

# **Design of a micro processor based automated Sun photometer**

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## **Plagiarism declaration**

I declare that the contents of this thesis are original and have not been submitted prior to this for an academic examination towards any qualification.

All work included in this thesis is my work. Where I have drawn from other sources, I believe that the text has been adequately reference.

Signed \_\_\_\_\_

22 October 2007

Janet Hewitson

## **ETHICS CLEARANCE FORM**

## **ACKNOWLEDGEMENTS**

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Secondly I would like to thank Prof Andrew Sass for his guidance and resources in working out the mathematics behind calculating the Sun's position. In the same line, much thanks is owed Shireen Davis of the Southern African Astronomical Observatory [SAAO] library and also Lisa from SAAO for all their assistance in this work.

Finally I must express great thanks to Gabrielle Coppez, Tory Madden, Kate Mcater and Sarah Thomas for the huge amount of grace and encouragement they've given me.

## **TERMS OF REFERENCE**

As a mechatronics honors thesis project and as a prototype for UCT based Climate System's Analysis Group, CSAG, the following terms of reference were specified for this report and the system it describes.

### **EEE4022S Deliverables**

- A technical report serving as a complete description of the identified problem, design process followed and final system design.
- A working installable automated Sun photometer supporting data transfer to and from a PC.

### **An automated Sun photometer terms of reference;**

- An instrument which measures level of direct solar irradiance with in a number of specific narrow wavelength bands to the exclusion of diffuse and scattered radiation.
- The sensor should have a field of view (FOV) to match that of the arc subtended by the Sun in the sky.
- The system will automatically position the sensor such that it is pointing directly at the Sun, based on calculations using the current date and time and the instrument's latitude and longitude.
- The system, for the most part, will obtain such data automatically without user involvement.
- An instrument sample rate of nominally 5-10Hz with data averaged to give values at 5minute intervals. This data should be buffered locally and transmitted on a serial or network link on request.
- Software should include fault detection code of the sensor and the mechanics of the tracking system, as well as subroutines for automated re-calibration.

- The system should be suited to both permanent residence in one location for periods of time extending to years and to being relocated for short time periods to new locations to be used in one off experiments.

## **ABSTRACT**

This report details the results of a design process followed in designing an automated Sun photometer system. This refers specifically to; an integration of an electronic Sun photometer within a system capable of continuously positioning this photometer such that it is aimed directly at the Sun without user intervention.

The manner in which this is done, its defects and possible solutions to such are outlined here along with the theory behind and for this instrument. A MC9S12NE64 microcontroller is used as the basis for system control and is therefore described in basic detail also.

The final design arrived at for this system; its implementation and intended implementation are described. For the most part this serves as a design document from which a complete system could be developed.

## TABLE OF CONTENTS

Ethics clearance form .....	3
Acknowledgements.....	4
Terms of reference.....	5
Abstract .....	7
Table of contents .....	8
Glossary .....	11
Chapter 1 Introduction, an automated Sun photometer system .....	12
1.1 Problem definition.....	12
1.2 Project objectives .....	13
1.3 Scope and limitations .....	14
1.4 Plan of development .....	14
Chapter 2 Purpose and use of Sun photometers.....	16
2.1 Use of Sun photometers .....	16
2.1.1 Theory behind use .....	16
2.1.2 Obtaining useful information .....	17
2.2 Value of information .....	18
Chapter 3 Theory regarding tracking the Sun .....	20
3.1 Mathematical approach.....	20
3.1.1 Time and date considerations.....	20
3.1.2 Coordinate systems .....	22
3.1.3 Orbit of the Earth around the Sun.....	24
3.1.4 Algorithmic calculation of the Sun's position in the sky.....	25
3.2 Alternative methods.....	29
3.2.1 Electrical sensor feedback .....	29
3.2.2 Mechanical .....	30
3.3 Design decision .....	30
Chapter 4 System Microcontroller .....	32
4.1 Overview.....	32



4.2	Timer Module .....	33
4.3	Analog-to-Digital Converter.....	34
4.4	Serial Communication Interface.....	35
4.5	Serial Peripheral Interface.....	36
4.6	Ethernet Media Access Controller and Ethernet Physical Transceiver	36
4.7	Implementation of the MC9S12NE64 .....	36
4.7.1	Mechanical and electrical considerations .....	36
Chapter 5	System overview.....	38
5.1	System structure .....	38
5.2	Components functionality.....	41
Chapter 6	Sun tracking system .....	42
6.1	System resolution.....	42
6.1.1	Motor resolution .....	42
6.1.2	Mechanical resolution .....	43
6.1.3	Experimentation .....	45
6.2	Real time keeping.....	45
6.3	FSOncore GPS system.....	47
6.4	Inclinometer feedback sub-system .....	48
6.5	Photodiode feedback sub-system.....	49
6.5.1	Mechanics .....	50
6.5.2	Electronics.....	51
6.5.3	Software .....	52
Chapter 7	Servo motor system.....	54
7.1	Hardware .....	54
7.2	Software .....	54
Chapter 8	The photometer sensor .....	56
8.1	Hardware implementation .....	56
8.2	Sensor-ADC interface .....	57
Chapter 9	System operation .....	59

9.1	Setup and calibration for a new location.....	59
9.1.1	Finding true North .....	59
9.1.2	Leveling .....	60
9.1.3	System calibration.....	60
Chapter 10	Conclusions .....	61
10.1	The system required accuracy was a major obstruction to project completion .....	61
10.2	This thesis' scope was too great but appropriate .....	61
10.3	The primary product of this thesis is a detailed design investigation into automated a sun photometer .....	62
10.4	A secondary result of value is the conclusion that LED's serve decidedly well as photometer-sensors and a basic working photometer design.....	62
10.5	The specified dual functionality of the system regarding it being both permanently located and yet portable is inappropriate .....	62
Chapter 11	Recommendations.....	64
11.1	Further systematic experimentation with LED's as sensors.....	64
11.2	Protective dome .....	64
11.3	Angle position feedback.....	64
11.4	Automated mechanism for determining sensor dark current values...	64
11.5	Implement some means of external communication .....	64
11.6	Code optimization and strengthening .....	65
11.7	Alternative means of coping with high accuracy demands. ....	65
11.8	Correction of PCB design errors .....	65
11.9	Mechanical design changes.....	66
References	.....	67
Appendix A:	Schematics.....	69
Appendix B:	.....	70
Appendix C:	Datasheet summaries.....	71

## GLOSSARY

**AOT:** Aerosol optical thickness

**CPU:** Central processing unit

**GPS:** Global Positioning System

**Irradiance:** The power of electromagnetic radiation incident on a surface, measured in watts/m<sup>2</sup> and inclusive of all frequencies.<sup>1</sup>

**LDR:** Light dependant resistor

**LED:** Light emitting diode

**mcd:** Milli Candela, a unit of luminous intensity<sup>2</sup>

**Photometer:** An instrument which measures the intensity of light, usually in lumens.

**PCB:** Printed circuit board

**Radiometer:** An instrument used to measure the radiant flux or power in electromagnetic radiation, typically used to measure infrared radiation.<sup>3</sup>

**Rayleigh scattering:** The scattering of light, or other electromagnetic radiation, by particles much smaller than the wavelength of the light.<sup>4</sup>

**RTC :**Real time chip

**Sun tracking:** For the purposes of this document the term 'Sun tracking' and any derivatives thereof refers to both a means of following the Sun's movement in response to a sensor input and to means of predicting the Sun's position in the sky.

**TOA:** Top of atmosphere

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<sup>1</sup> 2007 September 4, *Irradiance*, Available: < <http://en.wikipedia.org/wiki/Irradiance> >, [2007, October 22]

<sup>2</sup> 2007 October 15, *Candela*, Available: <<http://en.wikipedia.org/wiki/Candela> >, [2007, October 18]

<sup>3</sup> 2007 September 13, *radiometer*, Available: < <http://en.wikipedia.org/wiki/Radiometer>>, [2007, October 22]

<sup>4</sup> 2007 October 15, *Rayleigh scattering*, Available: <[http://en.wikipedia.org/wiki/Rayleigh\\_scattering](http://en.wikipedia.org/wiki/Rayleigh_scattering)>, [2007, October 12]

## **Chapter 1 Introduction, an automated Sun photometer system**

This report details an attempt to develop an automated Sun photometer for climate research. The actual sensor itself is amongst the components developed, however, the majority of development work regards the peripherals needed to automate the system.

At the most basic level, a Sun photometer measures Sunlight intensity, a value which is of use in a number of fields, one being climatology. Automating the system refers to incorporating a range of functionalities as peripherals to the actual sensor.

The project terms of reference have been given above and they give a basic outline of what is wanted and what defines the term “Automated Sun photometer”. As work has been completed on this it has become increasingly evident that such a scope is simply too great for a 12 week thesis. In response and result, this report is a record of design process followed, problems encountered and the proposed solutions, systems developed, and probably most valuably, of intent. That is, following this design process has produced final working designs and implementations for some of the components necessary for such a system. But beyond this and perhaps more valuably, this document in particular shows what has been found needed for such a system and possible means of obtaining it.

### **1.1 Problem definition**

The objective of this thesis was to design and build an automated Sun photometer. The sensor in and of itself is required to generate a signal proportional to the received irradiance. The system within which this is placed is to ensure 24hr, multi-year continuous operation. That being continuous positioning of the sensor such that it responds exclusively to direct solar radiation.

As an automated photometer, the system involves firstly finding the Sun’s position automatically, and secondly, having a structure and mechanism in place that serves to point the sensor at this location. Both tasks require a high degree of accuracy because of the nature of the Sun’s movement, its size and location with respect to the sensors and the need for excluding diffuse radiation.

Determining the Sun's position, as required by the terms of reference, involves knowing the sensors location on Earth, the exact time and date and, with the methodology employed here, the sensor's angle and orientation relative to horizontal and true North. Implementing a mechanism to aim the sensor at the Sun involves actuating, with accuracy, the Sun's found location and actively excluding diffuse light.

Beyond this basic functionality, the problem involves a degree of data handling. At the absolute minimum this involves data storage, but at a more sensible level, this would involve a degree of processing and preferably transfer to another location.

## **1.2 Project objectives**

This project's definition is to develop an automated Sun photometer with a range of specific customizations. This may be detail briefly by the following objectives.

### **To develop a system consisting of:**

- A sensor which measures direct solar radiation to the exclusion of diffuse and scattered radiation in 4 narrow wavelength bands.
- 
- A mechanical structure, within which the sensor will be supported, protected and positioned correctly to take measurements.
- 
- An electronic and software based environment from which the Sun's position may be found, the sensor aimed and the measurement data handled.

### **To develop a system with the following functionality;**

- 
- Position the sensor in whatever orientation needed such that it may exclusively measure the incident solar radiation.
- 
- Positioning this sensor must occur continuously for all time periods during which the Sun is above the horizon whether it is visible or not.
-

- Take sensor readings at an appropriate rate and deliver the data to a remote PC.
- 
- Continuous operation without user input for periods of time extending to year lengths.
- 
- Self fault detection including alerts to an operator of such.
- 
- Suited to both permanent residence in one location and to field experimentation. The latter requiring quick and easy calibration functionality.

### **1.3 Scope and limitations**

The definition of scope of this project is as set out in the terms of reference; namely to develop an automated Sun photometer with a stated level of additional functionality. Investigations and initial design on each aspect of such were carried out as far as possible. Time constraints have severely limited the degree to which this scope has been met.

This report therefore, attempts to describe all valuable work done. That being; all that has been taken as far as working final design and all results and conclusions investigation has led to. To a degree this therefore provides a broad reasoned potential whole system design alongside detailed design and test results of some systems.

### **1.4 Plan of development**

In light of the project objectives and scope, this report follows the following outline;

Chapter 2: Outlines the theory behind and purpose of Sun photometers as measurement instruments.

Chapter 3: Describes the theory and mathematics behind how the position of the Sun in the sky is calculated.

Chapter 4: Reviews the freescale MC9S12NE64 microcontroller.

Chapter 5: Provides a broad overview of the system as a whole.

Chapter 6: This details all the systems used and their integration in together as a Sun tracking mechanism.

Chapter 7: Describes the servo motor system used.

Chapter 8: Details the actual Sun photometer sensor design.

Chapter 9: Gives a brief overview of how a user might operate the system.

Chapter 10: Details the conclusions drawn.

Chapter 11: Describes the recommendations made.

Following these sections is a reference list, bibliography and appendix with appropriate data-sheets and schematics referenced in the text.

## **Chapter 2 Purpose and use of Sun photometers**

As outlined previously, a Sun photometer is an instrument that measures direct solar radiation. This section looks at the reasons for its use and elaborates on the principles behind its operation.

### **2.1 Use of Sun photometers**

#### **2.1.1 Theory behind use**

The sensor component of a Sun photometer uses some means to produce a signal proportional to the spectral irradiance received. The motivation for making this measurement lies in the fact that the difference between the measured irradiance and the known top of atmosphere [TOA] solar irradiance constant, is indicative of the contents of the atmosphere. That is, the quantity of radiation reaching the Earth's surface from the Sun, after having passed through the atmosphere, is dependant on the contents of the atmosphere. The difference between these two values is representative of the type and sizes of the particle in the atmosphere.

To consider the measurements taken valid requires a number of factors being ensured. Firstly, the principle depends on the radiation measured being only direct solar radiation. The apparent 'loss' of radiation in the atmosphere, which is found in the differential value, is due to light being absorbed and scattered by particles in the atmosphere. As such, the result of this difference is in fact the quantity of that light that has been scattered and absorbed.

Further, to derive the most information out of this comparison, measurements are taken within specific wavelength ranges only. For instance the instrument described in this document, examines two variables, aerosol optical thickness [AOT] and water vapor content. Both of these are found by examining particular wavelengths which are affected most by particular solid and water vapor particles. In the same way, other variables may be examined by taking measurements within other wavelength ranges.

Finally, the TOA irradiance constant is not truly constant. However, the value can either be assumed to be constant - and the subsequent error considered irrelevant - or it may be found from satellite measurements.



### 2.1.2 Obtaining useful information

Taken as they are, the values read from a Sun photometer are effectively meaningless. They are useful, however, when used to find standard quantities which are of interest such as the Angstrom exponent, and there by AOT values, and water vapor content.

For instance, AOT is wavelength dependant as particles of varying size will affect different wavelengths to different degrees respectively. The Angstrom exponent defines a relationship between AOT values of different wavelengths such that once AOT at one wavelength is known along with this exponent, the AOT at any wavelength, within limits, may be found. Generally the AOT at 2 wavelengths is found and the Angstrom exponent estimated from each, the average is taken to be the exponent's value.<sup>5</sup> Sun photometers specifically, commonly use 525 nm (green) and 625 nm (red) wavelengths as these standard wavelengths, from which the Angstrom exponent is then derived.

To find the AOT at a wavelength from a Sun photometer's measurement of irradiance is completed as follows;<sup>6</sup>

A calibration constant ( $V_0$ ) is determined based on the TOA irradiance constant. This value is sometimes also called the extraterrestrial constant in reference to the fact that it is simulating the voltage that would be produced by the Sun photometer if it were outside of Earth's atmosphere.

A term referred to as; total optical thickness, is found according to the following equation and is equivalent to the sum of the AOT and the non-AOT.

$$\text{Total optical thickness} = \sin(\theta)[\ln V_0 - \ln(V - V_D)] = \text{AOT} + \text{non-AOT}$$

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<sup>5</sup> Wikipedia, 2006 October 22, *Angstrom exponent*, Available: <  
[http://en.wikipedia.org/wiki/Angstrom\\_exponent](http://en.wikipedia.org/wiki/Angstrom_exponent) >, [2007, October 12]

<sup>6</sup> E. M. W. Hill, 2006 August 18, *CALIPSO outreach*, Available: <  
<http://calipsooutreach.hamptonu.edu/Sunphoto-sim/Sunphotometer.html#technical> >, [2007, October 12]

Where;

$V$  = the measured irradiance voltage

$V_D$  = the dark current voltage

$\theta$  = the Sun angle

Following this, non-AOT is found according to;

$$\text{non-AOT} = a_R(p/p_0)$$

Where;

$a_R$  = the Rayleigh scattering (non-aerosol) at standard sea-level atmospheric pressure

$p$  = actual atmospheric pressure

$p_0$  = standard sea-level atmospheric pressure (1013 millibars).

Therefore:

$$\text{AOT} = \text{Total optical thickness} - \text{non-AOT}$$

In a similar manner, the columnar water vapor content of the atmosphere is found using the differential degree of penetration of light at 920nm and 950 nm wavelengths as they fall within the water vapor continuum and the deep absorption band respectively.

## 2.2 Value of information

The measurements taken by a Sun photometer have significance in a number of fields, most significant of those being climatology, meteorology and astronomy. The measurements taken are unique to the observation site which has various implications in terms of their usefulness in either of these fields, and in both cases, are generally only useful as data recorded over a period of time. The instantaneous values themselves have little value. As time based records however, they have value for both determining local atmospheric status and in detecting trends and changes there from.

In astronomy, Sun photometers play a vital role in supplying information regarding how images should be corrected for distortion due to the atmosphere. Monitoring the atmosphere continuously through normal Sun photometer use allows conclusions to be drawn about what the likely atmospheric distortion was at the time at which a given image was taken. Knowing this, 'true' images can be generated and analyzed in a cleaner context.

With regard to their use in fields related to climate research Sun photometer measurements serve both a practical a theoretical purpose. Firstly, solar radiation drives the climate systems. As the only source of incoming energy to the climate systems of the planet, the quantity of irradiance received and its manner of distribution and absorption by the environment dictates to a large extent, how these systems behave. As described above, by measuring the incident radiation, concentration levels of various particles in the atmosphere such as; columnar water vapor and AOT can be derived. AOT itself being an array of variables including CO<sub>2</sub>, other pollutants and dust, each of which has specific implications for weather system behavior.

To elaborate, the atmosphere intercepts the solar radiating reaching the planet and as such its composition changes how the energy is received. The manner in which the energy is received, influences both lapse rates and inversion characteristics which significantly influence local climate. For instance, frost occurrence, minimum and maximum temperatures, pollution trapping (which has both agricultural and social implications) and the nature of local winds are all affected by radiation absorption.

Further, knowing the atmospheric composition means pollutants may be tracked over time. This serves as both a means of monitoring society's environmental impact and to provide information on a potential societal hazard. Beyond this, pollution also plays a large role in cloud formation, and therefore affects the location and nature of local rainfall.

Time based tracking of moisture content tracking is also made possible with these measurements of irradiance. This facilitates understanding of how circulation relates to the transport of moisture. Alongside satellite images, which serve to provide a macro and total atmospheric depth view of moisture content, the values found with a Sun photometer give insight into the lower boundary layer and its moisture content.

The alternative use for Sun photometers in climate research is that of serving as a means of calibrating and testing computer models used to simulate the climate.

## Chapter 3 Theory regarding tracking the Sun

The terms of reference for this system call for a sensor to be pointed directly at the Sun requiring some means of determining the Sun's perceived path across the sky. The Sun's movement is characterized by both its daily  $180^\circ$  traverse from horizon to horizon and by seasonal shifts of this arc in by  $47^\circ$  centered on  $0^\circ$ .<sup>7</sup> The actual perceived location in the sky of this arc is further dependant on the observer's latitude on the surface of the Earth.

The terms of reference further specify that this movement be tracked based on calculations rather than a sensor and feedback system. Following a design process for the system as a whole, using only equations causes a number of problems with regard to accuracy and as such alternatives were analyzed. The final solution implemented, is a system which requires careful initial setup but is based primarily on calculations which are then validated and offset according to sensor feedback.

### 3.1 Mathematical approach

Calculation of the Sun's position in the sky is dependant on time, date, latitude, longitude and elevation. In terms of the precision required for this system, the error due to neglecting elevation is considered negligible. The method used in this system to find the Sun's position and a basic overview of required theoretical background is given by the following.

#### 3.1.1 Time and date considerations

The Gregorian calendar, which is in current standard use, was first instituted in 1752. Prior to which, the Julian calendar, "...a continuous count of days and fractions thereof from, the beginning of the year -4712..."<sup>8</sup> was in use. A Julian year consists of 365.25. This extra 0.25 days was allowed to accumulate and form an extra day every four years. However, having been based on this assumption, of exactly 365.25 days a year, the calendar is in error by approxi-

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<sup>7</sup> C. H. Cotter, 'The Seasons, The elements of navigation and nautical astronomy, Glasgow: Brown, Son & Ferguson, p189, 1977

<sup>8</sup> J Meeus, 'SECTION TITLE', *Astronomical Algorithms 2<sup>nd</sup> edition*, Richmond Virginia: Willmann-Bell, Richmond, PGXX, 1998

mately 11 minutes a year, which is 3 days every 400 years. The Gregorian calendar takes this error into account simply by dropping 3 days every 400 years.<sup>9</sup> Much of the theory surrounding navigation and astronomy is based on the Julian calendar. Consequently the difference in calendars needs to be accounted for when using this theory.

The ideal calendar, for the purposes of analyzing the movement of astronomical bodies, would be one in which a year is the time it takes for the Earth to orbit the Sun once with respect to its equinoxes that is 365.3422 days. This particular length of time is useful in making some astronomical calculations and as such is termed a tropical year.

In terms of the measurements of time, solar time is the system generally used in every day life. A solar day is exactly 24hrs long and is the time taken for the Sun to appear to move from being at a local meridian till it reappears on that same meridian. Due to the Earth orbiting the Sun, in addition to its rotation on its axis, the passing of one solar day requires the Earth to rotate 360.986°, an extra 0.086°. To determine the horizontal coordinates of the Sun in the sky, local sidereal time is required as it considers a day as the time for the Earth to rotate exactly 360°. Sidereal time in general, is a measure of time which references distant stars, rather than the Sun, thereby making the extra 0.086° appear inconsequential. A sidereal day therefore lasts only 23hrs and 56 minutes.<sup>10</sup>

The classification of time used in the equations bellow is UT. UT is a measure of solar time as the modern replacement of GMT and as such is the number of hours, minutes, and seconds to have elapsed since the point at which the Sun is at a longitude of 180°, at Greenwich.<sup>11</sup>

UT is determined through astronomical observations at a specific observatory and due to irregularities in the Earth's orbit, measurements at different observatories result in different UT values. For this reason UT1 is defined which incorporates a correction factor. A further correc-

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<sup>9</sup> C. H. Cotter, 'The Calendar', The elements of navigation and nautical astronomy, Glasgow: Brown, Son & Ferguson, p215, 1977

<sup>10</sup> Martha, 2007 October 1, *Sidereal Time*, Available: <<http://www.astro.cornell.edu/academics/courses/astro201/sidreal.html>>, [2007, October 12]

<sup>11</sup> E. W. Weisstein, 2007, *Universal Time*, Available: <<http://scienceworld.wolfram.com/astronomy/UniversalTime.html>>, [2007, October 12]

tion to allow for annual changes in the Earth's rotation is applied to UT1 to give UT2. These correction factors sometimes accompany the values given by a GPS. As UT is local to Greenwich, a local UT, for any longitude other than Greenwich, is equal to UT + Longitude where positive longitudinal values are considered eastward and negative westward from Greenwich.

### **3.1.2 Coordinate systems**

Depending on the work being done, the fields of astronomy and navigation use a number of coordinate systems to map the Earth and solar system. The derivation of the Sun's position used in this system in particular, is accomplished using the following three systems.

#### **Ecliptic coordinates: Ecliptic or celestial longitude and latitude [ $\lambda$ , $\beta$ ]**

This is a spherical system analogous to the system of latitude and longitude used to map Earth and likewise has the units; degrees minutes seconds. The ecliptic and its secondary form its two fundamental planes, the ecliptic being the plane of orbit of the Earth around the Sun. The ecliptic longitude is given to be between  $0^\circ$  and  $360^\circ$  while ecliptic latitude is given as between  $0^\circ$  and  $\pm 90^\circ$ .

#### **Equatorial coordinates: Right Ascension and Declination [ $\alpha$ , $\delta$ ]**

This system references the Celestial sphere, an infinite sphere with the Earth as its centre and the plane of its equator being co-planar to that of the Earth's equator. This celestial equator is therefore inclined at  $23^\circ 27'$  to the ecliptic, this angle is known as the obliquity of the ecliptic. Again, the system is analogous to that used to map Earth. In concept, right ascension is equivalent to longitude and declination to latitude. Both are measured and notated in degrees,  $\alpha$  on a scale of  $0^\circ$  to  $360^\circ$  from the vernal equinox with positive as east and  $\delta$  as  $\pm 90^\circ$  from the equator with North as positive.

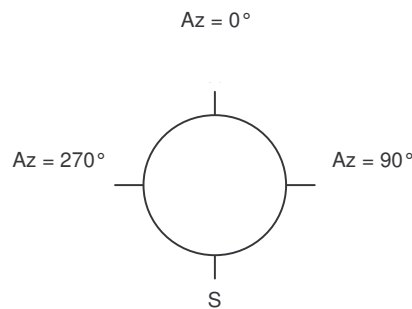
#### **Horizontal coordinates: Altitude and Azimuth [ $h$ , $A$ ]**

This system is centered on the observer and based on the horizontal and vertical planes found with respect to Earth's gravitational field.

To an observer on the surface of the Earth, a hemisphere of the celestial sphere is visible with the other being obscured by the Earth. The circular plane which divides the celestial sphere into these visible and invisible hemispheres is termed the astronomical horizon and is considered the horizontal in this system. The plane passing through the observer and cutting the horizontal

plane at  $90^\circ$  forms the vertical. The poles of the system are positioned at the point where a vertical through the observer cuts the celestial sphere and are termed the Zenith (above) and Nadir (below and invisible). Altitude and Azimuth are referenced relative to these two planes

Based on the above, altitude is defined as an angle ranging from  $0^\circ$  to  $\pm 90^\circ$ , with North as positive, centered at the celestial sphere's center and found between the point considered and the astronomical horizon, measured in the plane of the vertical circle on which the points lies. Alongside this, Azimuth is defined as the angle in the horizontal contained between the observer's celestial meridian and vertical circle on which the considered point lies. The angle size ranges from  $0^\circ$  to  $360^\circ$ . Different conventions are used as to which direction is considered positive. A convention of, eastward from the North is used in this derivation as shown in Figure 1.



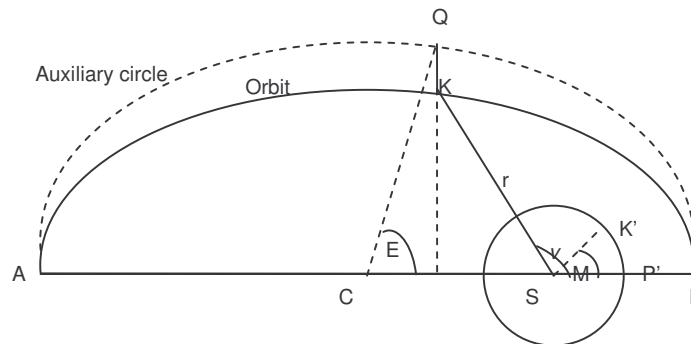
**Figure 1 Top view representation of Azimuth sign convention**

### **Use in calculations**

These 3 systems serve to facilitate finding the position of the Sun in the sky. The Sun's movement is most easily plotted in ecliptic coordinates as its seasonal apparent movement is due to the Earth's movement along the ecliptic. A translation into Equatorial coordinates allows the daily 12 hourly apparent movement of the Sun to be most easily calculated as these are with reference to the Earth's equator. Finally, a transformation of these values to the Horizontal coordinate system makes the Sun's position dependant on the observer's terrestrial location which is easily allowed for in this reference frame.

### 3.1.3 Orbit of the Earth around the Sun

To determine the Sun's position in the sky the Earth's orbit around the Sun must clearly be taken into account. This involves a number of variables which the following<sup>12</sup> attempts to define, it also serves by way as some degree of explanation of the values found in the calculations which follow.



**Figure 2 Half of an elliptical orbit representing the Earth's, K's, passage around the Sun, S.**

Figure 2 above is representative of the Earth's orbit around the Sun if that orbit is approximated as elliptical and where P is the perihelion and A the aphelion. From this, the true anomaly ( $v$ ) at this instant is defined as the angle PSK which is the angle through which Earth has moved since its last pass through the perihelion. In the same way, Earth's mean anomaly (M) is defined as the angle P'SK'. The purpose of the latter, M, being that it is the anomaly of a constant velocity (circular) orbit and is therefore easily found at any given instant.

The eccentricity,  $e$ , of the elliptical orbit, which is a measure of the deviation of the orbit from circular, may also be defined by this figure as the ratio  $e = CS/CP$ . Having both M and  $e$ ,  $v$  can subsequently be found by solving one of Kepler's orbital equations derived from his second law.

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<sup>12</sup> J Meeus, 'Equation of Kepler', *Astronomical Algorithms 2<sup>nd</sup> edition*, Richmond Virginia: Willmann-Bell, Richmond, pg 193 -196, 1998



That is, consider the angle PCQ, E, to be the eccentric anomaly. Kepler's equation states;  
 $E = M + e \sin(E)$

If this is solved for E then  $v$  can be found from;

$$\tan\left(\frac{v}{2}\right) = \sqrt{\frac{1+e}{1-e}} \tan\left(\frac{E}{2}\right)$$

Solving Kepler's equation involves using one of a number of methods which only approximate its solution. Due its wide use, however, solutions are published and as such the results and their derivatives have simply been implemented in a number of the following equations.

### 3.1.4 Algorithmic calculation of the Sun's position in the sky

The algorithm described bellow is arranged and chosen considering the accuracy requirements of this system and the limitations of the microprocessor, servo motors and other feedback systems. The formulae and algorithm used here are based primarily on those given in J Meeus's *Astronomical Algorithms*<sup>13</sup> and B. H. Granslo's *How to calculate the position of the Sun*,<sup>14</sup>, other sources, when explicitly used are referenced in text, otherwise a great degree of understanding is referenced in the bibliography.

With regard to accuracy, the Earth's orbit around the Sun has been assumed to be purely elliptical, which it is not, and some of the equations used have had terms removed, either as their contribution is negligible or simply because system limitations will render them ineffective. As such, these calculations determine the altitude and azimuth of the Sun to the nearest 0.01 degree for any given instant for the period 1 March 1900 to 28 February 2100.

#### i] Calculation of the time past from epoch J2000.0

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<sup>13</sup> J Meeus, *Astronomical Algorithms 2<sup>nd</sup> edition*, Richmond Virginia: Willmann-Bell, Richmond, 1998

<sup>14</sup> B. H. Granslo, 2007 October 1, *How to calculate the Coordinates of the Sun*, Available: <  
<http://www.astro.uio.no/~bgranslo/aares/calculate.html> >, [2007, October 12]

Let the following variable definitions stand;

$Y$  = The year

$M$  = The month of the year (i.e January = 1, February = 2 up to December =12)

$D$  = The day of the month

$Ut$  = The current UT in hours

$Jd$  = The number of whole Julian days past up till the considered date

$Jd_0$  = The decimal number of Julian days to have past inclusive of the fraction of the current day

$$A = \text{floor}\left(\frac{Y}{100}\right)$$

$$B = 2 - A + \text{floor}\left(\frac{A}{4}\right)$$

$$Jd = \text{floor}[365.25(Y + 4716)] + \text{floor}(30.6001(M + 1)) + D + B - 1524.5 \quad [1]$$

As a brief explanation of equation 1; the first term accumulates the number of days for the number of years past based on the Julian calendar. The addition of 4716 is to account for when the Julian calendar was begun making the formula valid for negative year too. The remaining terms accumulate the number of days to have past within the current year based on the month and day values. Explicitly, B accounts for the extra 3 days dropped by the Gregorian calendar, D the days past this month and the remaining 2 terms, all days in the prior months of the year of the date being considered.

For the purposes of these equations, the accommodation of negative years is removed and it is noted that B is always equal to -13 for the period for which these calculations are stated to be valid.

To find  $Jd_0$ , the number of days past in a year is expressed as N

$$N = \text{floor}\left[\left(\frac{275M}{9}\right) - k\left(\text{floor}\left\{\frac{M+9}{12}\right\}\right)\right] + D - 30 \quad [2]$$

$k = 1$  for a leap year and 2 otherwise

and it is noted that, the fraction of the day of the date being considered is equal to  $h$  where

$$h = Ut/24 \text{ days} \quad [3]$$

After rearranging and altering, the resulting formula for  $Jd_0$  is therefore:

$$Jd_0 = 367Y - \text{floor}\left[\left(\frac{7}{4}\right)\left(Y + \text{floor}\left[\frac{M+9}{12}\right]\right)\right] + \text{floor}\left(\frac{275M}{9}\right) + D - 730531.5 + Ut/24 \quad [4]$$

Following this, the number of Julian centuries  $T_o$  from J2000.0 is found based on there being 36525 days in a Julian century. This calculation in particular needs to have its accuracy maintained. As in a calculation of the number of centuries, an error of even 0.00001 is a difference of 8.767 hours.

$$T_o = \frac{Jd_0}{36525} \quad [5]$$

## ii] Finding the Sun's ecliptic coordinates

Using the above, the Sun's mean ecliptic longitude  $L_o$  is 1<sup>st</sup> found along with its mean anomaly  $M_o$ , both are found in degrees.

$$L_o = 280^\circ.466 + 36000^\circ.770 T_o \quad [6]$$

$$M_o = 357^\circ.529 + 35999^\circ.050 T_o \quad [7]$$

The Earth's eccentricity of orbit around the Sun is compensated for by its equation of center,  $C$ ;

$$C = (1^\circ.915 - 0^\circ.005 T_o) \sin M_o + 0^\circ.020 \sin 2M_o \quad [8]$$

The true elliptical longitude of the Sun  $L_S$  (in degrees) is therefore subsequently found as;

$$L_S = L_o + C \quad [9]$$

### iii] Transformation to equatorial coordinates

To transform ecliptic to equatorial coordinates is a matter of trigonometry simply requiring the appropriate value of the obliquity of the ecliptic,  $K$ . This is defined by equation [10] after which the trigonometric relationships between the coordinates are given in equations [11] and [12].

$$\varepsilon_0 = 23^\circ.439 - 0^\circ.013 T_o \quad [10]$$

$$\tan \alpha = \frac{\cos \varepsilon_0 \sin L_s}{\cos L_s} \quad [11]$$

$$\sin \delta = \sin \alpha \sin K \quad [12]$$

Of note, is that, in equation [11], if arctan is used to solve for  $\alpha$ , the result may need to be shifted to ensure it lies in the same quadrant as  $L_s$ .

### iv] Calculation of Sidereal time

To transform equatorial coordinates to horizontal coordinates, the observer's local sidereal time is required which is therefore found as follows;

On any given date at UT = 0<sup>h</sup>, the sidereal time at Greenwich is  $S_0$

$$S_0 = 6^h.6974 + 2400^h.0513 T_o \quad [13]$$

The Greenwich sidereal time at a particular hour,  $S_G$ , is therefore  $S_0$  offset by the current UT scaled by the ratio of the length of a solar year to the length of a tropical year in days, in order to convert the solar UT hours to sidereal hour units.

$$S_G = S_0 + \frac{366.2422}{365.2422} Ut \quad [14]$$

To finally obtain the local sidereal time  $S$  (in hours) for the geographical longitude  $L$  the longitude is simply added to  $S_G$

$$S = S_G + L \quad [15]$$

### v] Transformation to Horizontal Coordinates

Finally, the following equations enable the transformation from equatorial to horizontal coordinates. That is the altitude,  $h$ , and azimuth,  $A$ , of the Sun in the sky for an observer at longitude  $L$  and latitude  $B$ .

$$\sin h = \sin B \sin \delta + \cos B \cos \delta \cos (S - \alpha) \quad [16]$$

$$\tan A = \frac{-\sin(S - \alpha)}{\tan \delta \cos B - \sin B \cos(S - \alpha)} \quad [17]$$

Again it must be noted that the correct quadrant for  $A$  must be ascertained when arctan is used to solve equation [17].

## 3.2 Alternative methods

As stated, the mathematical algorithm outlined above is, by definition, inaccurate. Assumptions are made to simplify the calculations, rounding errors and further mechanical difficulties with practically implementing a system to respond to the generated numbers all mean that a tracking system based on calculations alone is likely to be insufficient. An alternative to this approach is to implement some form of feedback to which the aiming mechanism will respond. Depending on the sensor and aiming mechanism a number of solutions present themselves. The sensor may be electrical or mechanical and similarly the feedback signal may likewise be electrical or mechanical.

### 3.2.1 Electrical sensor feedback

Any sensor which is responsive to the quantity of incident light would serve as a feedback sensor for finding the Sun's position. Photodiodes, phototransistor and LDR's all commonly serve this purpose, but similarly some form of temperature sensor or other electrical-mechanical combination sensor would also serve. Considering the range of potential sensors, the practical implementation and use of photodiodes only is examined in full below. For the most part, the basic principles applied here will work equally well where phototransistors and LDR's are used.

For each axis of rotation the system relies on two sensors being placed with an opaque divider between them. When not perfectly centered on the light source one sensor will receive more light than the other generating a differential between the two outputted signals. Regardless of the circuit in which they are implemented, the result is a signal indicating that the system is off center and in which direction the light has moved in. The sensors' sensitivity themselves, the height of the divider in between them and the distance from the center at which the sensors are placed all affect the sensitivity of the system.

### **3.2.2 Mechanical**

A number of mechanical systems might also be used to center an instrument on the Sun. Some form of electrical-mechanical combination may serve, such as strain gauges placed on highly temperature sensitive materials. Or alternatively, a purely mechanical system could be setup. For instance, two pistons again divided with a divider and setup to move a focus as the fluid inside of each expands in proportion to temperature change due to incident light received would accomplish the same thing.

### **3.3 Design decision**

As mentioned a combination of the mathematical approach and some degree of feedback has been selected as the means of tracking the Sun for this system. The reasoning behind this is two-fold.

The reasoning behind the terms of reference specifying that a mathematical approach must be taken lies in the principle behind how a Sun photometer's measurements are used. The sensor must be pointed directly at the Sun, and not at the greatest source of light or heat. With all feedback systems based on sensor reception of such, the system is vulnerable to scattered light deflecting the system.

However, as noted, the equations are not perfect and when the sky is clear and scattering of no consequence a feedback system will provide better accuracy. As such, a photodiode Sun tracking system has been implemented alongside the mathematical approach and will be used by the operator to calibrate the mathematics on known clear days. That is, an operator may choose to calibrate the system by causing it to center itself on the Sun based on the photodiode system inputs rather than the calculated location of the Sun. The discrepancy between these

positions is then noted and used to offset all calculated values from this time on until the system is again calibrated.

## Chapter 4 System Microcontroller

The microcontroller chosen for this system was selected based on a range of factors. Apart from it being known and used by other students, the development software being on hand and it being easy to implement and program, its particular combination of processor and peripherals make it a suitable selection. As a 16 bit processor, it suited the need for high precision number calculations, and its ADC, timer module and various communication interfaces meet the other needs of this particular system. The following discusses the features of the MC9S12NE64 microcontroller in broad terms and makes particular reference to those aspects utilized in this project.

### 4.1 Overview

The MC9S12NE64 is based around the 16-bit HCS12 CPU. The following summarizes primarily only those peripheral which were either of use or at least of note in designing this Sun photometer system.

- A 4-channel/16-bit timer module, each channel configurable as either input capture or output compare allowing PWM generation
- An Ethernet media access controller with integrated 10/100 Mbps Ethernet physical transceiver
- Two asynchronous SCI modules
- One SPI
- One inter-IC bus
- An 8-channel/10-bit ADC
- An internal digital supply voltage of 2.5 V from a 3.15 V to 3.45 V external supply range.
- 70 I/O pins with 3.3 V input and drive capability (in the 112-pin package)
- Single-wire background debug mode (BDM)



## 4.2 Timer Module

The basic timer is represented as a block diagram in figure 315 below. As shown, it consists of a seven-stage prescaler driving a 16-bit counter both of which are programmable. 4 complete input capture/output compare channels and one pulse accumulator are present. The pulse accumulator shares timer channel 7.

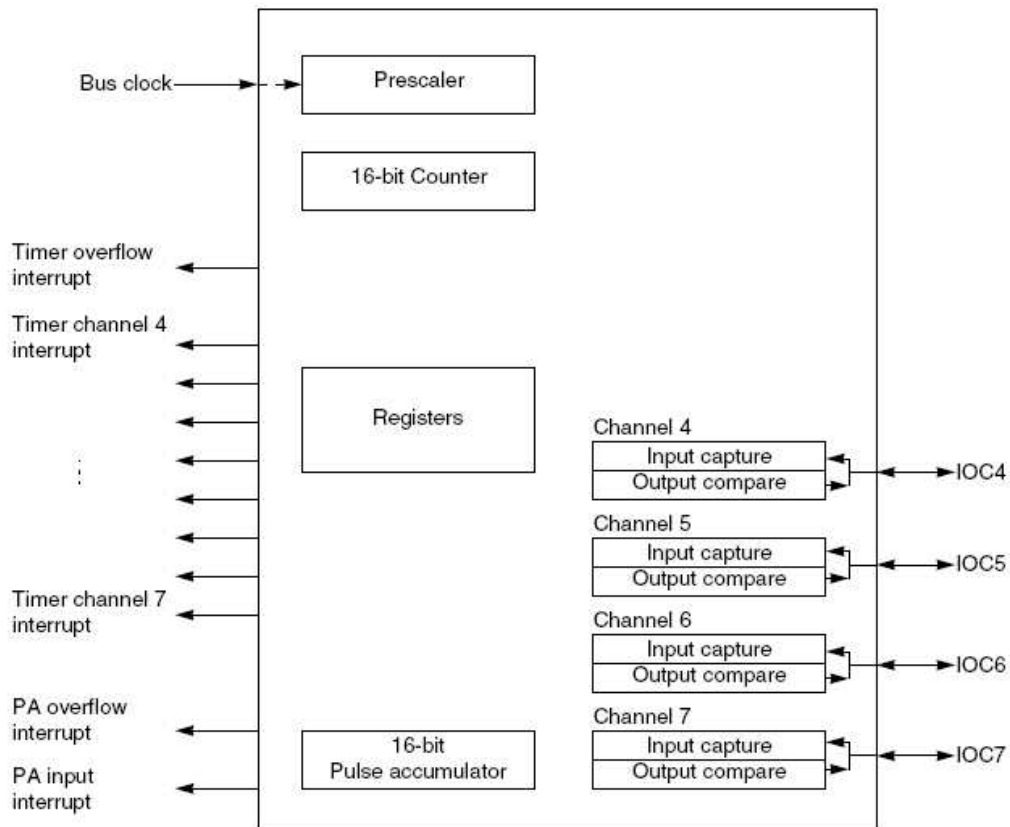


Figure 3 Timer module block diagram

<sup>15</sup> Freescale, 'Timer Module (TIM16B4CV1)', *MC9S12NE64V1 Datasheet Rev. 1.1*, Freescale semiconductor, pg182, Fig 6-1, 2006 June

### 4.3 Analog-to-Digital Converter

The ADC employed here is an 8-channel successive approximation converter, with selectable 8 or 10-bit resolution and a 7 $\mu$  second 10-bit single conversion time. The system consists of both digital and analog circuitry divisions, separate power supplies isolate noise of other microcontroller circuitry from the analog circuitry. The input analog signals must fall within the potential range of this power supply. Figure 4<sup>16</sup> below lays out the basic functionality supported.

A multiplexer connects one of the 8 input channels to the sample and hold circuit via a buffer. The sample and hold circuit operates in two stages, firstly using an amplifier to quickly charge the storage capacitor and then subsequently connecting the input directly to this capacitor to ensure accuracy. Beyond this, an external trigger system allows conversions to be caused in response to external events along with software signals. Each channel is programmable for single or continuous conversion and its input pin may serve as both a general purpose input pin and as the ADC channel pin.

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<sup>16</sup> Freescale, 'Analog-to-Digital Converter (ATD10B8CV3)', *MC9S12NE64V1 Datasheet Rev. 1.1*, Freescale semiconductor, pg207, Fig 7-1, 2006 June

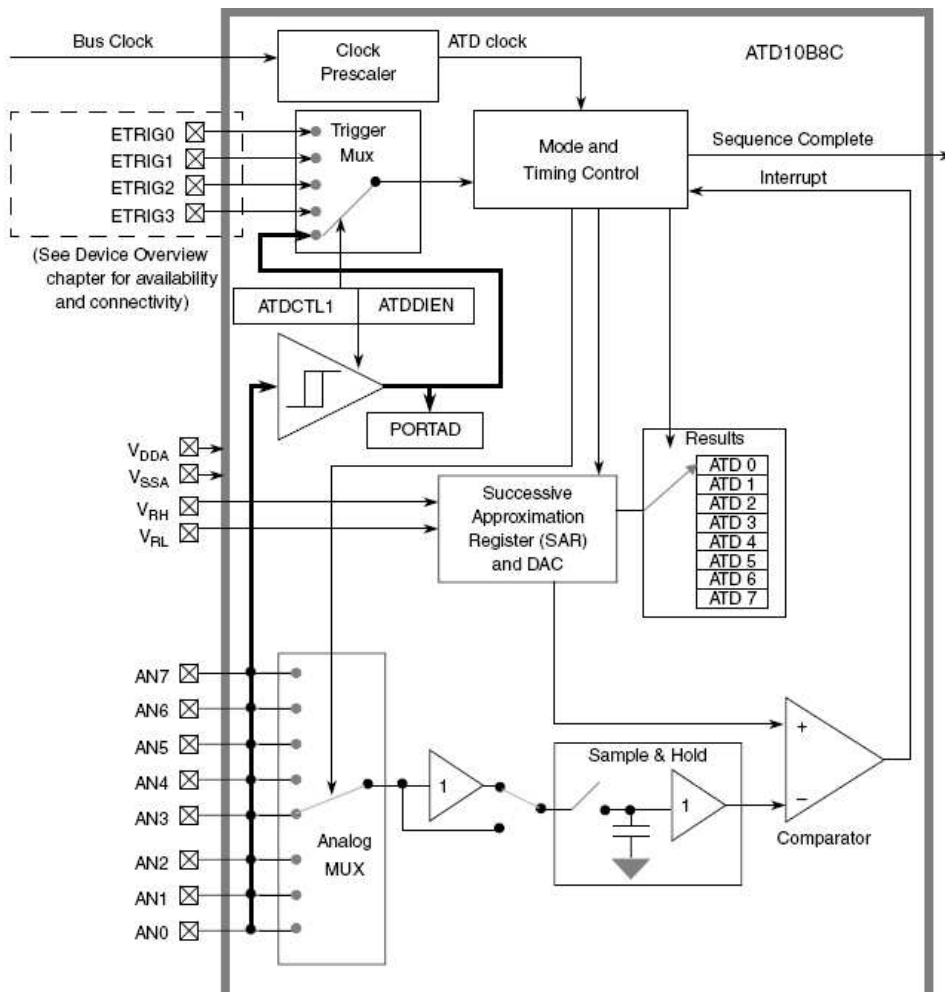


Figure 4 Block diagram representation of the ADC module

#### 4.4 Serial Communication Interface

The SCI module included in this microcontroller supports the following notable features;

- Full-duplex or single-wire operation
- Standard mark/space non-return-to-zero format
- 13-bit baud rate selection
- Programmable 8-bit or 9-bit data format
- Separately enabled transmitter and receiver (operating at the same baud rate)
- Interrupt-driven operation

## 4.5 Serial Peripheral Interface

This module allows duplex, synchronous, serial communication between the microcontroller and various peripherals. The communication may be poll or interrupt driven. In particular the following features are of relevance;

- Master and slave mode
- Bidirectional mode
- Slave select output
- Mode fault error flag with CPU interrupt capability
- Double-buffered data register
- Serial clock with programmable polarity and phase

## 4.6 Ethernet Media Access Controller and Ethernet Physical Transceiver

The Ethernet media access controller and physical transceiver are IEEE 802.3 compliant and support 10/100 Ethernet operation. Both support the medium-independent interface (MII) and the MII management. Used in conjunction, the two enable connection to an Ethernet network. The physical transceiver requires a 25MHz clock and interfaces through a standard RJ45 connector integrated with a 1:1 common transformer.

## 4.7 Implementation of the MC9S12NE64

The steps taken in developing the circuitry and physical system needed to use the microcontroller are outlined here.

### 4.7.1 Mechanical and electrical considerations

#### Power supply

The MC9S12NE64 requires power be supplied individually to; the I/O ports, A/D converter, oscillator and PLL, Ethernet Physical Transceiver and the digital core. For the most part this is a matter of connecting Vcc to particular pins. As the system runs of 3.3V, a LM317 regulator and appropriate circuitry are used to generate such from 12 volts dc, supplied by mains via an adaptor.

### **Ethernet interface**

To interface with the onboard Ethernet physical transceiver, a Pulse engineering made, J0012 integrated magnetics connector is used. This being a RJ45 connector combined with the appropriate transformer circuitry.

### **Chip pin-out**

As this is essentially a development board, with final pin assignments unknown at the time of creation, all unused port pins were routed out to connectors to allow their use for whatever was later required.

### **PCB layout and routing considerations**

A minimalist circuit for the use of the MC9S12NE64, and guidelines for the creation thereof is, suggested in the datasheet. The guidelines given exist primarily to ensure minimal noise as the physical Ethernet connection is particularly vulnerable to this. For the most part, these guidelines center on track lengths, distances between certain tracks (particularly those carrying signals to and from the Ethernet Physical Transceiver), ground plane and other power supply considerations, connection orders and the routes taken by certain connections.<sup>17</sup> The schematic and PCB design of the circuit implemented in this system are attached as Eagle cad files. Their design is based on the circuit given in the application note 'Implementing an Ethernet interface'<sup>18</sup>, this has been modified and added to as necessary.

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<sup>17</sup> Freescale, 'Schematic and PCB layout recommendations', *MC9S12NE64V1 Datasheet Rev. 1.1*, Freescale semiconductor, pg543, 2006 June

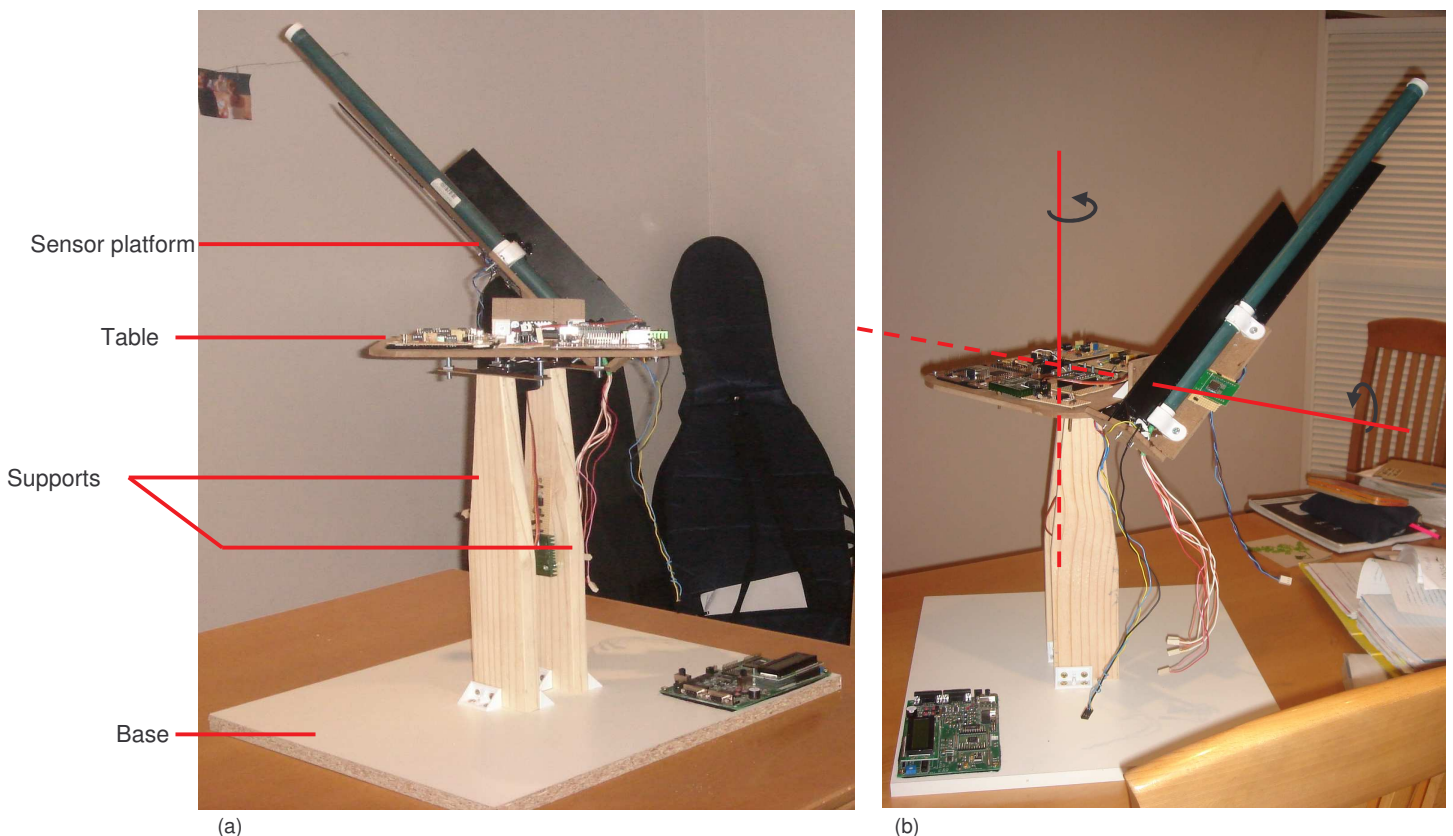
<sup>18</sup> Freescale, '112 pin Design example', *Implementing an Ethernet interface AN2759 Rev. 0.2*, Freescale semiconductor, pg15, Fig 8, 2004 September

## Chapter 5 System overview

As an automated Sun photometer system, this project consists of a number of functional components. This chapter seeks outline the broad system as a whole in terms of both mean practical implementation and of functionality.

### 5.1 System structure

The images below, in figure 5, show the broad system as a whole from two view points. In these views, the electronics happen to be unconnected.

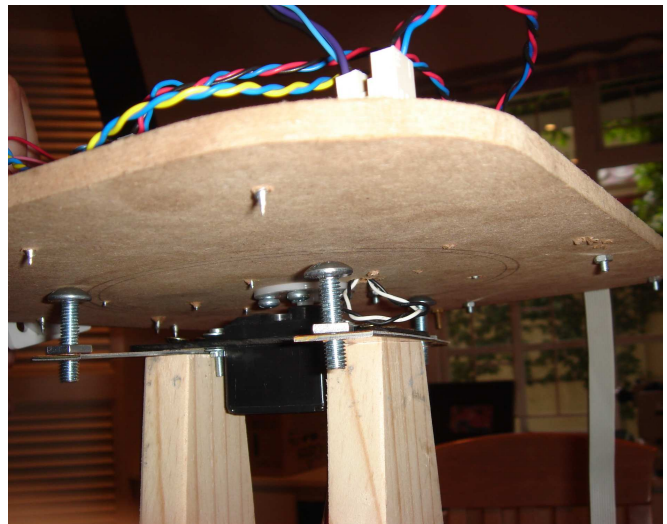
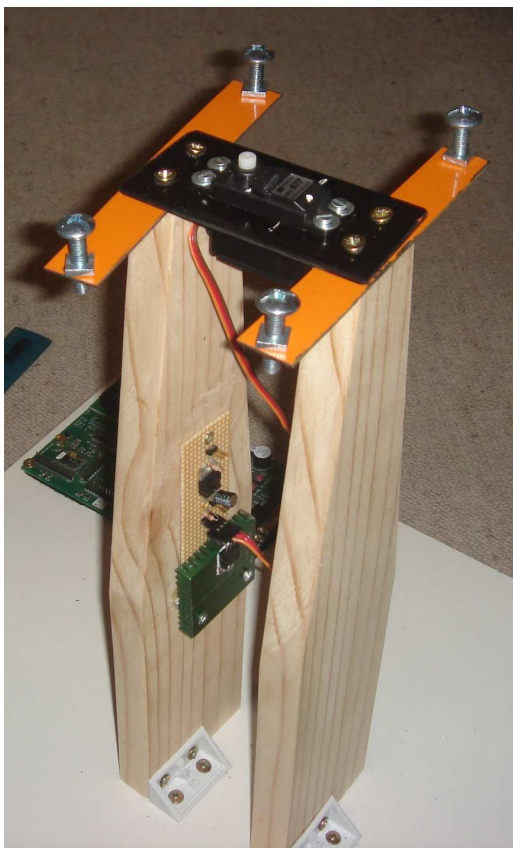


**Figure 5** The Sun photometer system. (a) and (b) are two views taken of the system reflecting both sides of the upper table and sensor arrangement.

To look at the system in more detail, it is divided into a base, a middle level horizontally rotating platform, termed “the table” for convenience, and a further “sensor platform” which rotates through the vertical.

The base holds the FSONcore GPS system and the stand on top of which the azimuth control servo is supported. Elevation above the base is necessary in order for the sensor platform to rotate 180°. However, an earlier design error, which has now been corrected, necessitated this degree of height above the table, hence its apparent excess. This is easily fixed as an earlier design's supports, which are shorter, still exist and simply need to be mounted.

The servo mounting on the top of these supports is shown in figure 6 below. The extended bar and bolt structure is in place to support the table as it rotates, as its weight distribution is highly lopsided due to the sensor platform's weight on one side.



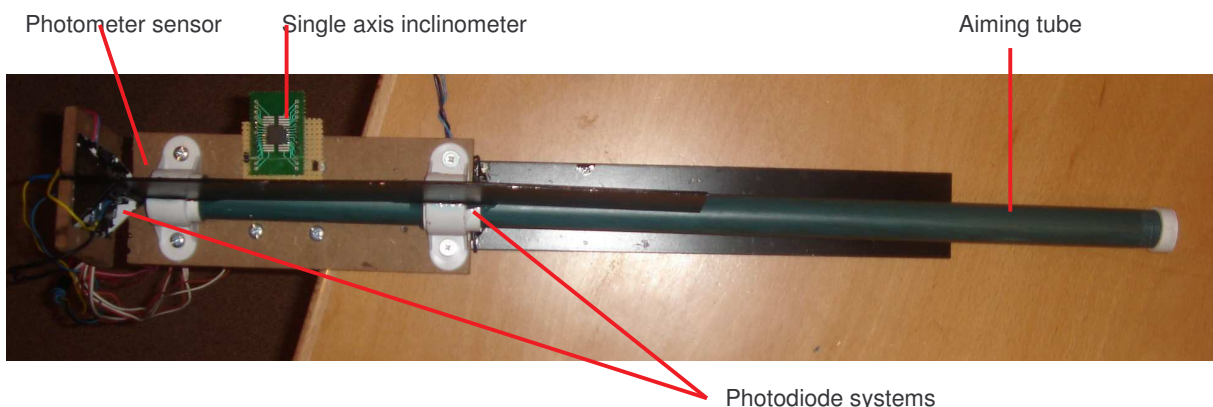
**Figure 6: Azimuth control servo mounting and table supports**

As many circuits as possible, which connect to the MCU, have been mounted on the table to minimize the number of wires requiring length to rotate. As such, the table supports the following shown in figure 7.



**Figure 7: Table component arrangement**

Finally, the sensor platform is shown below, containing as few components as possible with an inclinometer, the two photodiode systems and the photometer sensor tube and LED configuration.



**Figure 8: Rotating platform configuration**



## 5.2 Components functionality

As a functional whole, the system consists of the mechanisms used to aim the Sun photometer at the Sun and the photometer itself. Within the former, exists a suite of components used to provide various functionalities. These are listed as follows and are designed to meet the terms of reference for this project;

Sun tracking mechanism components:

- A 2 axis photodiode feedback system (2 BPW34 based systems)
- A 2 axis inclinometer feedback system (2 ADXL105's)
- A 16-bit microprocessor (MC9S12NE64)
- A FS ONcore GPS system
- A real-time time keeping chip (DS1302)
- 2 servo motors providing positioning control in the horizontal and vertical planes

## Chapter 6 Sun tracking system

The majority of systems implemented in this project exist purely to facilitate the means of tracking the Sun accurately. The accuracy with which this must be done is based on the necessity for excluding diffuse radiation from the sensors input for reasons previously outlined. The easiest way to do this is to aim the sensor directly at the Sun such that its field of view [FOV] can be limited to exactly the reception area required to see only the Sun.

To accomplish this, the following has been implemented in this system;

- A basic mechanical construct to appropriately limit the light received by the sensor.
- A GPS system capable of receiving values and a means of transferring them to the MCU.
- A Real-Time time keeping system
- A parallel photodiode Sun tracking system for calibrating the calculations.
- A 2-axis inclinometer system to assist in system setup and in calibrating the calculations
- A microcontroller capable of making the required calculation to with sufficient accuracy.

### 6.1 System resolution

The Sun subtends an angle of  $0.5^\circ$  and moves nominally  $0.25^\circ$  across an arc of the sky every minute. The terms of reference for this project call for a sensor sample frequency of 5 – 10 Hz where the measurements are then averaged over 5 minutes and for the sensor to have a FOV equal to the arc subtended by the Sun in the sky i.e. the  $0.5^\circ$ . The calculations used to find the Sun calculate its position to within  $0.01^\circ$ . Considering the above and the end purpose in making the measurements, the following is examined.

#### 6.1.1 Motor resolution

Regardless of how accurate a calculation of the Sun's position is made, the system resolution is fundamentally limited by the motor's resolution. Tests showed the motors to have a resolution of nominally  $0.2^\circ$ , however this resolution is not continuous, a resolution of  $0.4^\circ$  is more accurate on average but again. Although the motor's position control is in response to feedback from a potentiometer, the function of position relative to duty cycle isn't linear. In the absence of further

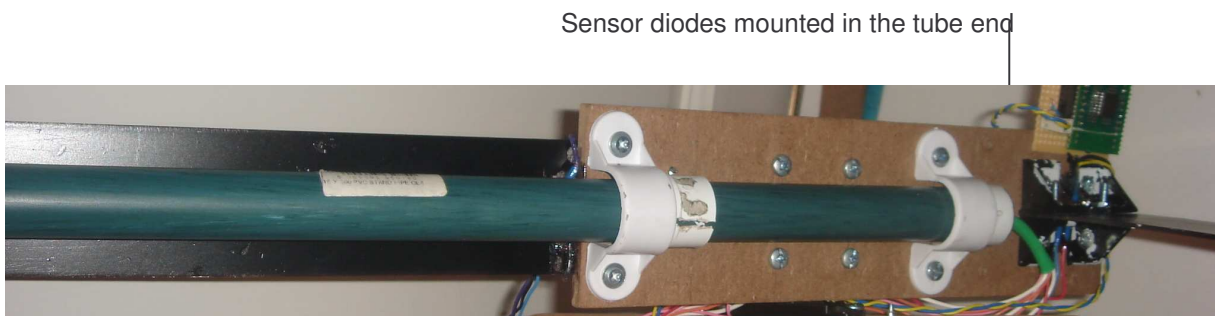
feedback, however, it has been assumed to be so which is not a valid assumption considering the level of precision required.

Specifically, motor 1 (Azimuth positioning) has an angular range of  $195^\circ$  which it moves through as the duty cycle changes from 2.86% to 12%. Motor 2 (Altitude positioning) has an angular range of  $200^\circ$  which it moves through as the duty cycle changes from 2.85% to 12.2%. Both position control signals are derived based on these values and assumptions and simply map the position calculated directly to a corresponding PWM generating value.

In addition, potentially, position resolution could be increased by externally gearing the motors, however, any such gearing will similarly gear up any position error. The loads being rotated are therefore attached directly to the motor shaft.

### 6.1.2 Mechanical resolution

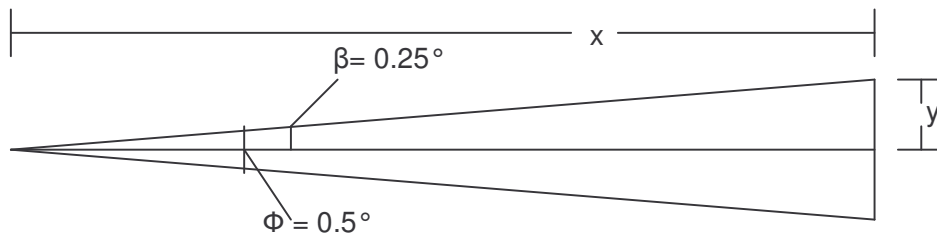
Meeting the FOV requirement mechanically influences the required system positioning accuracy. In order to exclude diffuse light being received by the sensor, the sensor diodes are mounted with in one end of dark lined tube as shown below in Figure 9.



**Figure 9: Tube containing photo sensors**

To subtend an angle of  $0.5^\circ$  at the sensor, which is 15mm in diameter, requires a tube of the same diameter to be 1700mm long by the calculations shown in figure 11. Clearly this is impractical and therefore a partial cover is placed on the tube end (see Fig 12) reducing the opening to a circular diameter of 5mm. The required tube length is then reduced to 573mm. As

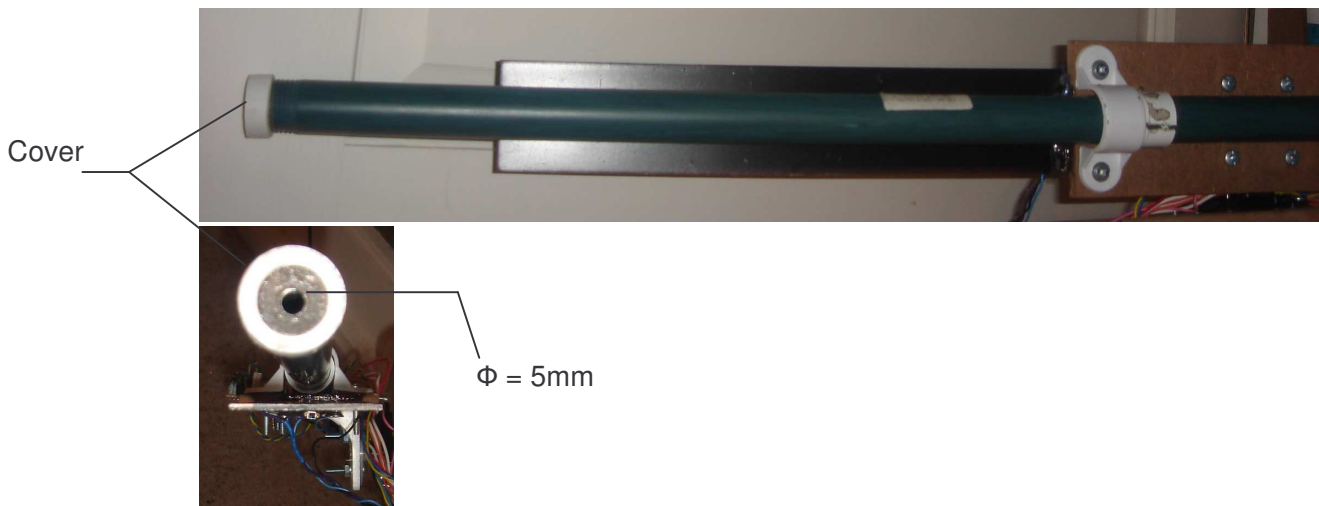
a prototype, for practical easy of implementation the 5mm diameter opening and a 400mm long pipe were used simply as they are standard sizes of parts used.



Opening diameter =  $2y$

$x = \text{tube length} = y / \arctan(\beta)$

**Figure 10 Tube dimension calculations**



**Figure 11: Tube end opening and dimensions**

### 6.1.3 Experimentation

Using a LI-COR Radiometer/Photometer the following readings were taken;

#### **With out the cover constriction:**

Centered on the Sun: Photometer reading =  $6 \times 10^4$  Lux

0.25° off center: Photometer reading =  $5.5 \times 10^4$  Lux

#### **With the cover restriction:**

Centered on the Sun: Photometer reading =  $6 \times 10^4$  Lux

0.25° off center: Photometer reading =  $1 \times 10^4$  Lux

These readings are based on imprecise experimentation but even at a macro level, they show the large divergence ( $6 \times 10^4$  Lux) from true values at a 0.25° off center when the FOV is enforced to be equal to the apparent size of the Sun. However, they also show the respectively small divergence ( $0.5 \times 10^4$  Lux) when the FOV is larger, subtending an angle of 2°.

As such, enlarging the FOV appears preferable considering the difficulties of aiming the sensor precisely enough to view the Sun and the apparent unimportance of keeping the FOV so small. Further experimentation will have to be done to determine how large the FOV can be made without significant errors in readings appearing, particularly with regard to when there is any form of cloud cover. Further investigation into the sensitivity of the atmospheric status values derived from these measurements is also needed. Knowledge of the implications of what degree of error will provide parameters with in which these accuracies will need to fall.

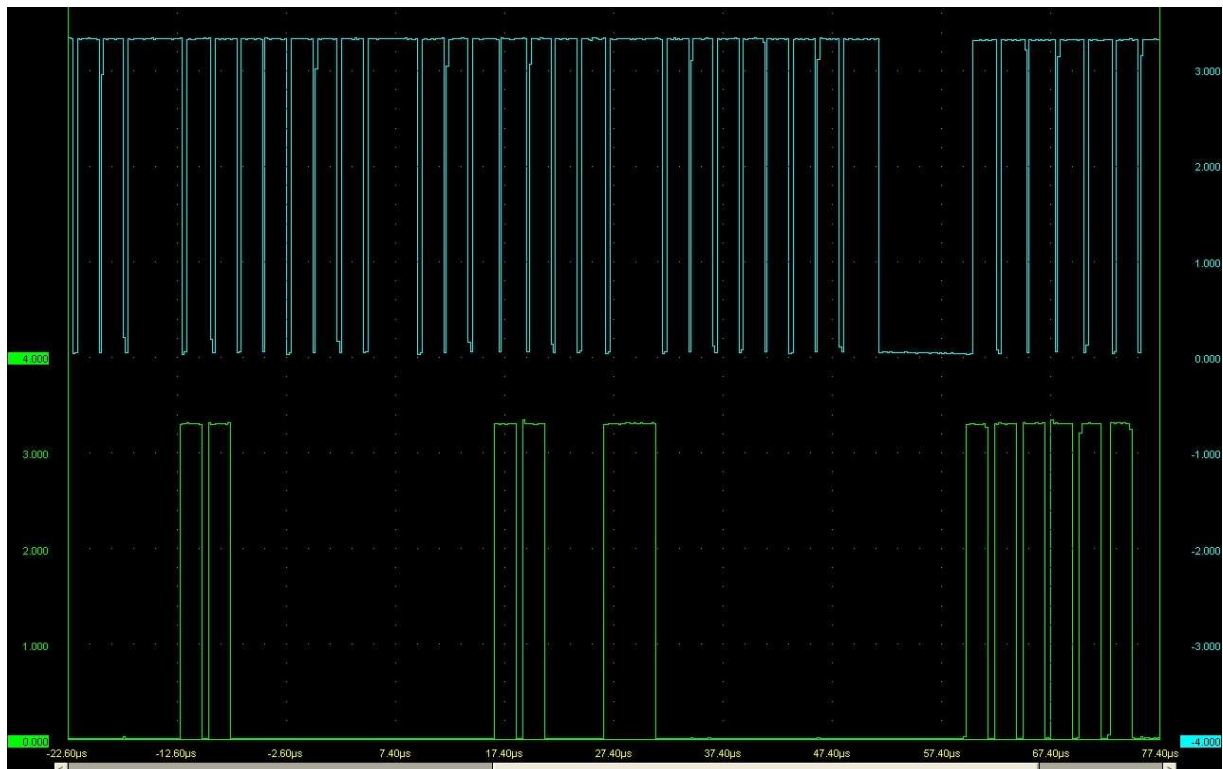
## 6.2 Real time keeping

To calculate the Sun's position at all requires an accurate knowledge of the time. To this end, a DS1302 time keeping chip is used to keep time once it has been set according to GPS delivered values. Doing so thus avoids having to continuously obtain time values from the GPS system, a poor solution considering that this may often not be possible due to lack of signal. Or alternatively, it avoids relying on the MCU timer unit, which is already busy generating 2 PWMs, to keep time.

In brief, the DS1302 receives year, month, date, day, hours, minutes and seconds' values and continues to keep track of each from initialization. It communicates easily with the MCU over a 3-wire interface, can run off 3.3V, the same as the MCU, and has its own oscillator. Its circuit implementation is shown in fig 24 in Appendix A

Reading and writing to the chip consists of sending an 8 bit command byte followed by an address of data to be either stored or read. To write and read to and from the time holding addresses a bust mode is used where by a single command byte is sent following which the data is either sequentially written or read without having to specify the addresses.

The code used in this project is based on code supplied by the application note<sup>19</sup> which has been modified and customized for this application and MCU. Communication between the chip and MCU is shown in figure 12 below.



**Figure 12: Scope image of communications between a DS1302 and the MCU. The top waveform shows the clock and the lower the data transferred on the IO line. Both waveforms span the same voltage range (0V - 3.3V) but have been offset for display purposes here.**

<sup>19</sup> Dallas semiconductor MAXIM, 'Program listing', *App Note 3449: Interfacing a DS1302 With an 8051-*

### 6.3 FSOncore GPS system

A GPS is required for this system in order to meet the easy setup and portability functionality requirements of this system, beyond initial setup at a location however, it serves no essential purpose. The GPS serves to supply local latitude and longitude and date and time information when the system is setup. Beyond setup, it serves only as a reference for periodic error checking of the system. It may be used to validate the DS1302 chip's correct operation and reset it if necessary.

The GPS system used in this project is one developed by Mr S. Ginsberg. Broadly, the system is based around the Motorola FS Oncore module, accompanied by Amtel's AT45DB041B flash memory chip, and a Motorola M68HC08 microcontroller. The system is designed to interface with both an on board LCD display and a PC via a serial communications link. Due to time constraints it was not possible to strip the system down to include only what is needed for this project and as such the system has been integrated as is. To extract the needed values, in principle, the serial communications between the M68HC08 and a figurative PC may be listened in on directly at the microcontroller output pins. This avoids having to complete conversions between RS232 logic and standard logic levels. As the microcontroller is a M68HC08, the code on board can be simplified as appropriate using Code Warrior.

In terms of the time data supplied by this system, it is notable that the UTC correction factor is not included in the data received by the system and therefore needs to be known and accounted for in the photometer's source code.

Unfortunately, time constraints have not allowed this module of the project to be developed beyond concept phase. Ideally, the GPS system would be stripped down to only what is needed for this system, a PCB board designed purely for such and the code onboard the M68HC08 orientated to talking directly to the photometer system's microcontroller.

## 6.4 Inclinometer feedback sub-system

The idea behind including inclinometers as a form of feedback arises out of the Sun tracking system being calculation based and the requirement for easy setup. The Sun tracking calculations produce altitude values which are converted into servo motor positioning values based on the assumption of the system as a whole being level and zero position on the altitude servo motor being indeed zero.

The inclinometer feedback is therefore useful in one of two forms; Firstly as offset values for the position control algorithms (although this is of limited value as appropriate adjustment can only be made in one axis) and secondly as dynamic feedback to the operator during set up provided a connection exists between the photometer and an external PC. The first being a matter of offsetting the altitude value given as the Sun's position by the amount indicated by the inclinometer and the second being a digital output to the user to indicate when they have the photometer correctly leveled.

The inclinometers used here are ADXL105's - single axis accelerometers – these were used instead of dual axis ADXL202's simply due to a shortage of those. The chip has an on board opamp shown in figure 8<sup>20</sup> which in this instance has been configured as an inverting amplifier with a gain of -7. The schematic of this circuit is shown in figure 23 in appendix A. The output is offset to  $V_{cc}/2$  to provide range for both positive and negative inclinations. The system is fairly noisy and as such is decoupled heavily

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<sup>20</sup> Analog Devices, 'High Accuracy 61 g to 65 g Single Axis iMEMS® Accelerometer with Analog Input', *ADXL105 datasheet Rev. A*, Analog Devices, pg 1



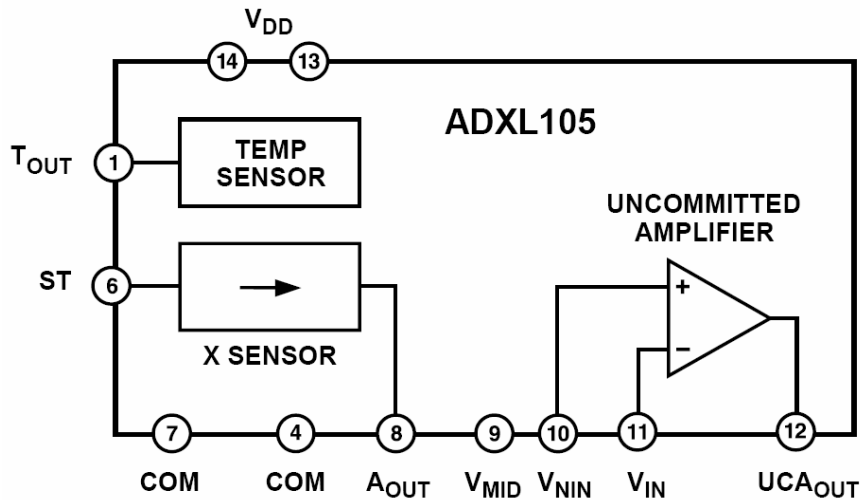


Figure 13: ADXL105 functional block diagram

## 6.5 Photodiode feedback sub-system

A parallel or secondary means of tracking the Sun has been implemented using photodiodes. The system consists of 2 light seeking circuits, each arranged on a respective axis. Original design concepts had this system as an optional extra. However, it has become increasingly clear that this system is essential to the correct operation of the Sun tracking system as a whole. The reasons for not making this or another feedback mechanism the primary Sun tracking system have been previously outlined in detail and have to do with such systems not being environment independent. Meaning, they cannot be guaranteed to work in all expected conditions. However, when conditions are appropriate a feedback based system holds significant advantages over the mathematics.

The idea behind having this system in parallel is therefore that when conditions are favorable, the advantages of feedback may be taken up. The feedback allows for mathematical and physical implementation error and compensates for it in a semi-dynamic manner. Without it, firstly the mathematical calculations of the Sun's position would simply have to be perfect to within the degree of accuracy required, secondly, the system would have to be constructed and setup at each new location with an equal degree of precision, a near impossibility and certainly not meeting the terms of reference for this system, which calls for it to be useable in the field, i.e semi-portable in that it is quick and easy to setup and use at new locations.

### 6.5.1 Mechanics

Physically, this system involves placing two photodiode on either side of an opaque divider inline with an axis of motion. Both sets have been placed on the side-rotating-platform which carries the sensor shown in Figure 14.



Figure 14: Photodiode system mechanics

### 6.5.2 Electronics

The photodiodes used here are Vishay made BPW34's. The circuit diagram used for each axis is shown below in figure 18. The circuit contains 3 basic stages, functionally represented in figure 15. The stages are detailed in figures 16 and 17.

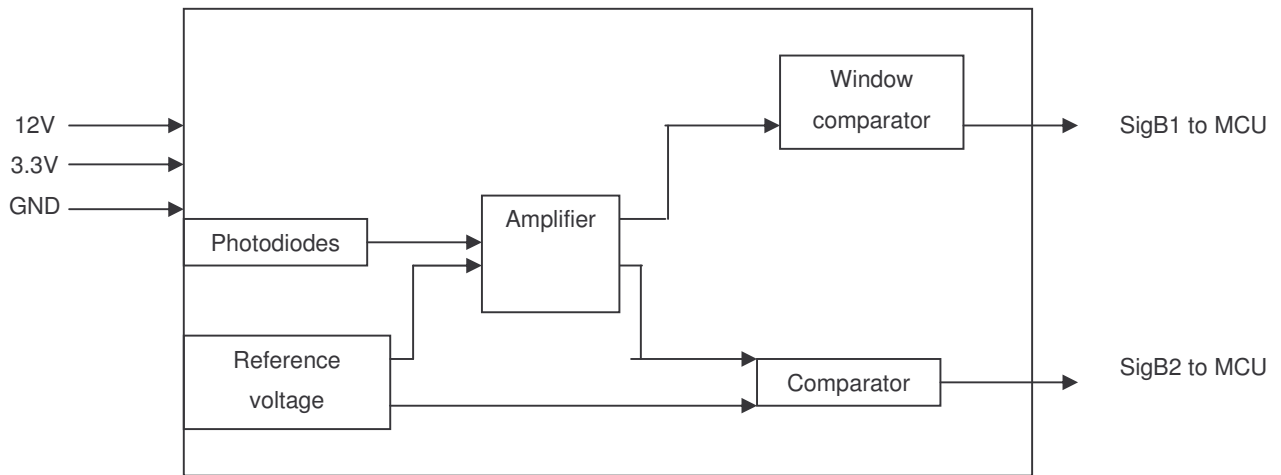


Figure 15: Photodiode circuit functional block diagram

The diodes are reverse biased here such that, as one receives more light than the other a corresponding voltage,  $V_{diode}$ , is produced at the output of the LF412. To avoid needing a negative rail the amplifier is offset by  $V_{ref}$  which is half of the 9V supply.

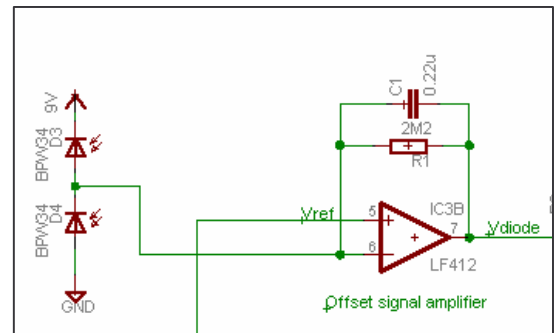


Figure 16: Amplifier

Vdiode is fed into a window comparator which uses two 20K pots and a 2k2 resistor to set the window to within 4.49V – 4.51V, this being +/- 10mV surrounding Vref across which Vdiode will move depending on which diode receives more light. The result of this comparator is sent as a logic signal to the MCU to indicate whether the system is centered or not. That is, a logic high on sigB1 indicates the diodes are centered as Vdiode is within the window. A logic low indicates that the system is off center.

To indicate in which direction to correct for, along side this, Vdiode and Vref are fed into a standard comparator giving a logical output, SigB2, which is also fed into the MCU.

Whether this is high or low indicates which diode is receiving more light from which the necessary corrective action can be derived from.

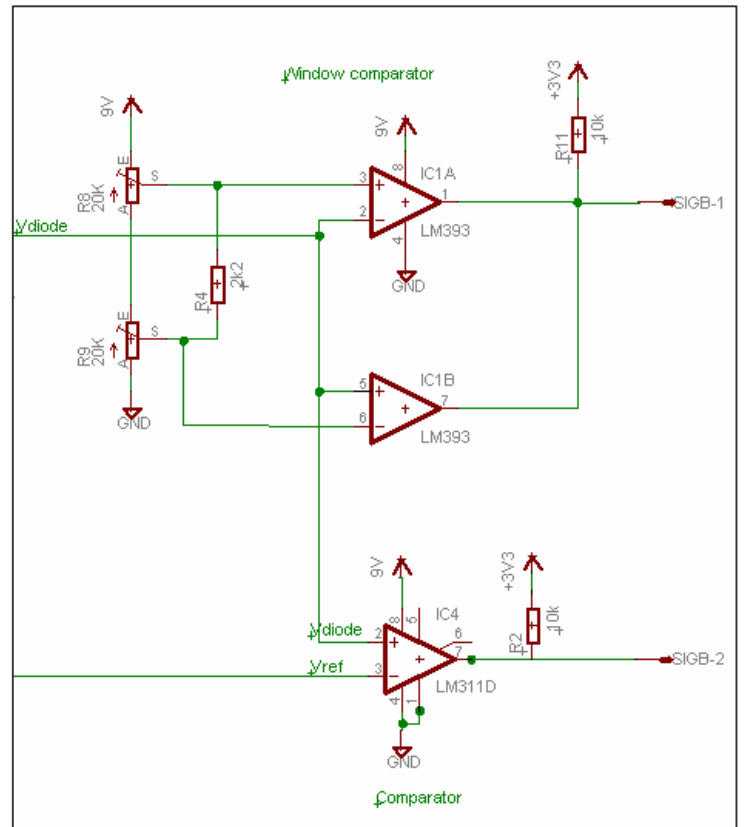


Figure 17: Comparators

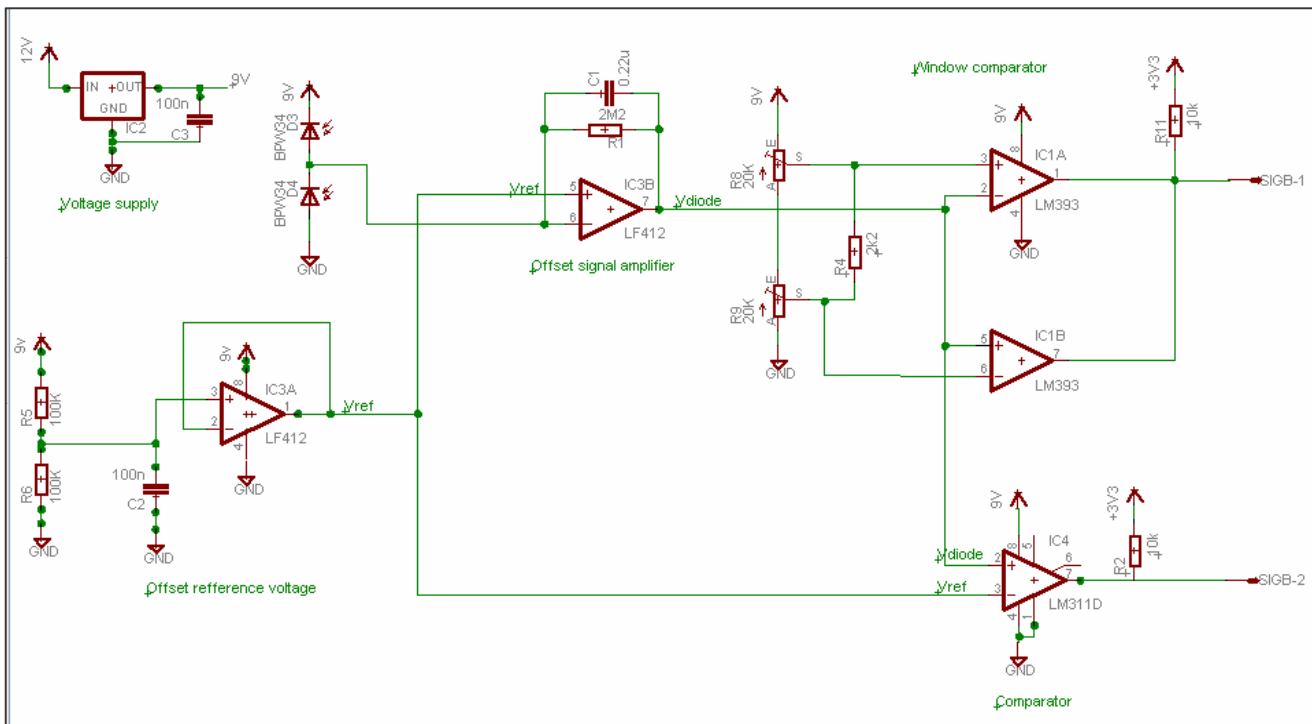


Figure 18: Complete photodiode circuit schematic

```

Signed char function photodiodePositionCalibrate ()
{
//Run this if the photodiodes indicate that they are not centered on the Sun
If (!sigB1)
{ //if-else statement determines which direction the system needs to be moved in
  if(sigB2)
  {
    //while loop to keep moving in the required direction until no longer needed and
    while (!sigB1&&sigB2)
    {
      move in direction1 with smallest possible increment;
      counter 1++;
    }
  }

  Else
    while (!sigB1&&!sigB2)
    {
      move in direction2 with smallest possible increment;
      counter1 --;
    }
}
Return counter;
}

```

A possible alternative to this might be to use a recursive algorithm. The above pseudo code has not yet been correctly implemented on the MCU due to lack of time.

## Chapter 7 Servo motor system

### 7.1 Hardware

As shown in chapter 5, two servo motors are used to aim the photometer sensor at the Sun, each providing motion in one of two perpendicular planes. Both are run of 5V, drawing around 600mA on average, depending on the positioning of the system. The PWM control signal is stepped up to this from the microcontroller's 3.3V through a basic transistor circuit (see figure 22 in appendix A) which also serves to buffer the micro from the motor and draw the current from a regulator rather. The only particular design consideration taken into account in this regard was the need for heat sinks on the regulators.

### 7.2 Software

As standard servo motors, these are driven using PWM's generated by the MCU. Generating a PWM with the timer unit in the MC9S12NE64 is completed as usual using the timer overflow and output compare functionalities. For this timer, channel 7's register is used as the reference register. That is, channel 7 has special authority to cause the counter to reset, generate interrupts and set and clear flags, when the timer overflows. It simply requires being setup the same as any other channel for output compare only beyond this certain control registers require having the appropriate values loaded. The PWM generated on ch5 is shown in figure 19 below.

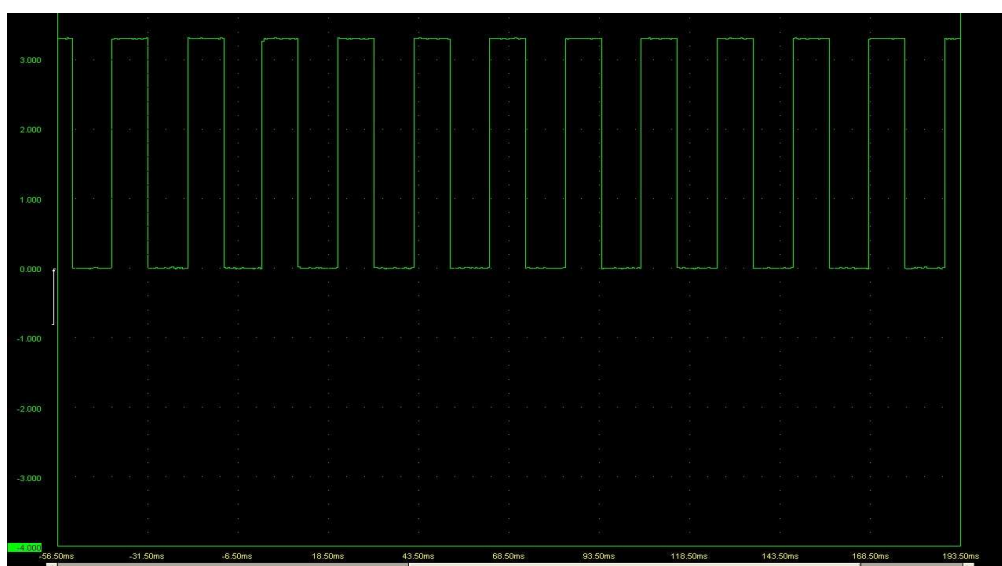


Figure 19: Scope image of Ch5 PWM running at 50Hz and 50.0016% duty cycle

The servo motor positions are given represented as PWM duty cycle values. The position needed is a function of the calculations completed giving the altitude and azimuth of the Sun at any instant. These values are therefore translated into representative duty cycle percentages and thus into timer channel register values. Each motor is nominally zeroed at around 3% duty cycle and positioned at 180°

In normal operation, the routines which calculate the Sun's position in the sky return a position angle in degrees. This value is transformed to produce the necessary channel register value to produce the PWM with the appropriate duty cycle.

The transformation is completed in a similar manner for both azimuth and altitude positioning. For azimuth positioning the channel register value is found as follows (the same method is used to find the altitude value, but includes the inclinometer offset and uses the appropriate motor characteristics)

The azimuth positioning motor is characterized by: 0° - 195° range corresponding to 12%-2.86% duty cycle.

$y^\circ = \text{Sun angle value} + \text{photodiode correction value}$ ; -- Position required in degrees.

$\therefore 1^\circ = 9.14/195 = 0.047\%$  duty cycle      -- Values here are dictated by the specific motor

$\therefore y^\circ = 0.047y\%$  duty cycle

$\therefore \text{ch7}/\text{ch5} = 0.047y\%$

$\therefore \text{ch5} = \text{ch7}/(0.047y)$       -- This is the value which is loaded into the ch5 register to position the sensor at  $y^\circ$

## Chapter 8 The photometer sensor

Apart from all the peripherals required to aim a sensor at the Sun, the actual photometer component of this whole system has a definable set of required characteristics. The purpose of a Sun photometer has already been described in detail along with the required sensor characteristics following on from this. This section seeks to describe the means used in this system to provide such functionality.

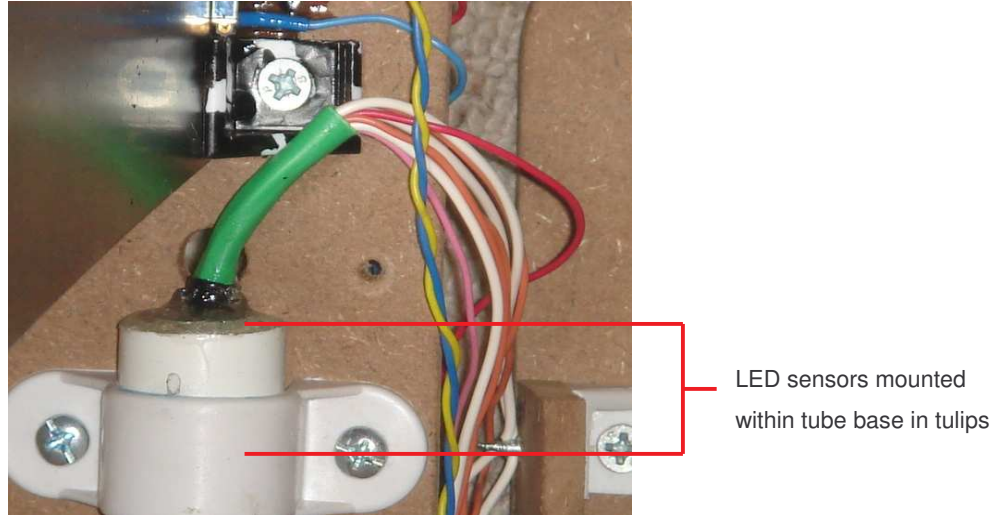
### 8.1 Hardware implementation

As discussed in chapter 3, a primary component of the functionality required of this sensor is the ability to measure received radiation at specific wavelengths to the exclusion of others. A standard manner of accomplishing this is to filter the light coming in before it reaches the sensor using filters which admit only a very narrow band of wavelengths. These filters serve this purpose well, however, they are expensive and have a definitely limited lifetime, for some this is decades but for a large proportion it is only a few years. In the case where these filters are used, the sensors themselves are generally photodiodes which produce significant voltage signals in response to received radiation making data capture relatively easy.

As an alternative, LED's have been proposed as possible sensors, instead of the photodiodes. Although to a lesser degree, they also respond to incident light in a manner that is easily enough registered and captured as data. Further, their response is, for the most part exclusive to a relatively narrow band of wavelengths, generally just shorter than their emitting wavelengths.

The wavelengths of interest in this system have been noted previously, the diodes selected are listed in appendix B. As literature regarding this use of LED's is limited and as this system is considered a prototype, or at least experimental, the diodes have been mounted in tulips with the expectation that tests will be carried out to determine those most suitable. For the same reason, those selected range in characteristics such as mcd value, viewing angle, casing material and shape. The image below just shows how the 4 diodes have been mounted within the aiming tube with fixed supply and signal wires exiting the back end.





**Figure 20: Photometer diode sensors mounted just inside the end of the aiming tube.**

## 8.2 Sensor-ADC interface

### ADC

An advantageous by-product of selecting the MC9S12NE64 microcontroller, is its on board 10 bit resolution ADC. That this is present, removes the necessity for integrating an external ADC of sufficient resolution as 10 bit resolution appears to be sufficient.

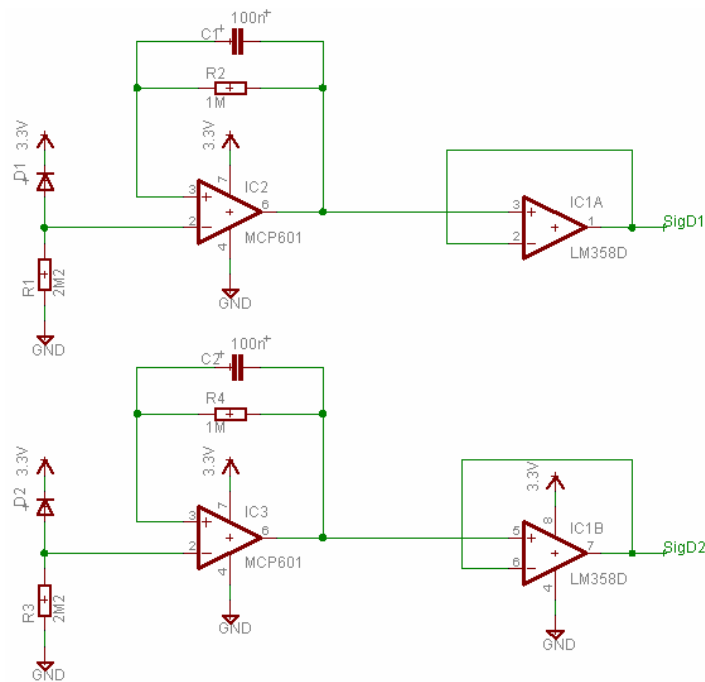
When the PCB for this system was designed an error was made which has limited the precision with which readings may be digitized. It was unfortunately not noted that it is possible to input a 0 – 5.12V signal into the ADC provided the external ADC high reference voltage pin  $V_{HR}$  is connected to such a supply. As it is, this pin is just routed to supply voltage, 3.3V, and so the interface circuitry developed limits the input to this range.

### Sensor amplification

As such, the LED's are implemented as sensors as shown in figure 21. The reverse biased diodes supply a signal which is passed through a non-inverting amplifier, the gain for which has been left adjustable for a range of 1 to 101 times gain. This was simply a practical design decision again based on the experimental nature of the sensor. As it is anticipated that different

diodes will be placed in the circuit for testing a variable gain will most likely be required. Beyond this is also the fact that lab testing and real environment signals are sure to differ quite probably to a great degree.

The opamp used here for the amplification stage is the single supply, cmos MCP601, chosen for its ability to operate on a single low voltage supply and inherent high input impedance. Beyond this, a LM358 is used simply to buffer the signal prior to inserting it into the MCU's ADC. The circuit shown in figure 21 below is representative of only half the circuit implemented, i.e., two identical duplicate of this are implemented alongside each other in the real circuit to make provision for a total of 4 LED sensors.



**Figure 21: LED photometer sensor circuit schematic**

## **Chapter 9 System operation**

### **9.1 Setup and calibration for a new location**

Part of the concept for this project was the idea that the system would be moderately portable. This had both physical and functional implications both of which have bearing on how the system is setup. The following describes the procedures needed to set the system up at a new location.

#### **9.1.1 Finding true North**

The system's positioning of the sensor is based on the assumption of the base being aligned with true North. A number of methods exist for finding true North. All of them, however, require user intervention and for sufficient accuracy require a fair amount of time.

##### **Using a compass**

This is the simplest method; a compass attached to the base of the photometer. However it requires accurate knowledge of current local magnetic declination. For Cape Town, this is currently  $-23^\circ$ . If Magnetic declination is known the photometer can simply be offset accordingly using the compass.

##### **Using shadows**

If the local magnetic declination is unknown this methods is sufficiently accurate provided enough time is taken over it.

- Stand a straight pointer vertically in the ground such that its shadow is visible and cast on a level surface.
- At some time at least an hour before noon, mark the location of the tip of the shadow and measure its length.
- Mark out an arc of this length with the pointer as its center.
- As noon comes and goes the shadow will shrink and grow. When it again reaches the original length, i.e when it crosses the arc, mark the location of its tip.
- Joining the two marked points in a straight line provides a west-east line, perpendicular to which is true North-South. North lies such that the first mark made is to the left and the second to the right.

- If the time of local noon is accurately known, an alternative to drawing an arc and watching the shadow's length is to simply note the position of the shadow tip at exactly the same time period before and after noon. Again joining these points provides a West-East line.

Neither of the above methods is ideal, however the 1<sup>st</sup> is possibly the easier to complete accurately and has been used in this project. Further de

### **9.1.2 Leveling**

Although the system receives input from 2 single axis inclinometers, only one axis can be compensated for directly by the code. The purpose of the other is to serve as a digital feedback to the operator when setting the system up. This feedback would be provided over the communications link established between this photometer system and a PC. As no such link has yet been implemented the system will need to be set up with a mechanical level to ensure it is perfectly level.

### **9.1.3 System calibration**

Calibrating a Sun photometer sensor is a complicated process which may be either highly mathematical or involve the lengthy process of comparing readings with a known calibrated instrument. Either method is beyond the scope of this project to detail.

Apart from the instrument calibration, however, it has been detailed at length that the photodiode sub-system and inclinometers are to be used to calibrate the system. Implementation of complete code for this system including a communications link would enable an operator to periodically run the calibration routines on known clear days. Long term experimentation would indicate how frequently such a task might be needed.

## **Chapter 10 Conclusions**

Coming to the end of the time allocated for this thesis project leaves much of the development work for this system unfinished. However, the investigations and implementation that have been done have laid the foundations for a relatively easy design completion. The following particular conclusions can be drawn.

### **10.1 The system required accuracy was a major obstruction to project completion**

The accuracy to which this system needs to be able to work to track the sun was a primary hindering fact in developing an automated sun photometer. The nature of the measurements wanted, meant that this accuracy had to be adhered to. This being said, however, it is no more than another engineering problem encountered in this project.

### **10.2 This thesis' scope was too great but appropriate**

Only after initial investigation and design was it evident that this project's scope was too great. In retrospect, alteration to its focus should have been made such that more electronic or software engineering might have been done as opposed to theoretical investigation and problem solving with regards to implementing this system in the real world. Generalizations and approximations might have been made to allow for more practical engineering to take place.

In the context of this being a university thesis, such actions seem like they should have been appropriate. However, engineering, as a field, is to a great degree about making systems work within the real world and as this thesis is an exercise in engineering, an investigative engineering process is perhaps not so inappropriate.

In terms of this being a mechatronics stream topic, it is most appropriate as a mixture of mechanical, electrical, instrumentation and control engineering.

### **10.3 The primary product of this thesis is a detailed design investigation into automated a sun photometer**

As this project was begun with the idea of producing a functional system, at every step in design the real world was taken in account and assumptions not allowed for. As such, those systems implimented are completely functional and the remaining investigation and design work is practical as well as theoretical and therefore has produced a thorough basis from which a functioning system might relatively easily be developed. To a degree this might be considered the real prodct of the thesis.

### **10.4 A secondary result of value is the conclusion that LED's serve decidedly well as photometer-sensors and a basic working photometer design**

The implementation of the actual photometer sensors using LED's was particularly simple. In light of the nature of the measurements being taken, they hold great advantage over photodiodes and filter systems. Even beyond this, they require minimal electronic filtering, are relatively cheap (although experimentation my find more expensive LED's to be more appropriate) and easily produce sufficient signal for high precision measurements to be made.

### **10.5 The specified dual functionality of the system regarding it being both permanently located and yet portable is inappropriate**

The design specifications for this system called for it to also be portable along with all other functionality. This requirement places a huge number of extra considerations on the system which compromise both operating modes apart from increasing cost. It would be more appropriate to design to different systems.

Where the one destined for permanent residence could have the appropriate long term durability accounted for in component material selection, it's power supply associatively designed along with its over all power usage design, and it's range of functions might be appropriately limited. The need for systems to assist in rapid setup would no exits while more remote error functionality may be required.

The design destined for portability would conversely have an entirely different material selection criteria, power consumption limitations, maintenance and error checking needs and would need the easy and rapid setup time functionality.

## **Chapter 11 Recommendations**

In conclusion of this project the following recommendations are made with regard to any future system development which might take place.

### **11.1 Further systematic experimentation with LED's as sensors**

Further experimentation into what configurations, wavelengths, packaging, mcd specifications and material types of LED's are most appropriate for these purposes should be carried out.

### **11.2 Protective dome**

The system as a whole needs a protective casing from within which it can operate. This design problem was never even broached but it is clear such would be needed. In designing this, the dual functionality of the system must be kept in mind with regards to it being both portable and resident.

### **11.3 Angle position feedback**

As the design process has demonstrated the high degree of accuracy required, apart from feedback from the sun, feedback regarding the systems position relative to itself would assist dramatically in acquiring this accuracy if the current mathematic approach remains the primary means of tracking the sun. A possibly useful form of this might be the use of inclinometers as angle detectors as the servo motor internal feedback control has demonstrated itself to have insufficient precision.

### **11.4 Automated mechanism for determining sensor dark current values.**

An optional extra functionality might be some means of remotely running a check to determine the sensors dark current values occasionally for calibration purposes.

### **11.5 Implement some means of external communication**

A primary lack and failure in this design is that no communications means has been implemented. All the broad design work was done with this in mind and as such the MCU used is capable of supporting either a serial communications link or Ethernet connectivity relatively



easily. Either of which should be implemented as a priority as the system is essentially useless without some means of delivering the measurements data elsewhere.

### **11.6 Code optimization and strengthening**

Clearly a large proportion of the code remains to be developed. When done so and when reworking the existing code, the system as a whole should be made more robust in terms of error checking both of its own code and of the system mechanics. Further the MCU used has many modes in which power consumption might be minimized which for a system running continuously is appealing and as such these should be implemented.

### **11.7 Alternative means of coping with high accuracy demands.**

As mentioned in text, the optimal FOV for the sensor should be investigated and in conjunction with this, it may be appropriate to situate each sensing LED within its own aiming tube. This would reduce the diameter of the point to which the Sun's half degree arc must subtend and would thereby shorten the required tube length. Dealing with the mounting and aiming practicalities of 4 tubes instead of one is simple enough if they are mounted at staggered angles from a central point, the positioning controls would just have to be offset accordingly and a sequence run through whenever measurements were taken in which each tube is correctly aligned to the sun one after the next.

### **11.8 Correction of PCB design errors**

A number of changes to the MCU PCB design would serve well.

Firstly the already mentioned alteration of the ADC external high voltage reference should be taken up to 5.12 volts to increase the sensors potential precision. Along with changing this, the actual photometer circuit voltage levels would also have to be appropriately raised to gain any benefit from this.

Secondly, as a basic functionality level, two of the capacitors used should have been through hole and not smd packages which therefore changes the footprints needed. And beyond this a more freely available and generic power switch would serve well.

## **11.9 Mechanical design changes**

Implementation of the mechanics of this system showed a number of elements which should be redesigned. Of primary importance, a stronger and more secure means of attaching both the table and sensor platform to their respective servo motors should be found as any instability in these connections naturally leads to accuracy errors. The mechanics could theoretically remain unchanged if better feedback systems were implemented but it is more likely that changing the mechanics will be both easier and cheaper and more reliable in the long run.

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## Appendix A: Schematics

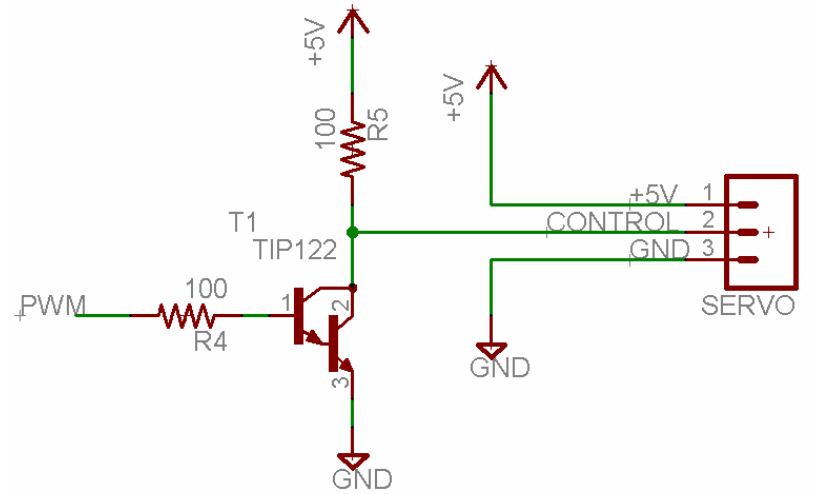


Figure 24 Servo motor control

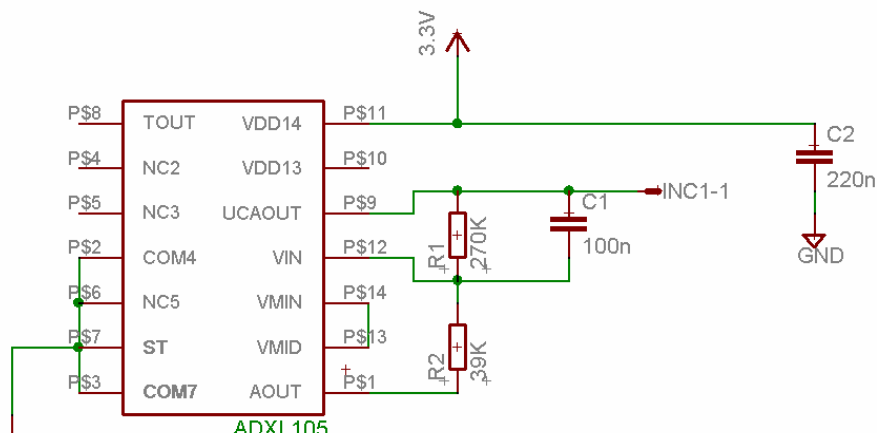


Figure 22 Inclinometer

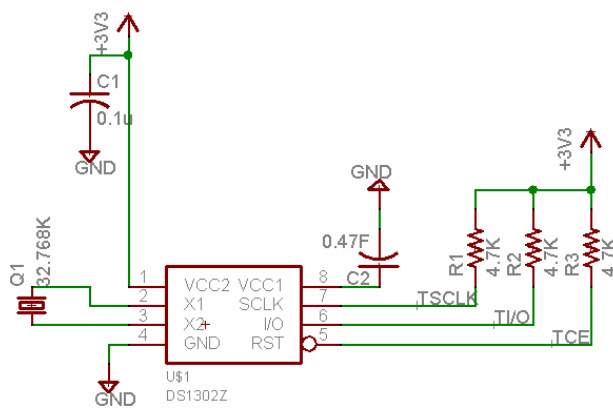


Figure 23 DS1302 circuit

## Appendix B

The photometer diodes used are king bright:

- L-53VGC-E (525nm green)
- L-53F3C (940nm)
- L-71135SEC-H (630nm)
- L-53EC (625nm red)
-

## **Appendix C: Datasheet summaries**

**A. Freescale MC9S12NE64 microcontroller**

**B. DS1302 RTC**

**C. ADXL105 accelerometer**

**D. BPW34 photodiode**

**E. BPW34 photodiode**

