching the chokers to the load, the rigging slinger signals the yarder engineer to lift the load free of the ground by shortening the pendulum line. As soon as the load is sufficiently elevated above the ground, the yarder engineer begins spooling in the mainline and spooling out the haulback at a rate which will allow the turn to swing due to gravity toward the landing while maintaining control of the load. As the load approaches the landing, the yarder engineer slacks both the haulback and the pendulum lines lowering the load to the ground and pulls the load into the landing area with the mainline in a manner similar to a conventional highlead or skyline operation. The load is unhooked and the chokers sent back to begin another cycle. Road changes follow conventional highlead practices, only over longer distances.

Conventional (Yo-Yo) Balloon System

The conventional balloon logging system (Figure 2) is briefly described to allow a comparison to be made between it and the pendulum swing balloon system. The conventional balloon system, also called the yo-yo system, utilizes a natural-shaped, helium filled balloon tethered to the ground by the main and haulback lines. Two large yarders are used for this system. One spools the mainline and another spools the haulback. The balloon is pulled to the point of load pick up, the load is attached to the chokers. Then the balloon, along with the load, is pulled to the landing area. A typical yarding cycle begins with the chokers on the landing. The mainline yarder engineer reduces pressure on the mainline brake and

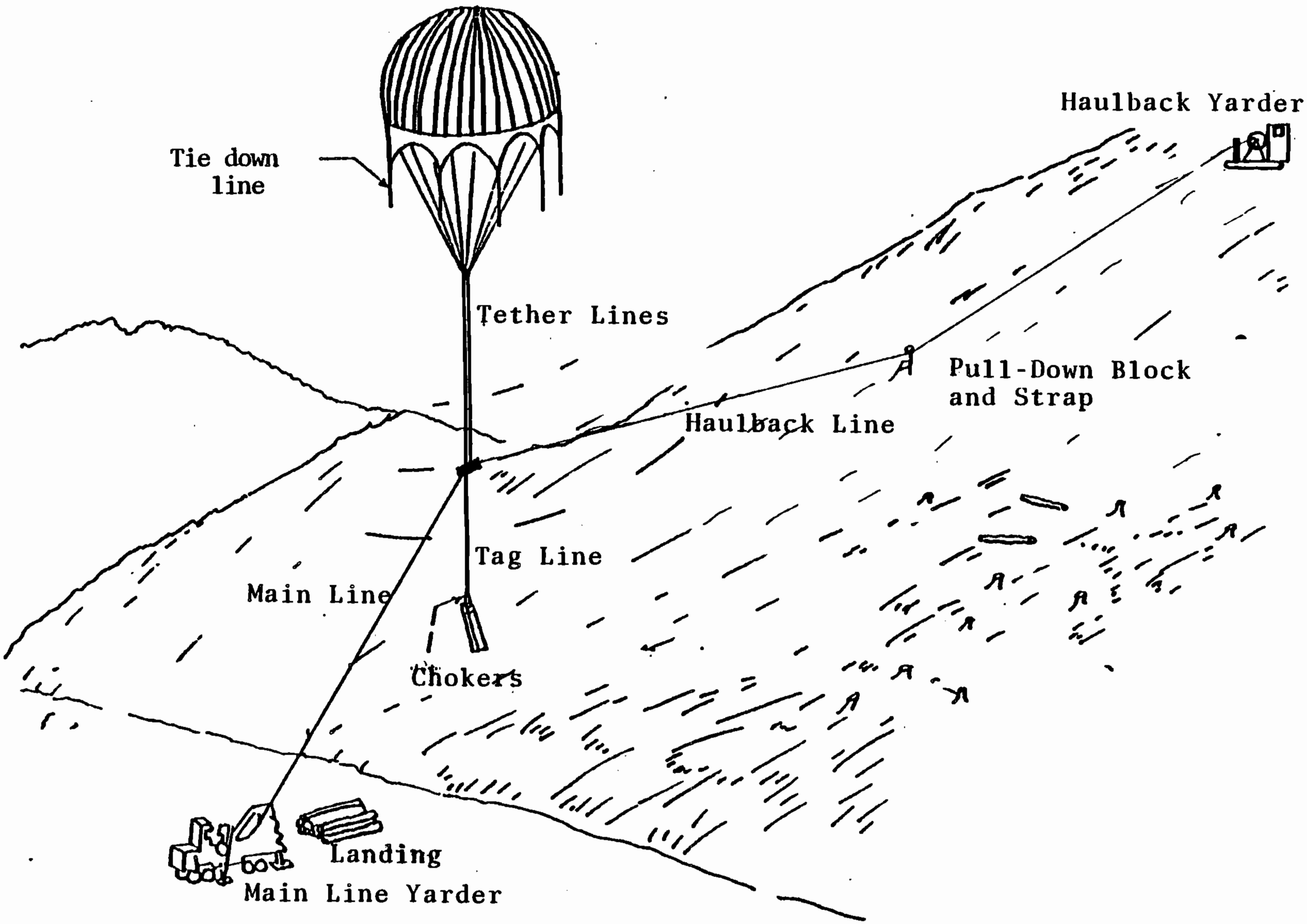


Figure 2. Conventional (Yo-Yo) Balloon Logging System

allows the lift of the balloon to pull line off the mainline drum. This allows the balloon and chokers to rise and move toward the area where a load will be attached. At the same time, the haulback yarder engineer begins to spool in the haulback which pulls the balloon and chokers toward the loading area. The mainline drum is stopped at a previously determined length. This allows the chokers to be returned to the same spot each cycle, if desired. The haulback yarder engineer continues to spool in the haulback which brings the balloon down to the area where the load is to be attached. The positioning of the chokers is accomplished through a system of blocks, one of which must be in the immediate area of the load. This block is known as a pull-down block. The farther the load is from this pull-down block, the longer must be the tagline from the carriage to the chokers. The load is attached to the chokers and the rigging slinger signals the haulback yarder engineer to reduce tension on the haulback, thus allowing the balloon to rise and lift the load free of the ground. As soon as the load is clear of the ground, the rigging slinger signals both yarder engineers. The haulback is slacked and the mainline yarder engineer begins spooling in the mainline pulling the load and the balloon toward the landing area. As the load approaches the landing area, the haulback is stopped at a previously marked spot. The mainline yarder engineer pulls the balloon and load down into the landing area when the balloon and load swing into the proper position. The chokers are unhooked, the cycle is repeated.

Advantages and Disadvantages

The advantages claimed for the pendulum swing balloon system as compared to the conventional balloon system are that 1) the balloon is more stable, 2) the yarding cycle is faster, 3) the operating lines are smaller, and 4) the horsepower required to operate the system is reduced (Bell, 1972). The disadvantages are that 1) the pendulum swing system requires a larger balloon to lift equivalent loads, 2) the system is more complicated to set up, and 3) a waiver is required to fly the balloon higher than present Federal Aviation Administration (FAA) regulations (Part 101, March 1974) allow.

In the conventional balloon system (Figure 2), the balloon is held in place by the mainline, the haulback, and the lift of the balloon. This configuration allows for two-dimensional stability only. Any forces perpendicular to the plane of the operating lines cause the balloon to move back and forth in the perpendicular direction. This movement is transmitted down the load line to the chokers and can make load attachment a difficult and dangerous operation. In the pendulum swing balloon system, the balloon is held in place by three guylines and the lift of the balloon. This gives the balloon stability in all three directions. Wind induced forces on the balloon should, therefore, be dampened and will not interfere with the load hooking operation.

In the conventional system, the long tag line between the point where the main and haulback lines meet and the chokers increases the cycle time. The crew at the load attachment point must wait for the line to stop swinging before they are able to hook the chokers to the load. On windy days this waiting period can amount to a significant part of the total cycle time. The landing of the load is also adversely affected since the mainline yarder is pulling almost straight down on the balloon and load as it approaches the landing. In this configuration, the yarder engineer has very little control of the position of the load and must have a large area in which to land it. The mainline yarder engineer must wait for the load to swing into the landing area and then must be very quick and skillful in order to land the load without hitting the equipment or personnel on the landing. The long tag line will continue to swing about after the load has been placed on the landing, thus interfering with the unhooking operation and endangering the chaser. In the pendulum swing balloon system, the mainline and haulback are attached very close to the chokers so there is much less movement in the rigging and the time required for the rigging to settle down will be minimal. Also the positioning of the chokers near the load will be more controllable. At the landing the yarder engineer will be able to lower the load to the ground on the perimeter of the landing area and then pull the load onto the landing. This allows the yarder engineer to bring the load closer to the machinery without endangering equipment or personnel. The ability to land a load under more control may also eliminate the need for a swing machine (tractor, crawler, or front end loader) on the landing to move logs, as is common with the conventional system.

In regard to other advantages, the conventional system uses 1" lines while the pendulum system uses 7/8", 3/4", and 5/8" lines. The conventional system uses two 635 H.P. engines while the pendulum system has one 430 H.P. engine.

On the disadvantage side, the pendulum balloon has 1.1 million cubic feet volume compared to .62 million cubic feet for the conventional system. This larger size, coupled with the guylines, required about fifty percent more time in handling, set-up, and road changes.

Present FAA regulations restrict tethered balloons to within 500 feet of the ground. The anticipated operating configuration of the pendulum swing balloon system will require a special waiver, as it is projected to fly from one-to-two-thousand feet above the ground. This restriction and waiver will have to be negotiated with the FAA at the time of implementation of the system at a specific site.

Project Goals

The overall project goals were to:

(1) determine static tensions in the guylines and operating lines of the system,

(2) determine dynamic tensions induced by swinging the load,

(3) determine the payload capabilities of the system,

(4) develop a general mathematical model to predict system performance over a wide range of operating conditions,

(5) estimate the economic viability of the concept.

Purpose of Paper

The purpose of this paper is to define the static tensions in the lines of a pendulum swing balloon logging system with various payloads, based on measurements made during a field study. Subsequent studies conducted by department staff covered the remaining project goals.

Field Study

The field study was conducted at the Forest Engineering Harvesting Systems Laboratory at Peavy Arboretum, approximately nine miles north of Corvallis, Oregon. The size of the area available and the size of the lines on the laboratory's yarder restricted the size of the system that could be used. The yarder is equipped with three-eighths-inch diameter wire rope (safe working load of 5,500 lbs), so a search was initiated for a balloon which would develop between one-to-five thousand pounds of static lift. Raven Industries, the manufacturer of the current logging balloons, established a contact with Mr. John Davis of Albuquerque, New Mexico, owner of a 37,000-cubic foot, 2,000-pound lift, helium balloon manufactured by Raven Industries. The balloon was leased to Oregon State University for a one-week period in August 1982. The field study system was designed around this balloon.

Purpose and Scope

The field study of the pendulum swing balloon logging system was designed to investigate three major questions identified as critical to balloon operation by the Forest

Service in 1972-1974, and which were not answered satisfactorily at that time.

1. What is the system's load lifting capabilities at various locations within the logging unit?

2. What tensions are developed in the guylines and operating lines during yarding operations?

3. How far does the balloon move during load pickup and transport, and is this movement significant?

To answer these questions, the research team formulated a theoretical model (Avery, 1983) and conducted a field study with a small balloon to validate the theoretical model. The field study did not utilize a true scale model of a full-sized system and so the results are not directly transferable to an actual logging operation. A true engineering scale model would require the proper relationship between mass, force, and dimensions. The major limitation being lines that had physical proprieties that would behave true to scale. For the conditions being studied, this was not a shortcoming that would seriously undermine the interpretation of the principles being observed.

Selecting Study Variables

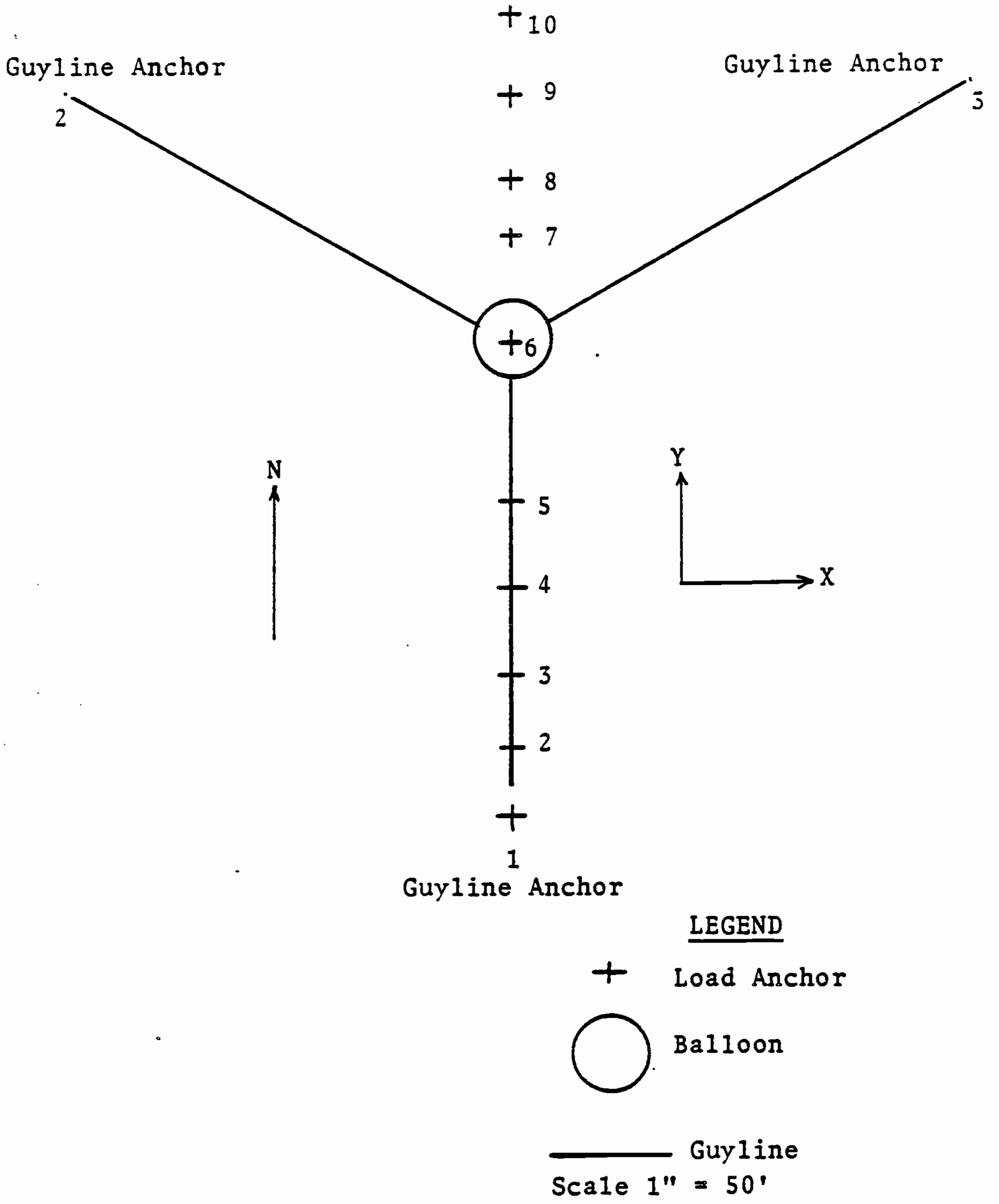
A simple two-dimensional mathematical model was developed to identify the variables to be tested in the field study. This model, code named "Sky Hook", is presented in the appendix. The model revealed that the variables controlling the size of payload which can be lifted and transported with this system are 1) the lift of the balloon, 2) the angle that the guyline opposite the pendulum line makes with the horizontal, 3) the angle which the pendulum line makes with the horizontal, and 4) the angle which the haulback line makes with the horizontal. Another factor influencing the maximum payload is the safe working tensions of the guylines, pendulum line, and the haulback. Due to the limited balloon time available, we decided to hold the guyline and haulback angles constant and vary the pendulum angle to determine what effect this has on the load capacity of the system. The lift of the balloon was to remain constant throughout the field study, and the limitations imposed by the safe working strength of the lines were observed.

Field Study System Configuration

Figures 3 and 4, respectively, diagram a plan and profile of the field study configuration illustrating the location of guyline anchors, load anchors, relative guyline angles, and height of the balloon.

Guylines on the pendulum swing balloon system may be located wherever they will produce a stabilizing force balance on the balloon. The guyline anchor locations on the field study system were designed so that the guylines would radiate from the balloon symmetrically at approximately 120 degrees, in the horizontal plane. One guyline was put in the plane of the load corridor. The vertical angle of the guylines was approximately 45 degrees. Guyline anchors 1 and 3 (Figure 3) were already in place. Anchor 1 was established at the top of the existing A-frame at the Harvesting Laboratory and anchor 3 was a large cluster of Big-leaf Maples growing on site. Anchor 2 was a concrete deadman anchor installed for the test, consisting of a five-inch diameter hole ten feet deep filled with concrete into which five-eighths-inch diameter reinforcing steel was placed. The steel rod had an eye welded into the end of it for the attachment of the guyline.

Ten anchors similar to guyline anchor 2, described above, were installed at predetermined locations selected to simulate different load locations. The locations were selected to cover a wide range of pendulum line angles on both sides of the balloon. Three additional concrete anchors were installed at load point 7 (Figure 3) to serve as tie-down anchors for the balloon.



<u>Figure 3</u>. Field Study Site - Plan View

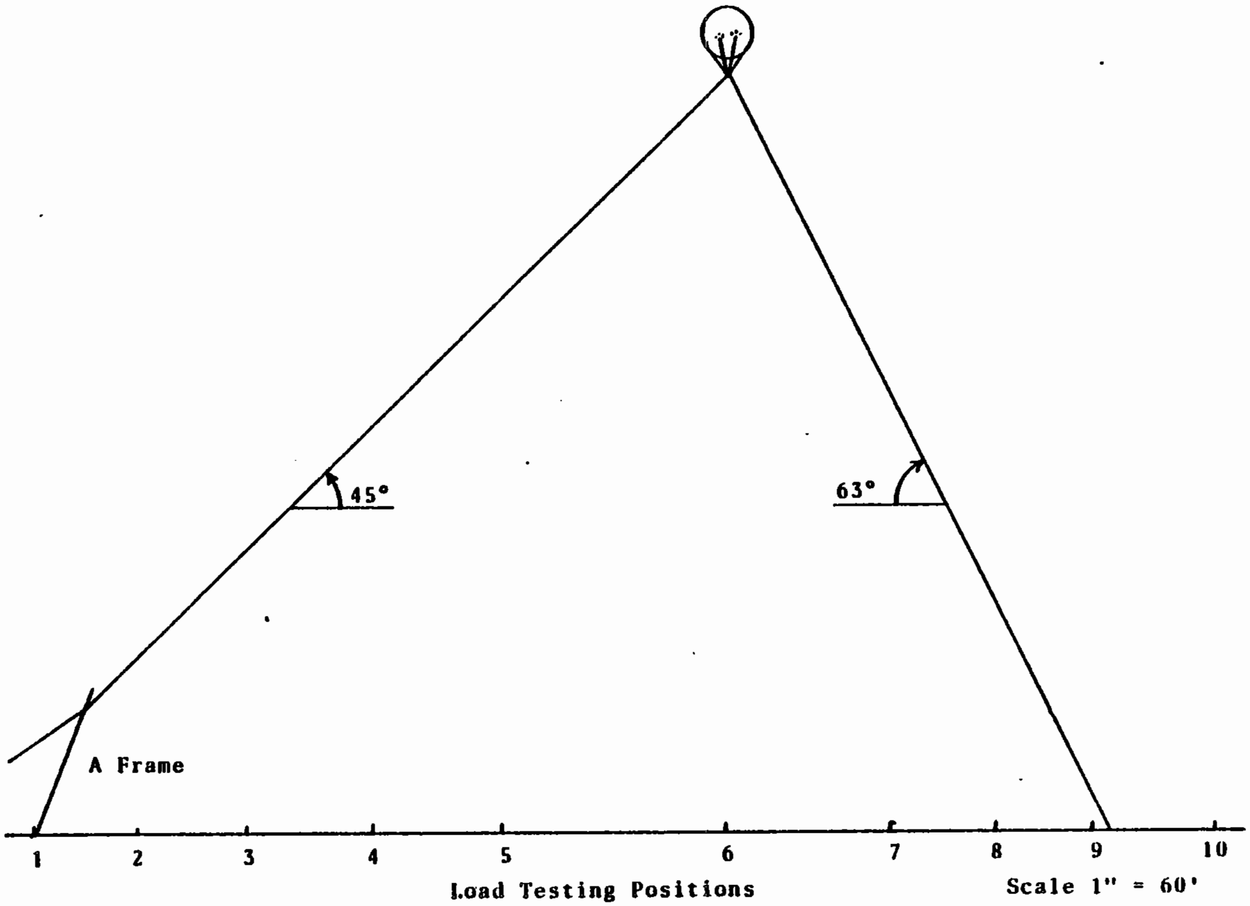
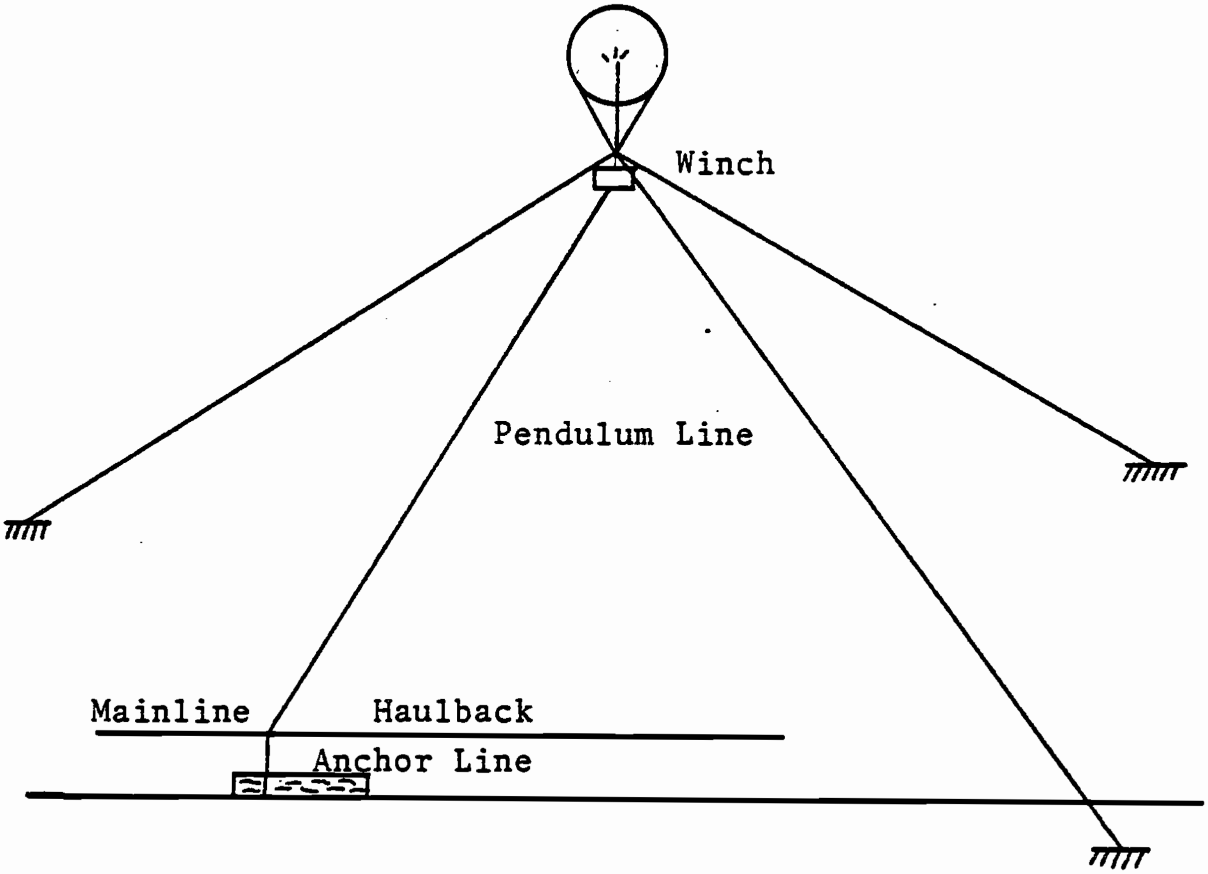
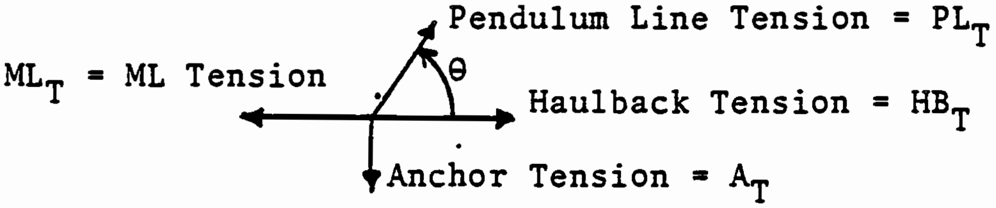


Figure 4. Field Study Site-Profile View .

The height of the balloon during testing was kept within 500 feet of the ground so that FAA waivers would not be required.

Mr. Bell's original design for the pendulum system specifies a hoist to be suspended beneath the balloon. Due to limitations of balloon lift and time required to find or build a suitable hoist, it was decided to use a North Bend rigging configuration to simulate the function of a hoist. A comparison of the two systems is illustrated in Figures 5 and 6. The free-body diagrams and the accompanying force balance show that the lifting force on the load anchor is the same for the North Bend test set-up as for Bell's design. The mainline, haulback and pendulum line tensions for the original design can be calculated from the tensions observed in the modified design.



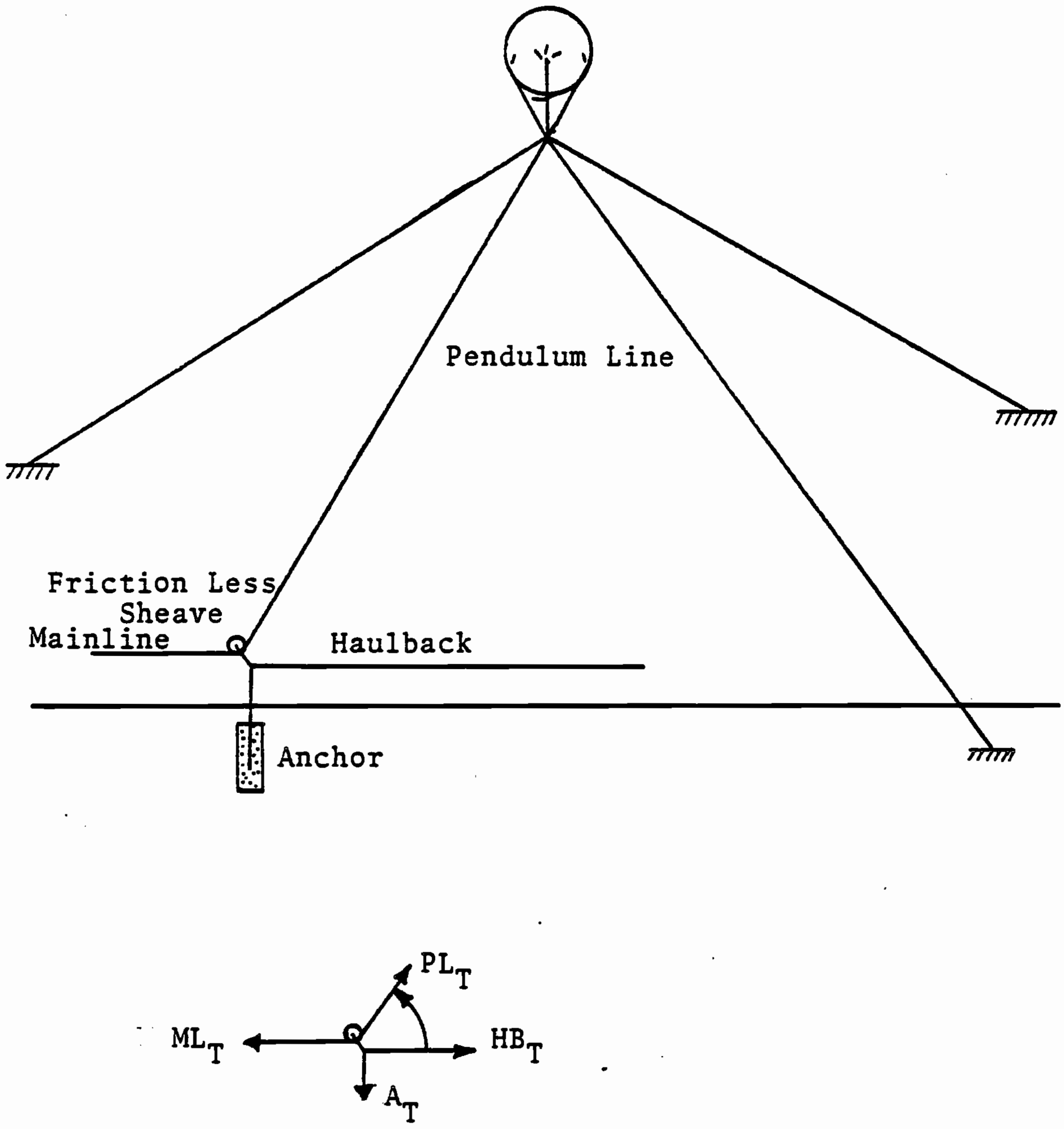


$$\Sigma F_x = 0 = HB_T + PL_T \cos \theta - ML_T$$

$$\Sigma F_y = 0 = PL_T \sin \theta - A_T$$

$$A_T = PL_T \sin \theta = \text{vertical component of pendulum line tension}$$

Figure 5. Pendulum Swing Rigging Configuration



$$F_x = 0 = HB_T + PL_T \cos \Theta - ML_T$$

$$F_y = 0 = PL_T \sin \Theta - A_T$$

$A_T = PL_T \sin \Theta =$ vertical component of pendulum line tension

Note: $ML_T = PL_T$

Figure 6. Modified Pendulum Swing Rigging Configuration

Equipment

The equipment utilized during the field study consisted of the balloon, load cells, a signal conditioning unit, theodolites, yarder, and an anemometer.

The balloon used for this study was a Raven Industries recreational "orbiter" model balloon. It is a 37,000 cubic-foot balloon which provides approximately 2,000 pounds of lift depending upon the surrounding atmospheric conditions. The balloon was attached to the 7/16" Kevlar guylines and 3/8" wire rope pendulum line shackle through a system of four carabiners similar to those used in rock climbing.

The load sensing links used to monitor line tensions were electronic load cells constructed by the research team. The signals from the load cells were routed to a signal conditioning unit and recorded on three strip chart recorders as pounds of tension in the respective lines.

The position of the balloon was obtained by observing the link directly under the balloon with two Wild T-2 theodolites placed at either end of a base line of known length. The theodolites were placed so that the line of sight of one was approximately perpendicular to the other to achieve a strong solution to the intersection relationship. Horizontal and vertical angles were observed and recorded for each test and were used to calculate the coordinates of the balloon location. In addition to balloon position observations, all related field system locations were surveyed and coordinates calculated.

A small two-drum yarder was used to operate the 3/8" pendulum and 3/8" haulback lines. This yarder was also used to raise and lower the balloon at the beginning and end of the test period each day. The three-eights-inch diameter wire rope has a safe working strength of 5,500 pounds.

An anemometer was attached to a vertical metal plate directly below the base of the balloon and wind speed and direction were recorded.

Measurement Techniques

During each test, tension in each of six lines, balloon position and wind speed, and direction were recorded.

For each test, tensions were measured continuously for one-to-two minutes following the positioning of the system. These tensions were recorded on three two-channel strip chart recorders. The load cells are accurate to ±10 pounds. Due to the length and elevation of the leads to the guyline load cells, difficulties were encountered when the cells were located at the base of the balloon. The leads functioned as a radio antenna and transmitted a local radio station signal to the strip chart recorders, thus masking the tension signal. This problem was eliminated by moving the load cells to the lower end of the guylines.

Balloon position was determined by intersection. The horizontal and vertical angles readings were recorded to ±one second. However, the wind caused the balloon to move in a cyclic manner and the position of the target could not be determined closer than ±one foot.

Wind speed and direction were monitored on an intermittent basis and recorded by hand once during each test. The wind speed is assumed to be accurate, however the wind direction is only approximate because the anemometer was mounted at the base of the balloon which rotated in the wind.

DATA COLLECTION AND ANALYSIS

Data Collection

Once the balloon was aloft and all system functions verified, the data was collected and recorded in the following sequence.

1. Select anchor - An anchor or load point was selected for measurement and all rigging necessary for a test was shifted to that point. The anchors were sampled sequentially from one to ten.

2. Position rigging - Since the main and haulback lines were capable of adding or subtracting from the lift measured by the anchor load cell, they were kept horizontal and the anchor line was kept vertical during all sampling. The height of the mainline above the anchor point was recorded to establish the coordinates at the lower end of the pendulum line.

3. Record zero lift data - The pendulum line was lengthened until the anchor line was slack and readings were recorded for balloon position, line tensions, and wind velocity.

4. Shorten pendulum line - The pendulum line was then shortened until the anchor load cell indicated a measurable tension, usually 75 to 100 pounds. Tension

readings were again taken by running the strip chart recorders for a minute or two. Observations were taken and recorded to determine balloon position and wind velocity. The process of shortening the pendulum line in small increments was continued until only small changes in anchor tension were observed for changes in pendulum line length. At this point, the pendulum line was shortened by a large increment (30 to 40 feet) to observe what influence a large change in the geometry of the system would have on line tensions.

5. Move anchor location - Upon completion of the test at the first anchor, the rigging was moved to the next anchor and the process was repeated until all ten anchors had been sampled.

Data Processing

At the completion of the field study, there were sixty-seven strip charts (Figure 7) containing over eight thousand seconds of observed line tensions. This data was digitized onto magnetic tape using the Hewlett Packard 9830 computer in conjunction with the HP 9864A digitizer and the HP 9862A plotter. A sample of this data is shown in Table 1. Errors due to the inability of the operator to follow the trace on the strip chart with the digitizer should be small and random. Given the sample size, random

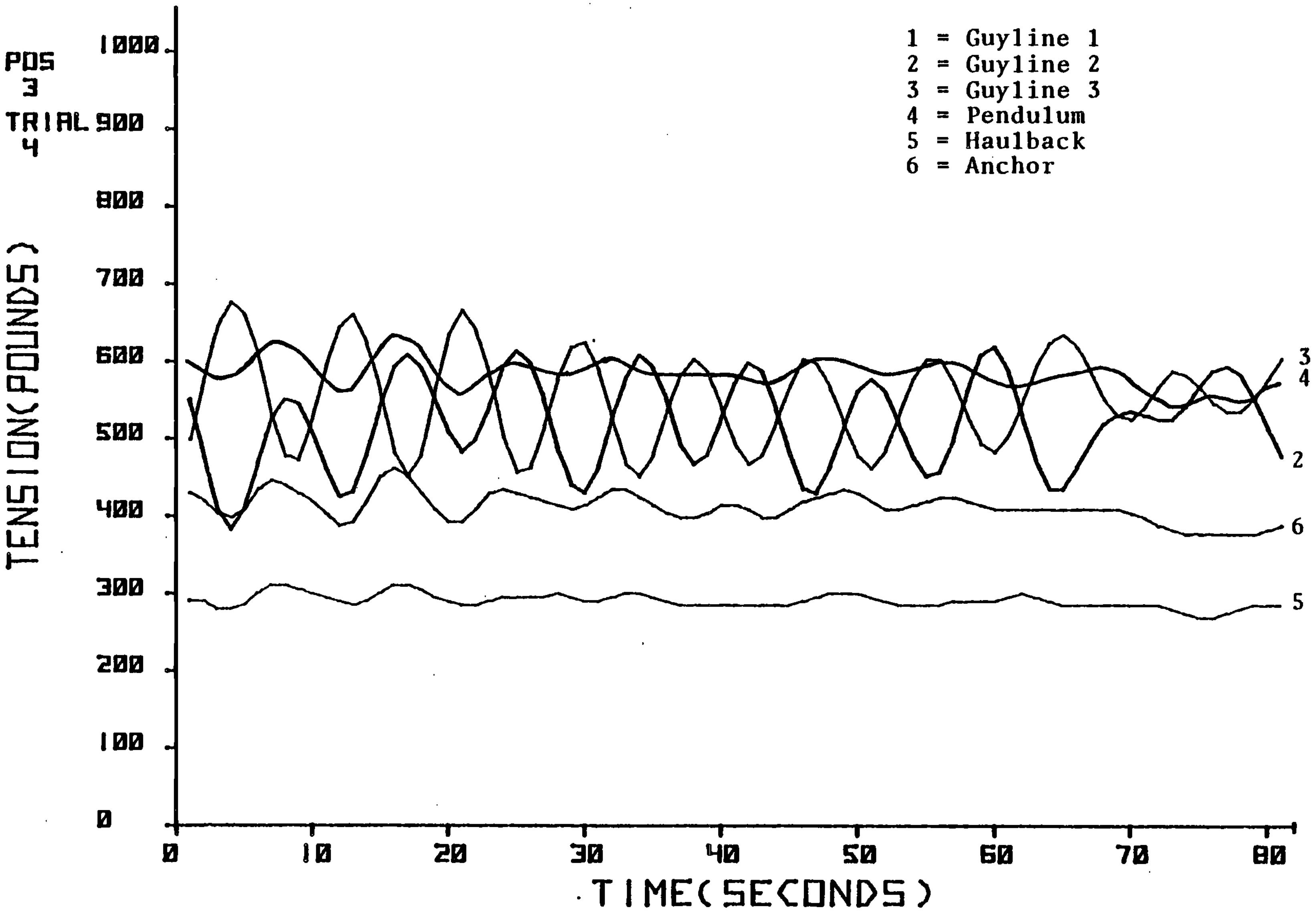


Figure 7. Plot of Tension -vs- Time For Field Test

TABLE 1. Computer Array of Field Data (Pounds)

TIME (Sec.)	GUY1 (lbs)	GUY2 (lbs)	GUY3 (lbs)	PEND (lbs)	HB (lbs)	ANCHOR (lbs)
0	-16	646	756	583	236	378
1	0	662	740	583	252	394
2	0	677	709	599	252	394
3	0	693	677	614	252	394
4	0	709	677	614	252	394
5	0	693	693	599	252	394
6	0	693	709	583	252	378
7	0	677	725	567	252	378
8	0	677	709	599	236	394
9	0	677	677	614	236	410
10	0	693	646	614	252	425
11	0	693	646	630	268	425
12	0	693	646	614	268	410
13	0	693	677	599	252	394
14	0	677	725	583	252	362
15	0	622	725	567	252	362
16	0	662	709	551	252	378
17	-16	677	693	583	252	394
18	-16	677	662	614	252	425
19	-16	693	630	614	252	425
20	0	693	646	614	268	410
21	0	677	677	599	252	394
22	0	677	709	583	252	378
23	0	662	740	567	252	378
24	0	662	740	567	236	362
25	0	662	725	583	252	378

error should not significantly affect the final answer. Each strip chart was checked against the data stored in the arrays to identify any errors in digitizing. Each strip chart was digitized at one second intervals and 50 to 120 data points were digitized for each test. The vertical scale of the strip charts was such that an error of 0.01 inches in establishing the axis on the digitizer corresponds to a plus or minus 16-pound error in the recorded data. Some charts were redigitized because of the failure to properly establish zero on the charts. In other cases, the sample size was adjusted to eliminate erratic sections of data caused by gusty winds.

Balloon position for each test was calculated by intersection using the recorded field angles and the known coordinates of the theodolite stations.

Data Analysis

The tension data was analyzed to verify the appropriateness of the digitizing process and to reduce it to a form which would be useful in meeting the objective of the field study.

An accumulated average of tension recorded in each line was calculated to determine if error in the starting and stopping points on the strip chart would affect the resulting mean. Figure 8 is a plot of the accumulated

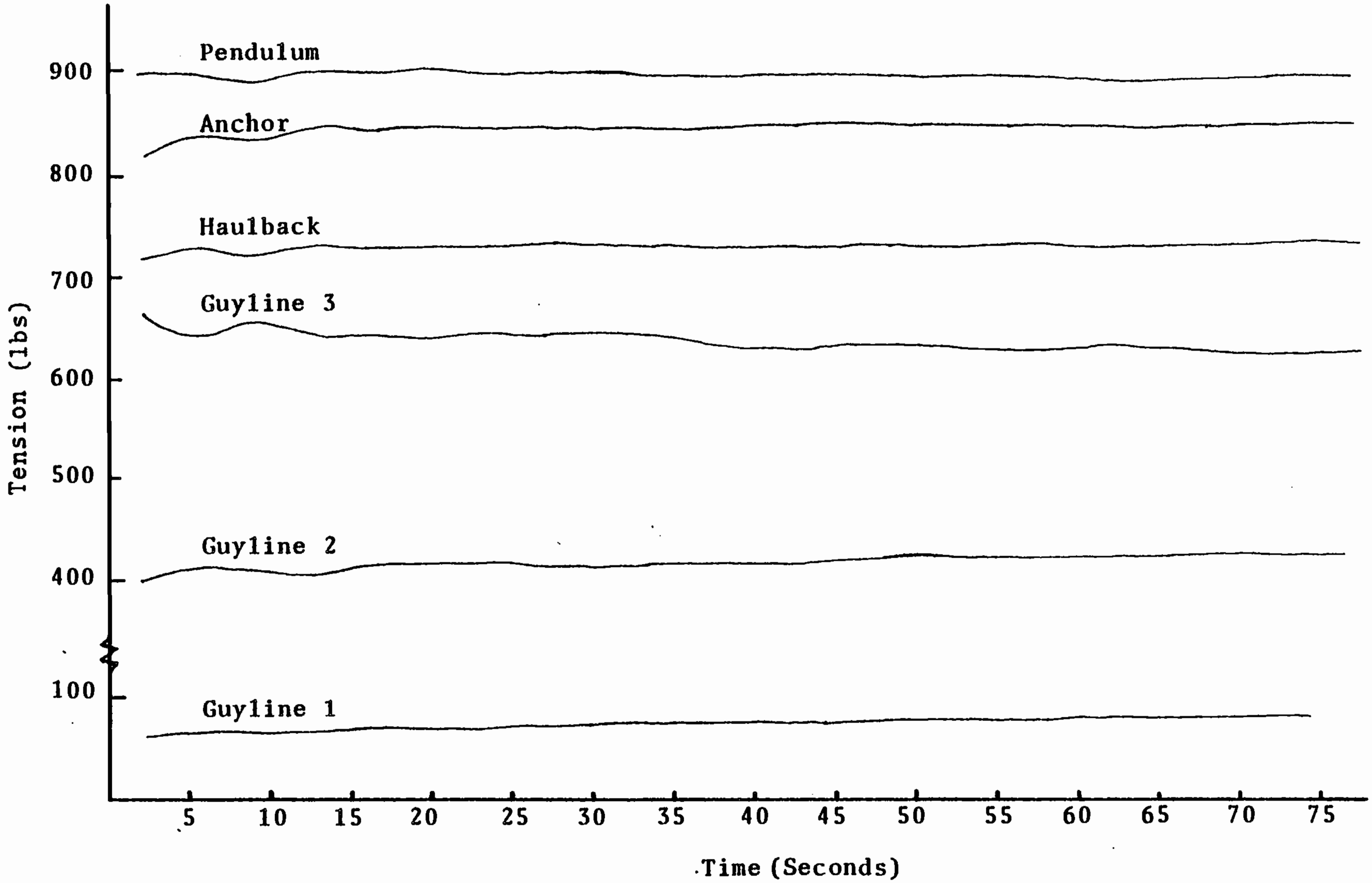


Figure 8. Running Average of Line Tensions

average for a typical test. It can be seen that the average settles down to a consistent value long before the entire sample is included and then remains at that value to the end of the sample. This procedure assisted in locating several tests where mistakes were made in the digitizing process.

Once the above calculations were made following the data checks, the mean tension for each line, standard error of the mean, the maximum and minimum tensions observed, and the sample size for each test were computed. Table 2 gives these values along with anchor number, trial number, and pendulum line length for several tests.

Data Verification

Force balance calculations at the base of the balloon and the lower end of the pendulum line were performed to verify the accuracy of the recorded data. Catenary assumptions were used.

The residual forces were compared to the force induced by wind drag for the wind speed and direction observed for the test. As an example, at anchor 4, trial 1, the residual forces were 16.8 pounds in the minus x direction and 133.6 pounds in the minus y direction or a resultant force of 134.6 pounds. Given the geometry of our experiment, this translates to a force imbalance

TABLE 2. Summary of Field Data - An Example (lbs)

ANCHOR # = 2
TRIAL # = 0
PEND LENGTH = 420

LINE	TENSION	S-ERR	MAX	MIN	N
1	462	7	599	236	121
2	644	5	788	536	121
3	729	8	945	599	121
4	86	1	110	63	121
5	67	1	79	47	121
6	-2	1	16	-16	121

ANCHOR # = 2
TRIAL # = 1
PEND LENGTH = 410

LINE	TENSION	S-ERR	MAX	MIN	N
1	268	5	362	126	121
2	617	5	756	504	121
3	670	7	898	551	121
4	246	1	268	221	121
5	134	1	158	110	121
6	117	1	142	95	121

ANCHOR # = 2
TRIAL # = 2
PEND LENGTH = 400

LINE	TENSION	S-ERR	MAX	MIN	N
1	37	1	47	16	121
2	578	2	630	536	121
3	594	4	693	473	121
4	539	2	599	457	121
5	225	1	252	173	121
6	337	2	378	252	121

ANCHOR # = 2
TRIAL # = 3
PEND LENGTH = 405

LINE	TENSION	S-ERR	MAX	MIN	N
1	15	1	32	0	107
2	595	4	709	536	107
3	600	4	709	488	107
4	581	5	725	410	107
5	231	2	284	173	107
6	358	4	473	221	107

directed South 7 degrees West. Field notes for this test show the recorded wind speed is 7 miles per hour from the north with gusts to 14 miles per hour. Using the drag formula for natural shaped balloons (Goodyear, 1964), a drag force on the balloon of 54 pounds, for a 7 mph wind, and 217 pounds for a 13 mph wind is calculated. A wind speed of 11 mph would put the balloon in almost perfect equilbrium with the 134.6 pound force imbalance we calculated. In all of the tests numerically checked, the force imbalances observed could be directly related to the wind. The majority of the force imbalances observed fell within 5 percent of the lift of the balloon at the time of the test. It was, therefore, concluded that the observations and recorded tensions were sufficiently accurate to portray the behavior of the balloon during the field test.

The force imbalance at the lower end of the pendulum line was larger than the imbalance at the balloon. Even so the imbalance rarely exceeded 10 percent of the tension recorded in the anchor line.

RESULTS

The results will focus on the three important areas identified at the beginning of the paper. 1) What is the system's load lifting capabilities at various locations within the logging unit? 2) What tensions are developed in the guylines and operating lines during yarding operations? 3) How far does the balloon move during load pickup and transport and is this movement significant?

Payload

In any logging system, one of the most important questions is how much it will carry at various locations within the logging unit. Of equal importance to the logging planner is what factors influence how much the system will carry.

From the simple static model presented in the appendix, the lift of the system depends upon the lift of the balloon, the haulback line angle, the guyline angles, and the pendulum line angle.

The lift of the balloon is a function of the size of the balloon and for any system is very nearly constant. During the study, the lift did vary due to helium leakage.

The affect of leakage was accounted for by expressing the payloads and tensions as a percent of the available lift.

In the field study, the haulback line angle was held constant at a zero percent slope because its contribution to payload is well understood and can be calculated. The influence of the haulback angle can be significant. Figure 9 shows computed payload as a percent of available lift versus pendulum line angle for two different haulback angles assuming weightless lines. When the haulback is at thirty degrees above the horizontal, a significant increase in payload can be realized.

The angle which the pendulum line makes with the horizontal when the load is being lifted has a major influence upon the weight which the system will support. Figure 10 is a family of curves of predicted payloads versus pendulum line angles for three different opposing guyline angles based on the weightless line model. In this figure, load capacity decreases as the load point moves away from the balloon, ie., the pendulum angle decreases. Figure 11 compares observed and predicted payloads versus pendulum line angles for the field study. As expected, the measured payload decreases at smaller pendulum line angles. The rate at which the observed payloads decrease closely approximates the predicted value. The difference in magnitude between the predicted

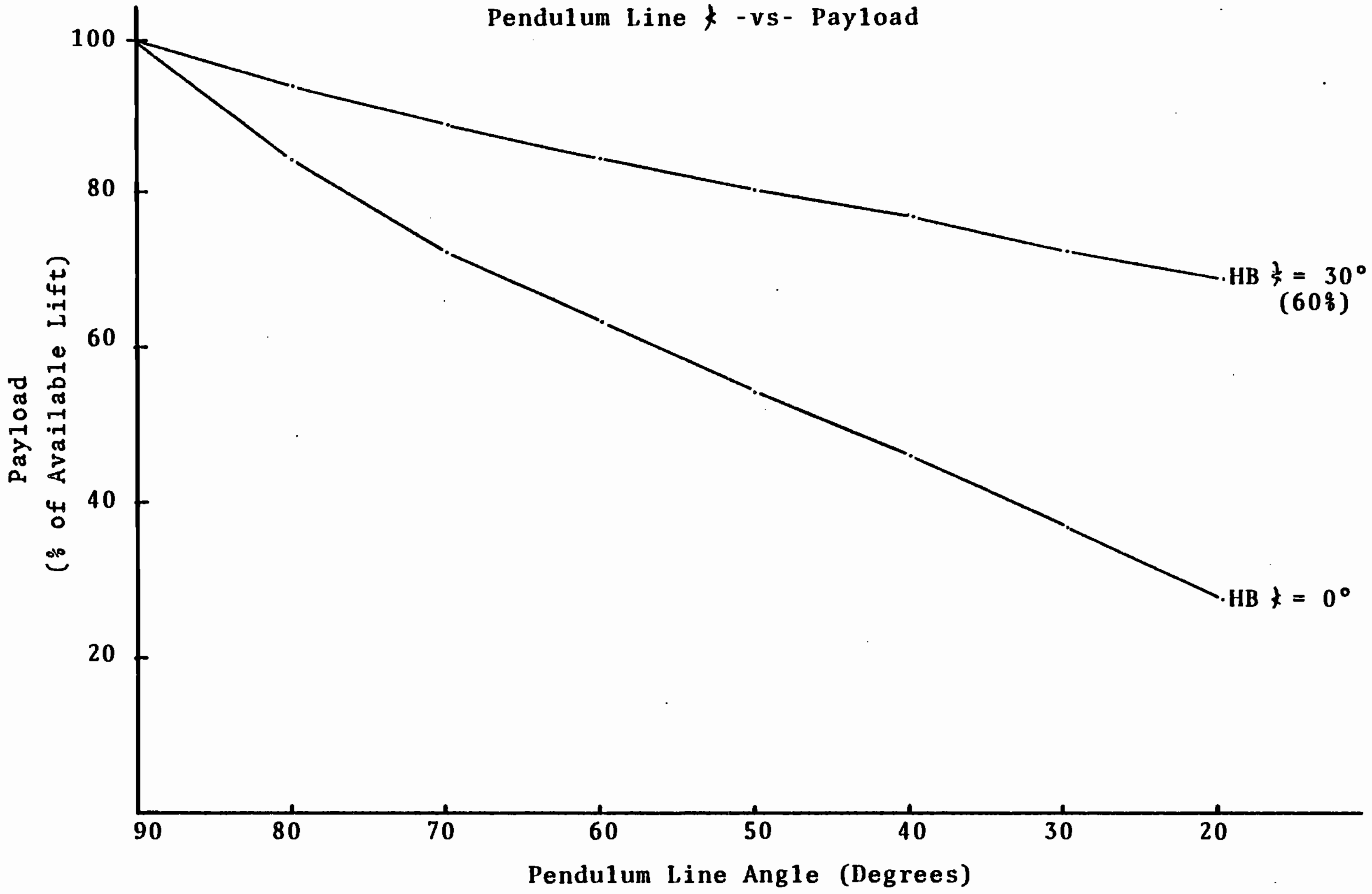


Figure 9. Pendulum Line Angle -vs- Payload for Two Haulback Angles

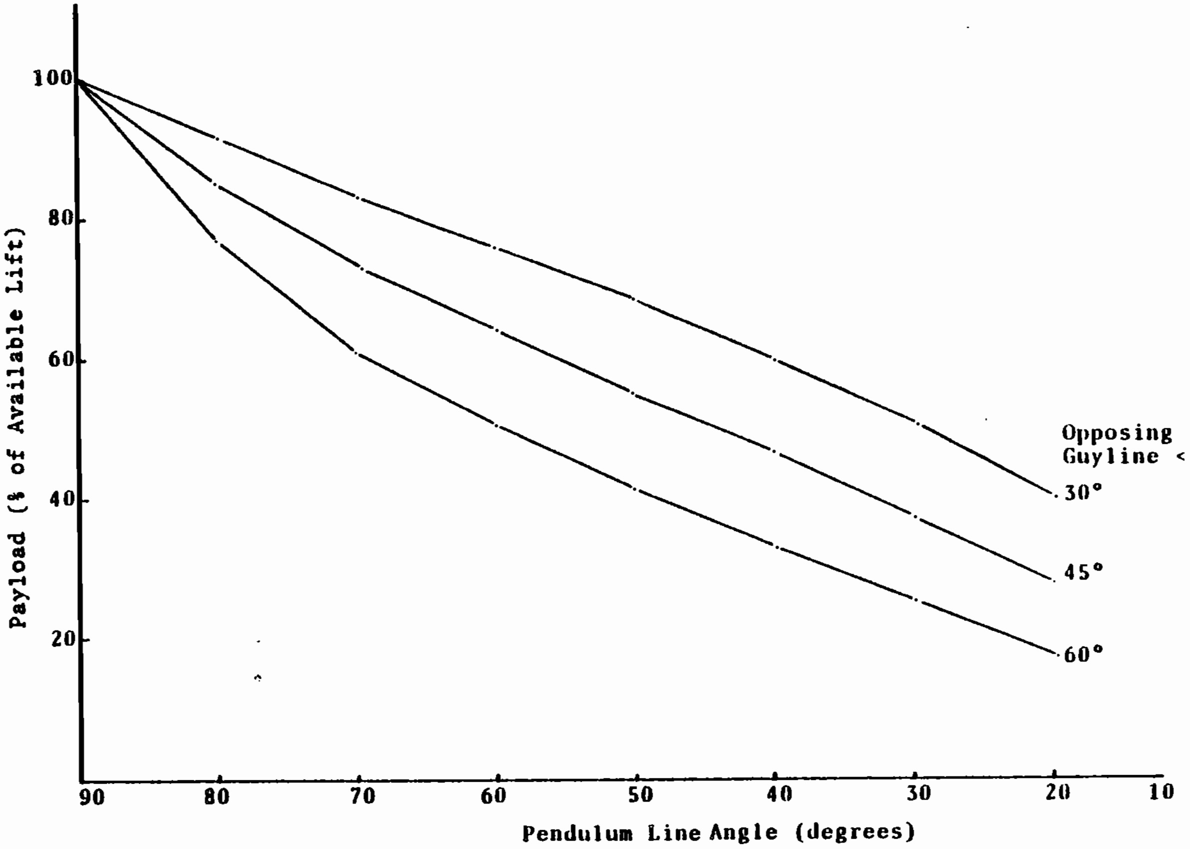
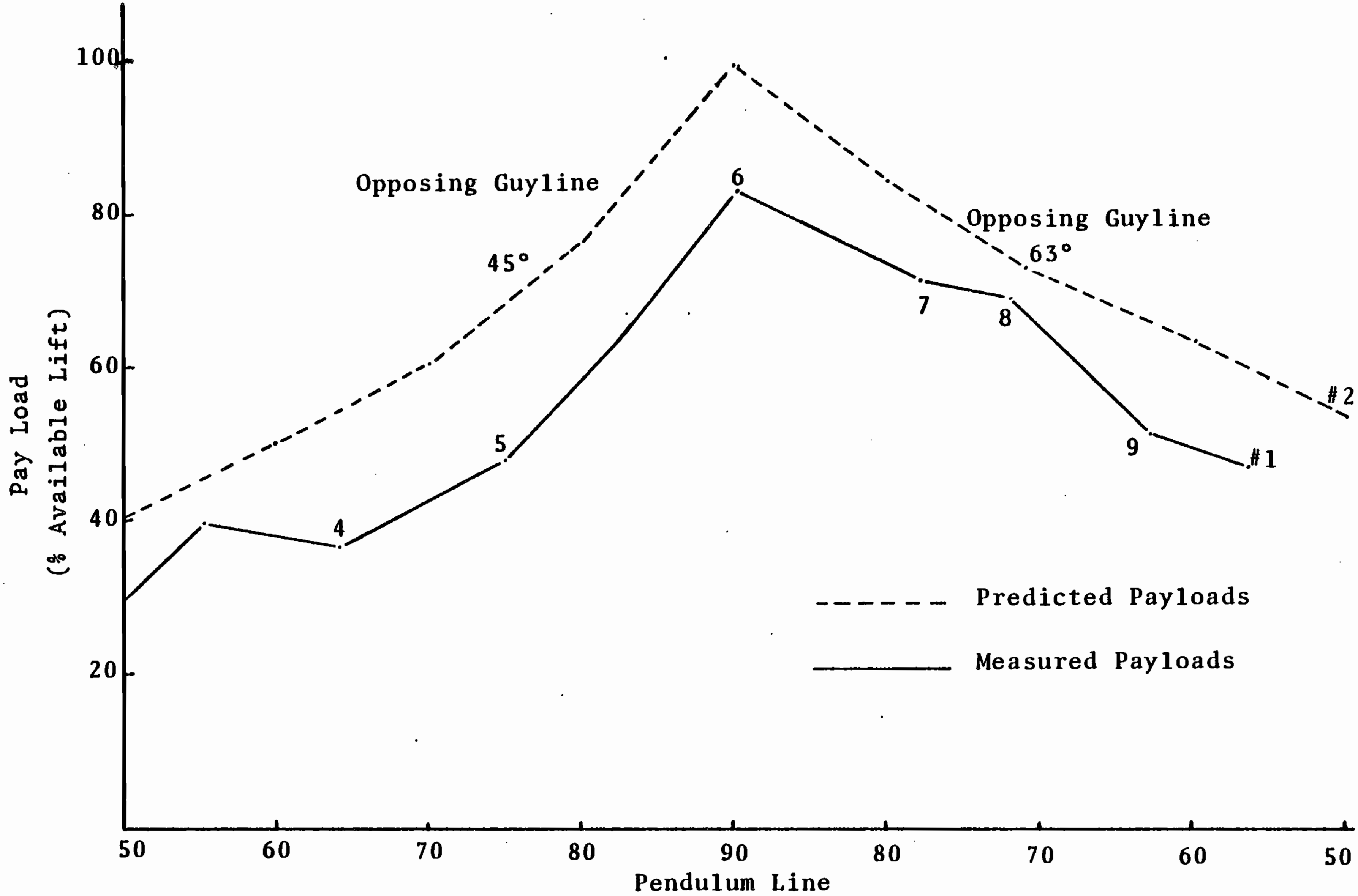


Figure 16. Pendulum Line Angle -vs- Payload for Three Opposing Guyline Angles



<u>Figure 11.</u> Pendulum Line Angle -vs- Payload For Field Study: Predicted and Measured

and observed values is due to the weight of the lines and rigging which are not considered in the predictions and also to the errors inherent in measuring and recording field data.

The angle which the guyline(s) opposing the pendulum line during load pickup make(s) with the horizontal also influences what the system will support at any given pendulum line angle. Figure 10 shows that as the guyline angle becomes more horizontal the payload increases for any given pendulum line angle. This same relationship can be observed in Figure 11 for the field data. For example, when the payload is being lifted at load points 3, 4, or 5, the opposing guyline resultant is at approximately 63 degrees from the horizontal and the payloads are less for any given pendulum line angle than when the loads are at points 7, 8 or 9 and the opposing guyline is at 45 degrees.

Guyline And Operating Line Tensions

The tensions developed in guylines and operating lines in the pendulum swing balloon system need to be known to determine the size of the lines to be used. The tensions developed can be separated into static and dynamic components. This field study concentrated on the static component of line tensions. The dynamic forces are treated in another phase of the project (Beary, 1983).

Guyline tensions for the unloaded balloon can be calculated given the lift of the balloon, the anchor geometry, and the length of the guylines. When the system is loaded, the guyline(s) on the same side of the balloon as the load will go slack as the pendulum line is shortened and the balloon is pulled toward them. The response of the guyline(s) opposing the pendulum line can be predicted using the weightless line model. Two cases are possible. In case 1, the load is picked up inside the triangle defined by the guyline anchors; in case 2, the load is picked up outside this perimeter. Figure 12 illustrates opposing guyline tensions as a percent of net available lift versus pendulum line angle for the two-dimensional model.

When the system is not loaded, the tension in the opposing guyline can be determined by substituting guyline G1 for the pendulum line on the graph. Entering Figure 12 on the pendulum line axis with the angle of the guyline G1, which is on the same side as the pendulum line, and read up to the line which represents the angle of the opposing guyline G2 then read over the opposing guyline tension.

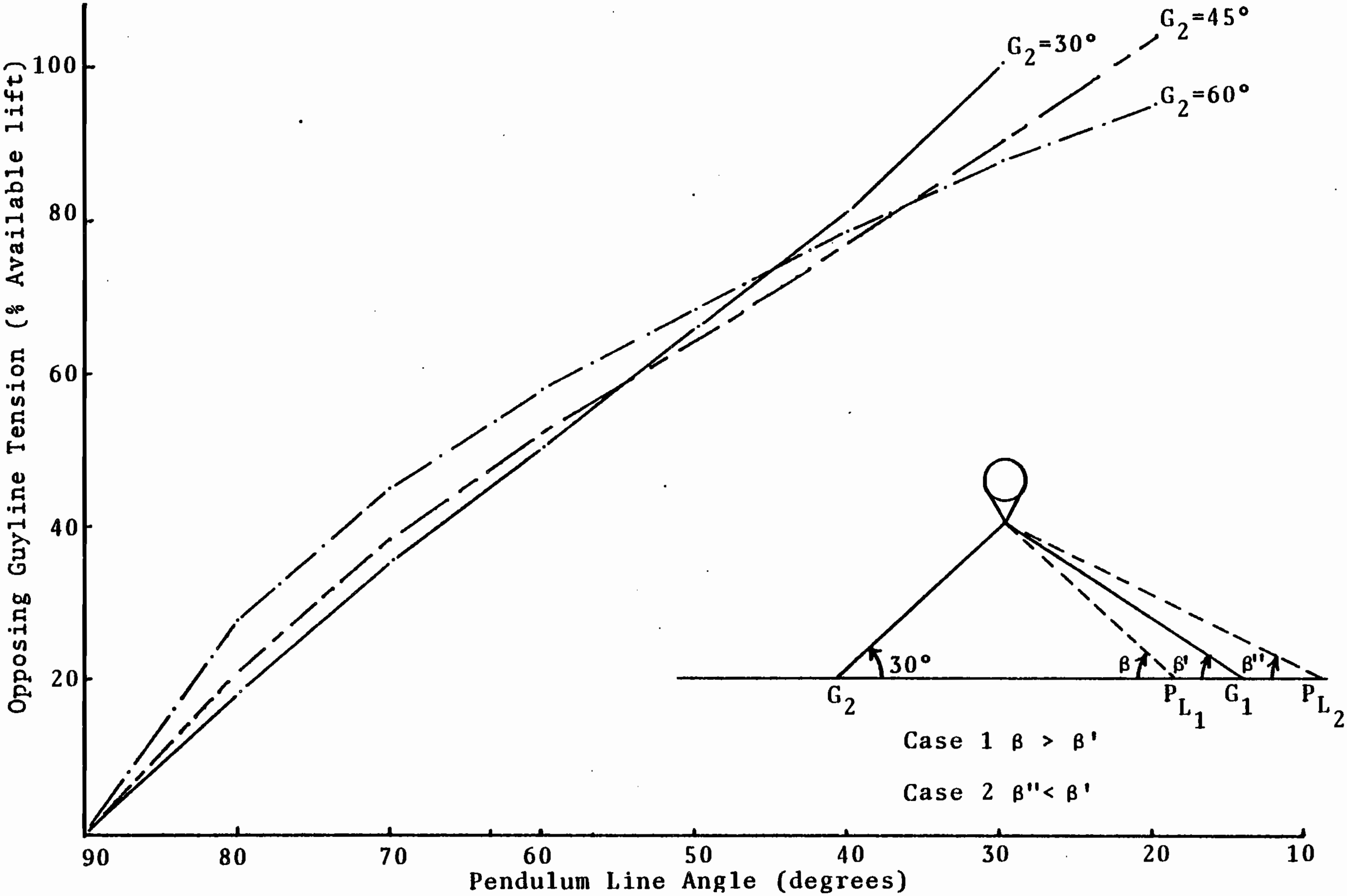


Figure 12. Pendulum Line Angle -vs- Opposing Guyline Tension

In case 1 of the loaded situation, the pendulum line angle (β) is greater than the angle (β') of the guyline G1 on the same side as pendulum line. The tension in the opposing guyline G2 is found by entering Figure 12 with the angle (β) and reading up and over to the vertical axis. When (β) is greater (β') the opposing guyline tension will be lower for the loaded situation than for the unloaded. This is because the pendulum line has a larger vertical component of tension than the guyline which it is replacing, leaving less of the lift of the balloon to be supported by the opposing guyline.

In case 2, the pendulum line angle (β'' double prime) is smaller than the angle (β' prime) of the guyline G1. In this case, Figure 12 would predict a higher tension in guyline G2 for the loaded case than for the unloaded case.

Results from the Sky Hook model should correlate with results of the field study. Figure 13 illustrates tension in the opposing guyline versus pendulum line length for load points 7, 8, 9, and 10. Notice that the pendulum line is shortened as we move to the right on the graph. Referring to Figure 4, we see that load points 7, 8, and 9 are inside the guylines and load point 10 is slightly outside. From Sky Hook, a drop in the tension fo the opposing guyline should occur at load points 7, 8, and 9 as the pendulum line is shortened and the system loaded.

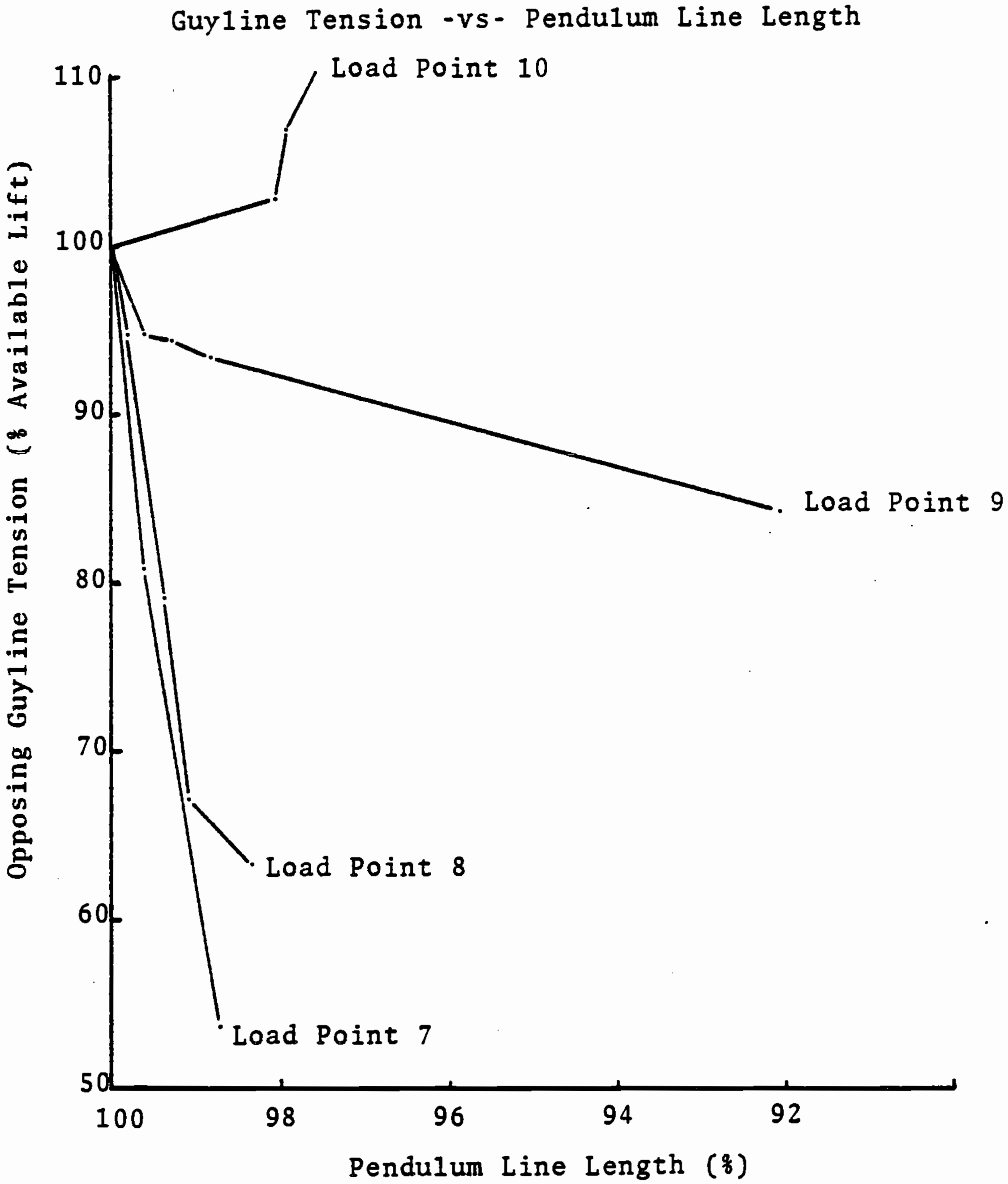


Figure 13. Pendulum Line Length -vs- Guyline Tension

Figure 13 shows that for load points 7 and 8, the reduction in opposing guyline tension is immediate and very pronounced. At load point 9, the reduction in tension is not as sharp, but the trend is still evident and is in the correct direction. The analysis predicts that the tension in the opposing guyline should rise for load point 10. Field observations confirm this fact after making allowances for scatter of the data.

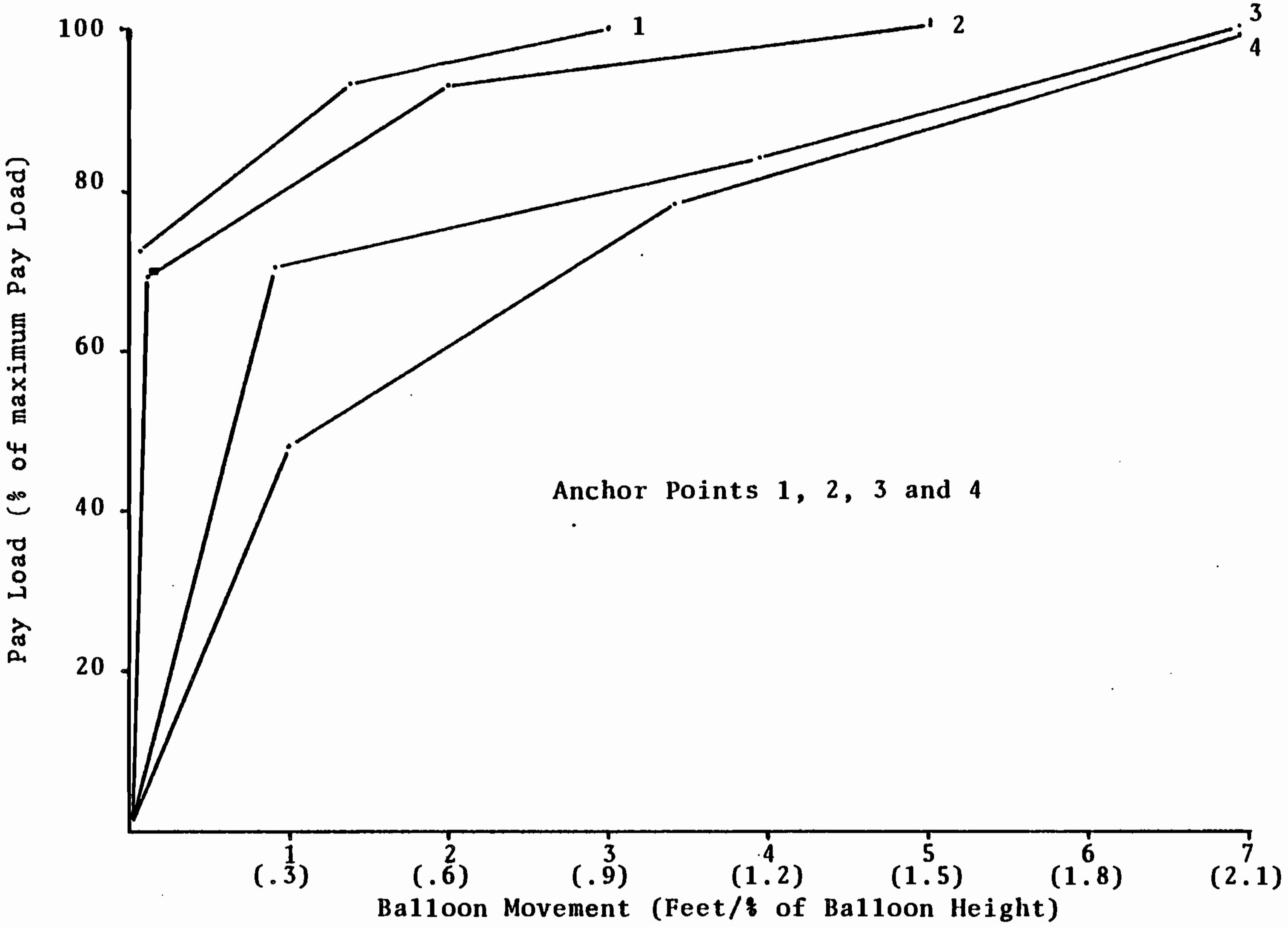
Balloon Movement

Quantifying the relationship between balloon movement and load requires a definition of load. In the pendulum balloon system, loading begins as the pendulum line is connected to the payload and the line is shortened. When this happens, one or more of the guylines will begin to go slack. A loaded system is any situation in which at least one of the guylines has a vertical component of tension at the lower end at or near zero. Guyline tensions for any load situation can be determined using the catenary equations. Conversely, the lift of the system can be evaluated when the vertical component of tension at the lower end of a guyline is at or near zero.

The coordinates of the balloon position were calculated for each test and from these cordinates balloon movement was calculated as deviation from the unloaded position of the balloon.

Figure 14 shows balloon movement as a function of payload for load point 1, 2, 3, and 4. As the pendulum line is shortened, payload increases very rapidly initially and then the rate of increase drops to almost zero. This demonstrates that relatively little balloon movement is required before a guyline goes slack and the system is loaded. A great deal of balloon movement would be required to increase the payload beyond this value. The result is logical if the system is viewed as three catenary guylines holding the balloon in place and all sharing equally in the vertical tension induced by balloon lift. A small movement of the balloon in the direction of one of the guyline anchors quickly reduces the vertical tension in the lower end of that guyline to near zero.

Exactly how far the balloon will move for a given load is very difficult to quantify but is a function of balloon height, guyline lengths, guyline angles, ground slope, load position, and pendulum line angle. The higher the balloon and the longer the guylines, the more the balloon will move. In any case, the movement will be a very small percent of the yarding distance. In the system



<u>Figure 14.</u> Payload -vs- Balloon Movement

used in our field study, the balloon moved no more than 10 feet with respect to any anchor point even when fully loaded (Figure 14).

DISCUSSION

It was not feasible to accurately scale the field experiment to a larger, operational system. Therefore, it is not possible to directly transfer the magnitude of the reactions observed in the field study to a full-scale system. However, some general conclusions about the performance of a pendulum swing balloon system can be drawn from the field experiments. 1) Balloon movement does not appear to be a major problem given the differences between an unloaded and a loaded balloon position as observed in the field study. For anticipated applications, the balloon may be viewed as fixed in position. 2) The payload that the system will support is a function of four variables: a) the lift of the balloon, b) the haulback angle, c) the pendulum line angle, d) the opposing guyline angle. The results of the field experiments confirmed the importance of these variables predicted by the weightless line analysis. 3) The lift of the balloon will be relatively constant for a given situation. 4) On a given harvest unit, the pendulum line angle measured from the horizontal should be kept as large as possible to maximize payloads consistent with other considerations. 5) The opposing guyline angles should be minimized to maximize payload. 6) The steeper the haulback angle, the more this line will assist in picking up a load.

These guidelines are not mutually attainable and the limits imposed by allowable line tensions and line weights will enter into any system planning.

OPPORTUNITIES FOR FURTHER RESEARCH

1. Develop the techniques to optimize the system configuration to attain the highest possible payload consistent with other system constraints.

2. Implement a full-scale field project to test the optimization model and evaluate payload capabilities.

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APPENDIX

BALLOON PAYLOAD AND CONSTRAINT EQUATIONS

Problem: Maximize W for any given L and γ

When:

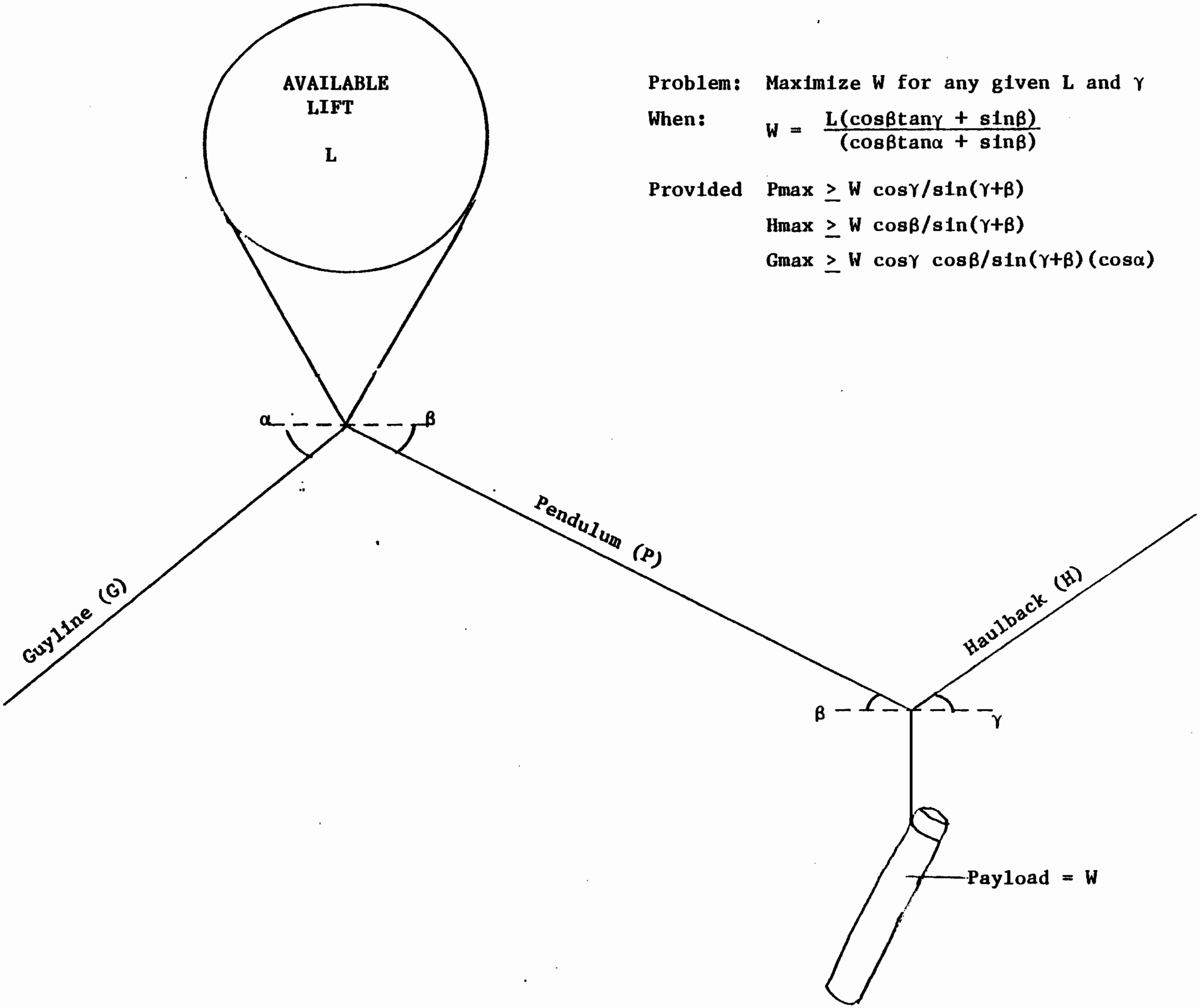
$$W = \frac{L(\cos\beta\tan\gamma + \sin\beta)}{(\cos\beta\tan\alpha + \sin\beta)}$$

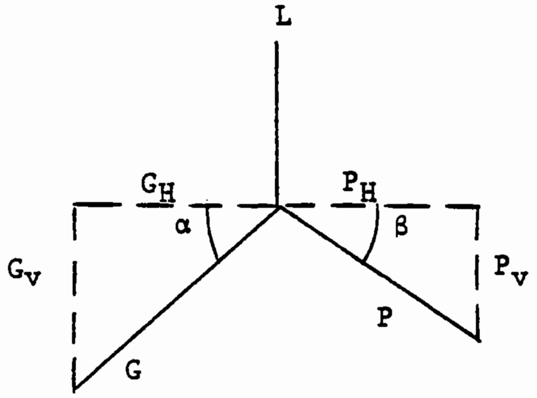
Provided

$$P_{max} \geq W \cos\gamma/\sin(\gamma+\beta)$$

$$H_{max} \geq W \cos\beta/\sin(\gamma+\beta)$$

$$G_{max} \geq W \cos\gamma\ \cos\beta/\sin(\gamma+\beta)(\cos\alpha)$$





Assume Static Equilibrium

1. $G_H = P_H \qquad G_H = G \cos \alpha \qquad P_H = P \cos \beta$

   $\therefore \; G = \dfrac{P \cos \beta}{\cos \alpha}$

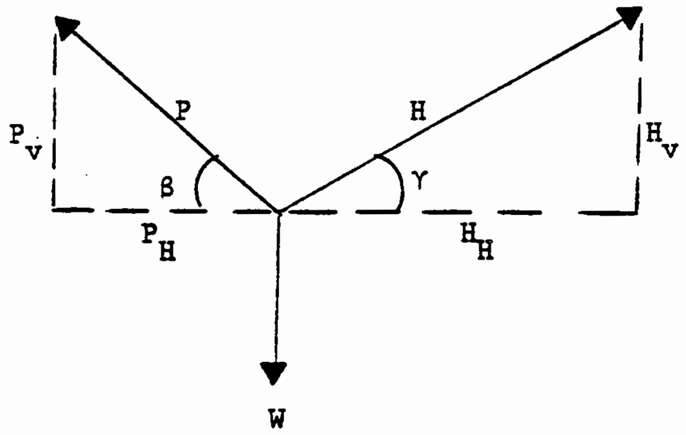
2. $G_V = G \sin \alpha = \dfrac{P \cos \beta}{\cos \alpha} \sin \alpha = P \cos\beta \tan \alpha$

   $P_V = P \sin \beta$

3. $L = G_V + P_V = P \cos\beta \tan\alpha + P \sin \beta$

   $L = P(\cos\beta\tan\alpha + \sin\beta)$

4. $\therefore \; P = \dfrac{L}{\cos\beta \tan\alpha + \sin\beta}$



5. $H_H = P_H = P\cos\beta = \dfrac{L\cos\beta}{\cos\beta\tan\alpha + \sin\beta}$

6. $H = \dfrac{H_H}{\cos\gamma}$ $\quad H = \dfrac{L\cos\beta}{(\cos\beta\tan\alpha + \sin\beta)\cos\gamma}$

7. $H_v = H\sin\gamma$ $\quad H_v = \dfrac{L\cos\beta\sin\gamma}{(\cos\beta\tan\alpha + \sin\beta)\cos\gamma}$

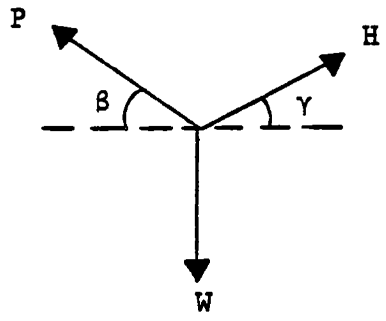
$H_v = \dfrac{L\cos\beta\tan\gamma}{(\cos\beta\tan\alpha + \sin\beta)}$

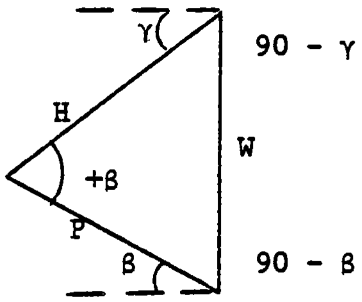
8. $P_v = P\sin\beta = \dfrac{L\sin\beta}{\cos\beta\tan\alpha + \sin\beta}$

9. $W = P_v + H_v = \dfrac{L(\cos\beta\tan\gamma + \sin\beta)}{\cos\beta\tan\alpha + \sin\beta}$

This gives us W in terms of L and the angles. However, we are constrained by the strengths of our various lines. Therefore we need constraint equations for these.

CONSTRAINTS



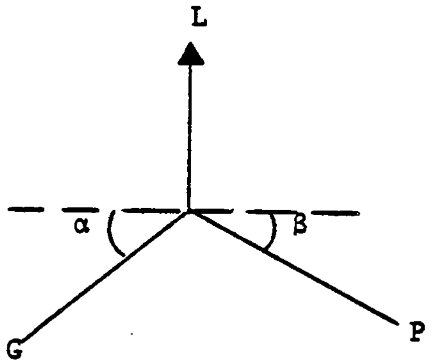


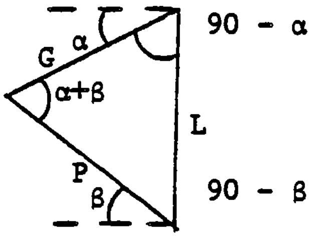
By Sine Law

$$\frac{W}{\sin(\gamma+\beta)} = \frac{H}{\sin(90-\beta)} = \frac{P}{\sin(90-\gamma)}$$

$$\therefore \quad H = \frac{W\sin(90-\beta)}{\sin(\gamma+\beta)} = \frac{W\cos\beta}{\sin(\gamma+\beta)}$$

$$P = \frac{W\sin(90-\gamma)}{\sin(\gamma+\beta)} = \frac{W\cos\gamma}{\sin(\gamma+\beta)}$$





By Sine Law

$$\frac{G}{\sin(90-\beta)} = \frac{P}{\sin(90-\alpha)} = \frac{L}{\sin(\alpha+\beta)}$$

$$\therefore \quad G = \frac{P\sin(90-\beta)}{\sin(90-\alpha)} = \frac{P\cos\beta}{\cos\alpha}$$

By substitution

$$G = \frac{W\cos\gamma\cos\beta}{\sin(\gamma+\beta)\cos\alpha}$$

Also $G = \dfrac{L\cos\beta}{\sin(\alpha+\beta)}$

PROGRAM: SKYHOOK (SKY J)

: FOR HP-41C

PURPOSE: To determine the payload of the pendulum swing balloon system given the lift, guyline angles, pendulum angles, and haulback angles.

```
01◆LBL "SKYJ"
02 "LIFT?"
03 PROMPT
04 STO 01
05 "LIFT="
06 ARCL X
07 PRA
08 ADV
09◆LBL 01
10 "GUYLINE∠?"
11 PROMPT
12 STO 02
13 "GUYLINE∠="
14 ARCL X
15 PRA
16 ADV
17 "PENDULUM∠?"
18 PROMPT
19 STO 07
20 "PENDULUM∠="
21 ARCL X
22 PRA
23 ADV
24 "HAULBACK∠?"
25 PROMPT
26 STO 04
27 "HAULBACK∠="
28 ARCL X
29 PRA
30 ADV
31◆LBL 02
32 RCL 07
33 INT
34 STO 03
35 RCL 03
36 COS
37 RCL 04
38 TAN
39 *
40 RCL 03
41 SIN
42 +
43 RCL 01
44 *
45 RCL 03
46 COS
47 RCL 02
48 TAN
49 *
50 RCL 03
51 SIN
52 +
53 /
54 STO 05
55 "PAYLOAD="
56 ARCL X
57 PRA
58 ADV
59 RCL 05
60 RCL 04
61 COS
62 *
63 RCL 04
64 RCL 03
65 +
66 SIN
67 /
68 STO 06
69 "PEND-TENSION="
70 ARCL X
71 PRA
72 ADV
73 RCL 05
74 RCL 03
75 COS
76 *
77 RCL 04
78 RCL 03
79 +
80 SIN
81 /
82 "HB-TENSION="
83 ARCL X
84 PRA
85 ADV
86 RCL 06
87 RCL 03
88 COS
89 *
90 RCL 02
91 COS
92 /
93 "GL-TENSION="
94 ARCL X
95 PRA
96 ADV
~~97 ISG 07~~
~~98 GTO 02~~
99 GTO 01
100 .END.
```