Abstract

AkiTi Limited offers to design passive greenhouses, each one individually fashioned for its unique site. Several features are incorporated into the design to make it more energy-efficient: first, the south face is configured to enhance the greenhouse's ability to exploit sunlight over a specified period. Second, much area that does not admit direct sunlight is covered with insulation rather than glazing. Third, the north wall is painted reflective white and angled to reflect sunlight onto the ground rather than back out of the greenhouse. These features enhance greenhouse performance while cutting cold-weather operating costs by about forty percent.

For information, contact

David Binner
e-mail: use the contact address on the thothworks website
Web Site: http://www3.telus.net/thothworks/home.html

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1 Introduction

This paper describes the procedure by which AkiTi designs a passive greenhouse for a specific site. The results of this approach are incorporated into a fictional greenhouse, The Abbotsford Model, which is described in Section 2.

The first element of AKiTi's design to note is the south face of the greenhouse. This face is often angled according to some "Rule of Thumb" or simply set vertically. AKiTi, on the other hand, employs a computer program to determine the angle at which glass must be oriented to maximize sunlight transmission over a specified period[1]. Appendix A-1 explains the basic theory on which the computer program is based.

Another element of AKiTi's design that distinguishes it from other designs is the north wall. Rather than being covered with glazing material, it is an opaque, insulated, wall. In addition, it is angled appropriate to the site latitude and painted reflective white.

2 An Example Design - The Abbotsford Model

The Abbotsford Model is a fictional greenhouse used to illustrate the process by which AkiTi designs a greenhouse for **any** site. It is a stand-alone greenhouse assumed to be situated in Abbotsford, BC, Canada.

For good sunlight penetration into the greenhouse, the ratio of length (East-West dimension) to width (North-South dimension) was kept in the range 1.5:1 to 2:1.

The entrance to the greenhouse was placed on the North side through a storage area that doubles as an airlock to prevent cold drafts of air from directly hitting plants. Furthermore, the storage area adds to the structural stability of the building.

Four-foot square vents were included on the upper portions of the East and West sides. Areas on the North side of the vents and above the vents are insulated. In the winter, these vents are assumed to be sealed and insulated. See Figure 1 for a floor plan and Figure 2 for a side view.

2.1 Orientation

The Abbotsford model was assumed to have an unobstructed view of the Sun over the desired period. As a result, it was given the best orientation possible: it faces true south[2]. In the real world, however, a site may suggest another orientation: (1) It may be convenient to attach the greenhouse to

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[1] This orientation angle need not be confined to use in greenhouse construction; any application utilizing sunlight benefits by knowing the angle which best receives it: sunrooms and covered patios, for example. Photovoltaic cells oriented optimally would receive more sunlight than if they were fixed at some random angle.

[2] True south is NOT magnetic south. In Abbotsford, they differ by about 21°. If you were to face south as indicated by a magnetic compass, true south would be found by turning 21° to your left. This value is not the same everywhere; to find the magnetic declination at a given site, consult a local geologist or airport.

an existing building, which may not permit a true south face; (2) Obstructions may hide the Sun for portions of the day. For example, if trees block early morning sunlight, greenhouse performance might be better if it faced west of true south; (3) Early warming may be desired, so the greenhouse may be faced east of true south to better utilize morning sunlight.

2.2 The South Face

The south face of The Abbotsford Model was divided into two sections to make it more effective than it would be as a single section. A large-angle section takes advantage of sunlight when the Sun is low. A small-angle section takes advantage of sunlight when the Sun is high. The south face could have been further divided to further improve its performance; ideally, it would be curved. However, the design would have become too complicated. The present model is an effective compromise: it is relatively simple yet provides efficient year-round operation[3].

The period of study was then chosen. The coldest two months of the year in Abbotsford are December and January; however, these months receive negligible sunshine (Appendix A2 contains data for Abbotsford). Attempting to use sunlight over a period that has none is pointless. On the other hand, summer months are warm enough; the ability to exploit free heat from sunlight is not as critical during summer months as it is during colder seasons. The south face of The Abbotsford Model was finally configured for two periods: March/April and September/October. These periods are similar in terms of temperature and the path the Sun follows in the sky. A design that enhances greenhouse performance for spring enhances autumn performance as well–the benefits are doubled.

The rear wall was angled at NW° (the reason is given in the next section) and the maximum greenhouse height set at HH feet. To ensure good light penetration into the greenhouse, a spot was picked on the rear wall four feet above the ground and a south face configuration found that would transmit the most light to that spot.

The resulting configuration for the south face was found to be a low section angled at LL° to the horizontal and an upper section angled at UU° to the horizontal (See Figure 2). This configuration admits 30% more sunlight than a single vertical south face. Alternately, the best angle for March alone is MM°. Over the same periods, a single MM° section admits 99% of the sunlight admitted by The Abbotsford Model. Since these two configurations admit almost identical amounts of sunlight over the specified periods, why not use the simpler, single-face, design? A two-section design was chosen instead of a single-section design because a two-section south face enhances the greenhouse's ability to utilize sunlight when the Sun is low. This consideration is important because the Sun's path in the sky is lower during the coldest months of the year than at other times. As a result, a steep angle is better for cold-weather operation than a shallow angle (in fact, the best angle for the coldest month of the year, January, is JJ°). A south face that includes a section angled at LL° makes the greenhouse more effective over all non-summer months--performance is improved not just for the periods March/April and September/October, but for November, December, January, and February as well.

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[3] Although the south face is configured for spring and autumn, it still performs well in the summer. It admits more sunlight than it would as a single vertical face; however, it does not perform as well as a face designed specifically for a summer period.

2.3 The North Wall

The north wall of The Abbotsford Model is opaque and well-insulated; heat losses are reduced but direct sunlight is still admitted through the other three sides. To ensure that sunlight is admitted throughout the year, the north wall was given an angle to coincide with the Sun's angle at its highest point of the year. A larger angle would be pointless because the Sun never goes any higher; a larger angle would simply cause more heat loss (the south face would have to be extended; more area would be covered by glazing and less by insulation).

The highest point the Sun reaches in the sky is at noon on the day of summer solstice, generally around June 21. In Abbotsford, this angle is approximately NW° above the horizontal. The north wall of The Abbotsford Model was, therefore, given an angle of NW° above the horizontal (See Figure 2).

The largest benefit of an opaque, insulated north wall is the reduction in heat loss. A greenhouse with all sides covered by glazing loses much more heat during cold weather (See Figure 3). Assuming an R-value of 28, The Abbotsford Model loses 40% less heat than the greenhouse with glazing on all sides. In addition, construction costs are reduced (glazing is more expensive than insulation). Insulating the walls of the storage area in addition to insulating the north wall further reduces heat loss.

An opaque north wall does not adversely affect plant growth; in fact, one study indicates that a north wall painted reflective white promotes better plant growth than a north wall covered with glazing material[4]. Because a reflective white north wall reflects direct (strong) sunlight whereas a glazed north wall admits diffuse (weak) sunlight, the overall level of light in the greenhouse is raised by having a reflective north wall instead of a north wall covered by glazing material.

The downward angle of the north wall provides a benefit as well: less sunlight is reflected back out of the greenhouse. In other words, more heat stays in the greenhouse.

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[4] Heeschen, Conrad. "The Greenhouse as a Solar Collector." The Solar Greenhouse Book. McCullagh, James C,. ed. Emmaus, PA: Rodale Press, 1978. pp 7-35.

3 Choices

Before a greenhouse can be designed, some information is required:

(1) A Southern Horizon Profile must be drawn depicting features of the landscape that might block sunlight from the greenhouse (See Figure 4 for an example. Figure 5 is a blank chart; it can be copied and used for other sites.).
(2) The orientation must be decided. For reasons mentioned in Section 2.1, the greenhouse may not face true south.
(3) The latitude and altitude of the site must be known.
(4) A period must be chosen for which the south face is to be configured. AKiTi's computer program can be set for the periods September 9 - November 8, January 1 - May 1, or a combination of sub-periods.
(5) The average temperature and pressure over the specified period must be known.
(6) The amount of growing area must be chosen. Is a storage area in the rear desired? If so, should it have a minimum height?
(7) The maximum height of the greenhouse must be decided.
(8) The range of angles for the roof must be specified. Do local laws regulate this angle?
(9) The angle of the north wall must be chosen. Is it to be set to the Sun's angle at summer solstice or does the gardener wish it to be lower?
(10) Does the gardener have any other factors to take into account (ie - vents)?

Given the factors listed above, AKiTi determines the shape of a greenhouse which represents the best compromise: the angle(s) of the south face are computed; simple diagrams like Figures 1 and 2 are produced (AKiTi does not draw proper blueprints); and a comparison is made between the amount of sunlight admitted by AKiTi's design and a vertical south face.

A few of the points listed above deserve elaboration. First, consider the angle of the roof. Where snow loads are small, the gardener may have a range from which to choose. By keeping the angle small, the height of the greenhouse is kept low, thereby lowering construction costs and the amount of surface area through which heat is lost. On the other hand, the proposed site may be where snow loads are large; the angle may have to be kept above a minimum specified by municipal laws.

Next, consider the angle of the north wall. For efficiency, the greenhouse should be no higher than necessary; in other words, the north wall angle should be no larger than necessary. AKiTi generally uses the Sun's angle at summer solstice as a maximum for the north wall angle. A smaller angle lowers the greenhouse height, but it also creates shadows in the rear of the greenhouse when the Sun is high in the sky (see Figure 6). This situation may be convenient for some gardeners; after all, the Sun is highest in the middle of summer days when overheating is a problem. In fact, some gardeners may choose to lower the north wall angle specifically to reduce overheating in the summer while at the same time reducing the amount of area covered by glazing material. As long as the angle is not so small that the greenhouse becomes an awkward place in which to work, heat losses in the winter would be reduced.

The south face, also, can be fine-tuned to the wishes of the gardener and the unique features of the site. One gardener may want a simple design configured for a single month only. In this case, a single section might be acceptable (rather than a two-section design like The Abbotsford Model). Another gardener may wish to pick sub-periods in determining the configuration of the south face. For example, the sub-periods October 1 - October 31 and February 1 - March 2 might be chosen. The gardener may go further and decide that the first and last hours of daylight are insignificant. The gardener may also try to account for consistent weather: for example, cloudy mornings and clear afternoons. AKiTi's computer program can handle either of these conditions to create a greenhouse that is better adapted to its site.

The desire for year-round operation is another factor that affects greenhouse design. If the greenhouse is intended to operate all year, and is situated where December and January receive sunshine, the gardener may decide to configure the south face for these two months. Alternately, the gardener may decide to configure the south face for spring and autumn anyhow; enhancing performance for all non-summer months instead of just two is more cost-effective. Either way, artificial heating and lighting are still required in northern locations over the coldest periods.

The presence of vents, their sizes and shapes, the type of glazing material, and the level of insulation are yet more factors that must be decided by the gardener. The structure may also be modified by insulating upper portions of the east and west sides. Increasing the area covered by insulation would reduce heat losses, yet low-angle sunlight from the morning and evening Sun would still be admitted through the lower portions. Here is yet another way in which a gardener can personalize the greenhouse. The point should be stressed that **each greenhouse is custom-designed. Characteristics of a greenhouse at one site are not identical elsewhere**.

4 Summary

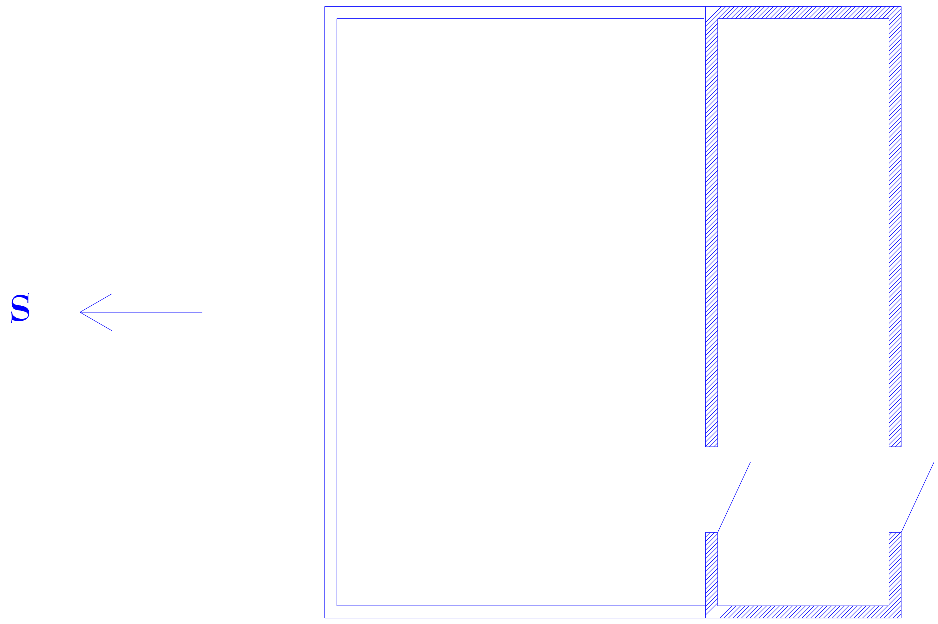
AKiTi Limited offers a flexible design process in which features of a site are engaged to create a more energy-efficient greenhouse. Starting with a few basic parameters given by the gardener, AKiTi employs a computer program to determine the configuration of south face that admits the most sunlight into the greenhouse over a specified period. For example, the south face of The Abbotsford Model admits 30% more sunlight over the months of September/October and March/April than it would as a single vertical face. Stated another way, simply by configuring the south face properly–no sophisticated, expensive materials–a heat gain of 30% is achieved.

To further make the greenhouse energy-efficient, AKiTi replaces much glazing with insulation. In the case of The Abbotsford Model, heat loss is reduced by about 40%. Heat loss is further reduced by angling the north wall downward instead of setting it vertical; more sunlight is reflected onto the ground rather than back out of the greenhouse.

The greenhouse's ability to exploit free heat from sunlight enhances its capacity both to extend the season and to be used year-round. As a season extender, AKiTi's design brings Spring into the greenhouse sooner and pushes Winter back later. This ability benefits year-round operation as well: extending the growing season reduces the time for which artificial heating is required. When artificial heating does become necessary, the amount required is reduced by a well-insulated structure. In conclusion, designing for a site's unique characteristics rather than erecting an indiscriminate design yields a greenhouse with enhanced performance. As The Abbotsford Model illustrates, a thoughtful design reduces heat losses by about forty percent year after year.

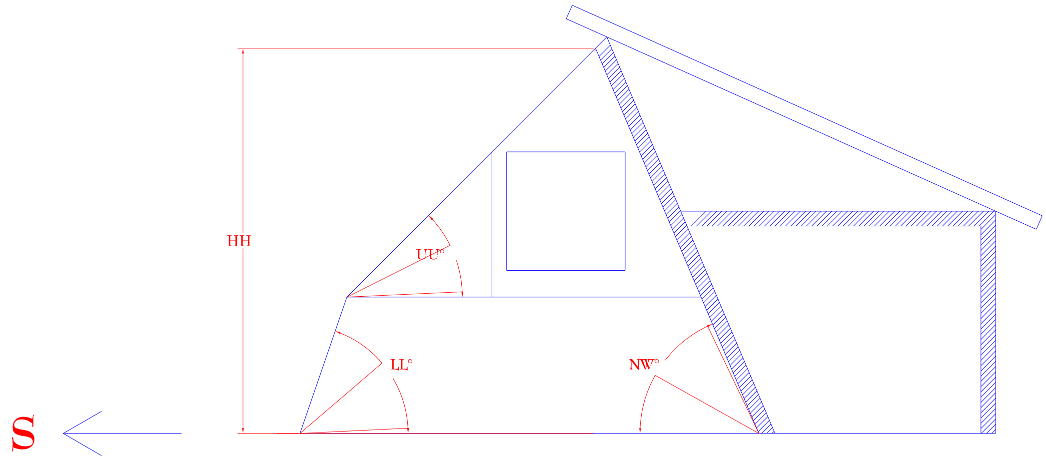
5 Figures

Figure 1



Top View

Figure 2



View From East

Figure 3

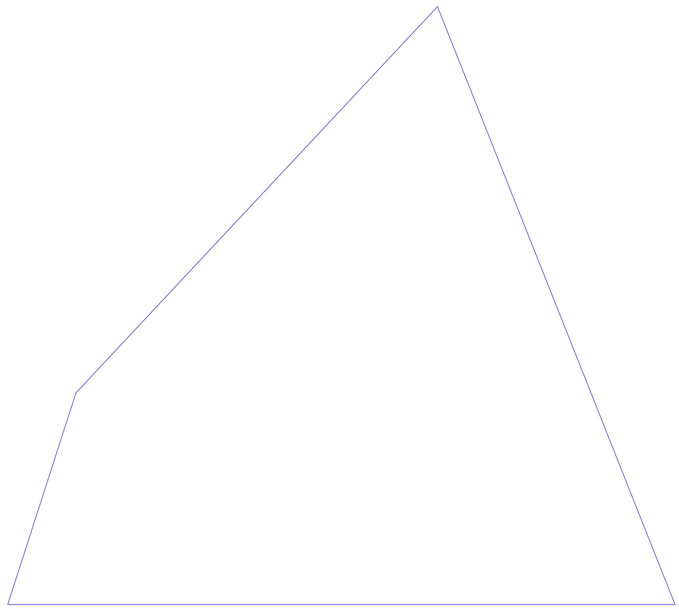
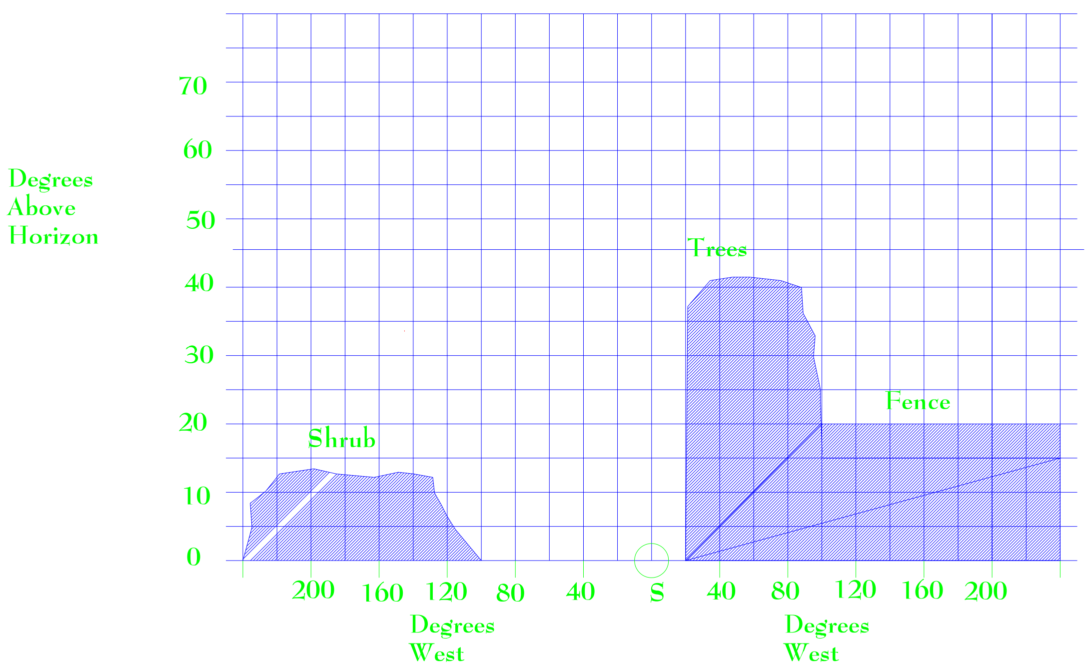


Figure 4



View to South

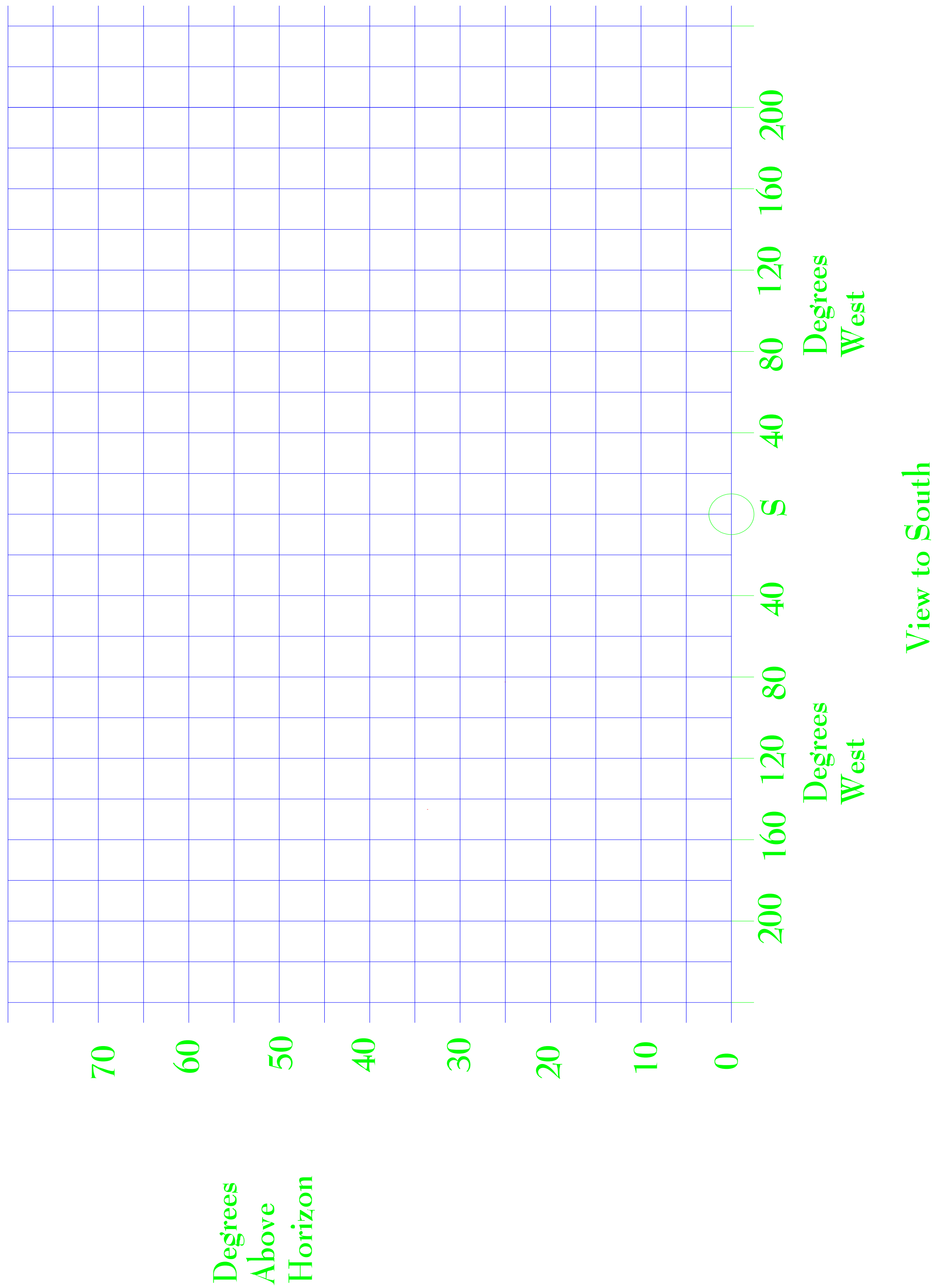

View to South
S
Degrees West
Degrees West
40
80
120
160
200
40
80
120
160
200
Degrees Above Horizon
0
10
20
30
40
50
60
70

Figure 5

Figure 6

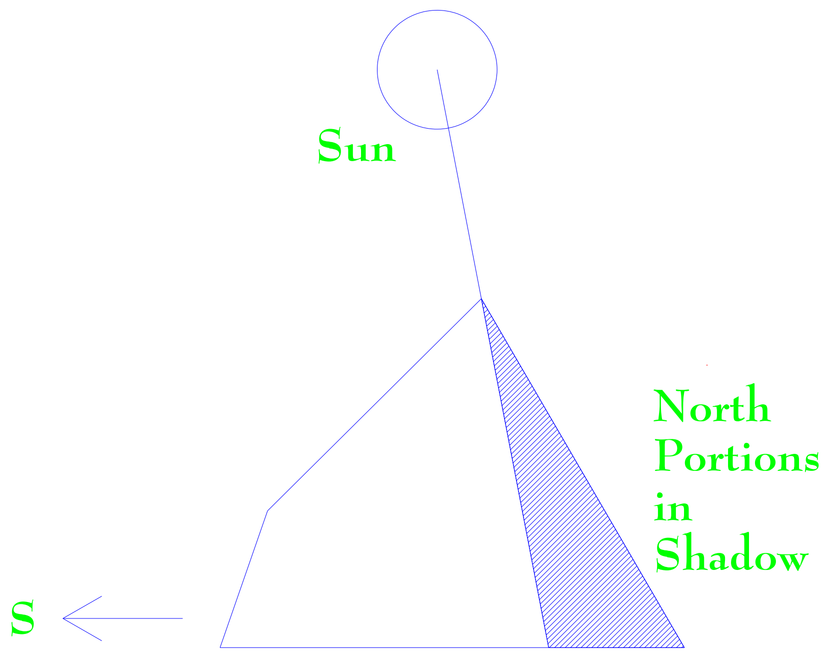
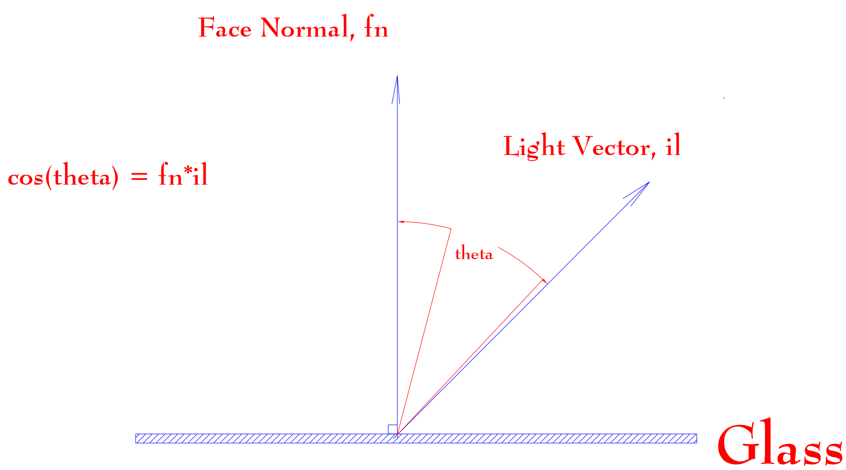


Figure 7



Depiction of Vectors

Appendix A1 - A Description of the Computer Program

To maximize the amount of free heat that can be obtained from sunlight, light transmission through the south face must be maximized. For the purpose of designing a greenhouse, a south face angle is found which admits the most sunlight during specified periods. By optimizing for a period or periods, rather than a particular instant in time, a more substantial heat gain is realized.

To find the face angle(s) which best transmits light over the specified period(s), some vector mathematics is necessary. In the explanation that follows, vectors are depicted in **boldface** type. First, the vector normal to the glass face, **fn**, is found. Then, the incident light vector, **il**, is found. The fraction of light that is transmitted through the glass is found by calculating the dot product of these two vectors ($\cos\theta = \mathbf{fn} \bullet \mathbf{il}$). See Figure 7 for a two-dimensional depiction of the vectors. In reality, these vectors are in three dimensions; the computer program, in fact, does all calculations for three-dimensional vectors.

Once the greenhouse is built, its south face angle does not change in time (**fn** is constant). However, the Sun moves across the sky during the course of the day. In other words, the value of **fn•il** constantly changes throughout the day. To find the amount of light that enters the greenhouse, calculate **fn•il** and determine how long this quantity is valid. For example, at any instant **il** has a particular value. Assume it has this value for a time Δt_1. The amount of light entering the greenhouse in this time is $(\mathbf{fn} \bullet \mathbf{il})\Delta t_1$. Over the next time interval, Δt_2, **il** has a different value and, therefore, so does the quantity $(\mathbf{fn} \bullet \mathbf{il})\Delta t_2$. Over the course of a day (from sunrise to sunset), all these little quantities add up to yield the daily total of sunlight entering the greenhouse. In mathematical terms,

$$\textit{Day Transmission} = \int_{sunrise}^{sunset} (\mathbf{fn} \bullet \mathbf{il})\, dt$$

The daily transmission is calculated for every day in the specified period to yield a sum for the specified period.

The south face configuration is then changed (hence **fn** is changed) and the procedure repeated to yield a different sum. If the result is a larger number, a better south face configuration has been found (more light gets transmitted over the specified period). The south face configuration is changed several times and the sums calculated in this way. The south face configuration which yields the largest sum is the one which best transmits light over the specified period.

The computer program which does all this work is built around a numerical integration routine. The rest of the program tracks the Sun's vector, taking into account the Earth's rotation, spheroid shape, and precession, as well as the site latitude, altitude, temperature, and pressure.

Appendix A2 - Weather Data for Abbotsford

This data comes from Environment Canada's Publication "Canadian Climate Normals. British

Columbia, 1961 - 1990 ", which represents the average for the past thirty years. The site at which data was collected is described below, followed by the actual data. The "N"s in the "Sunshine" row indicate that the number of hours of sunshine for the month are negligible.

Abbotsford, British Columbia, Canada
Latitude: 49.02 Degrees North
Altitude: 54 meters above sea level

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily Max, °C	5.4	8.4	10.9	13.9	17.4	20.4	23.2	23.6	20.5	14.9	9.0	5.7
Daily Min, °C	-1.0	0.7	1.7	3.8	6.5	9.4	10.9	10.9	8.5	5.1	2.2	-0.5
Daily Mean, °C	2.2	4.6	6.3	8.8	12.0	14.9	17.1	17.3	14.5	10.0	5.6	2.6
Sunshine, Hours	N	N	N	166.4	203.9	216.9	287.6	254.5	182.3	N	67.9	N
Pressure, kPa	101.02	100.96	100.84	100.96	100.99	100.95	101.01	100.91	100.94	101.04	100.85	100.97

Appendix A3 - Calculations of Heat Loss

Using data from Environment Canada, some rough calculations can be made to estimate thermal qualities of a fictitious greenhouse located in Abbotsford, BC. The coldest months of the year in Abbotsford are December and January, so these two months were used for the calculations.

	January	December
Temperature, max	5.4	5.7
Temperature, min	-1.0	-0.5
Temperature, mean	2.2	2.6
Pressure, kPa	101.02	1009.7

Opaque surfaces of the greenhouse will be covered with insulation that has an R-value of 28. Calculations follow.

Area of lower front glazing: ()() = ft^2
Area of upper front glazing: ()() = ft^2
Area of lower sides: (2){(0.5)()() + ()() + (0.5)()()} = ft^2
Area of upper sides: (2){(0.5)()()} = ft^2
TOTAL AREA OF GLAZING: ft^2

Area of insulated north wall: ()() = ft^2
Area of insulated portions of sides: (2){(0.5)()() + (0.5)()() + ()()} = ft^2
TOTAL INSULATED AREA: ft^2

Assume that the glazing material is double-walled clear Lexan with an R-value of 3. Also assume that the average outside temperature for December and January is 5.55° Celcius (= 42° Fahrenheit) while the minimum allowable temperature in the greenhouse is 15° Celcius (=59° Fahrenheit).

Average heat loss per hour is given by the formula

$H = U \times A \times (T_i - T_o)$,

where H = heat loss per hour, Btu/hour;
U = U-value = 1/R-value;
T_i = inside temperature, degrees Fahrenheit;
T_o = outside temperature, degrees Fahrenheit.

Heat loss through the glazing is

H = (1/3)()(59 - 42)
= Btu/hour

Heat loss through the insulated north wall is

H = (1/28)()(59 - 42)
= Btu/hour

So far, the greenhouse loses ?? Btu/hour. Assume that losses due to infiltration around vents, etc. amount to one-quarter of this amount. (= ?? Btu/hour).

TOTAL HEAT LOSS FROM GREENHOUSE = Btu/hour

Now consider a similar greenhouse with no insulation (see Figure 3). The glazed area is the entire surface area of the greenhouse: ?? ft^2.

H = (1/3)()(59 - 42)
= Btu/hour

Including infiltration: ()(0.25) = Btu/hour

TOTAL HEAT LOSS FROM GREENHOUSE WITHOUT INSULATED NORTH WALL = ?? Btu/hour.

The conclusion that can be drawn from these calculations is that

HEATING LOSSES ARE CUT BY ALMOST 40% BY INSULATING THE NORTH WALL AND UPPER PORTIONS OF THE SIDES RATHER THAN COVERING THESE AREAS WITH GLAZING.