DE-Link, an antenna pointing system for stratospheric balloons

Gustav Stenberg, Johan Selinder and Kalevi Hyyppä

Abstract

The DE-Link attitude determination and pointing system onboard stratospheric balloons provides a low cost, low weight and high accuracy method to increase the efficiency of WLAN communication between balloon and ground station. By determination of the 6-dimensional pose of the balloon gondola in real-time, the WLAN antenna can be pointed toward a known position on the ground. This removes the need for power-consuming omnidirectional antennas. It also gives an improvement in communication speed and reduction of overall weight by the removal of heavy RF power amplifiers. The design uses a combination of GPS receivers, accelerometers and magnetoresistive circuits to determine the absolute attitude and position of the gondola in real-time, and two DC motors to point the antenna in azimuth- and elevation directions to compensate for the movements of the gondola. Ground based tests have shown the system to function well with a pointing error of less than $\pm 2^\circ$.

1 Introduction

An attractive alternative to expensive experiments carried out in space, either onboard space stations, satellites or sounding rockets, is the use of stratospheric balloons to reach near space conditions for a limited time, from a few hours to up to 45 days [1]. One large drawback of the use of balloons is that data has to be stored onboard and then retrieved from the balloon once it has landed. This often takes at least six hours and depending on weather conditions and the location of the landing site this time can be weeks. Many experiments have problems to keep data relevant for such extended period of time, and therefore real-time data acquisition for stratospheric balloons has been requested by the scientific community.

On the Swedish launch site Esrange, owned by the Swedish Space Corporation (SSC), a real-time WLAN communications system, E-Link, has been developed to meet this

©Copyright 2005 IEEE. Published in the 2005 International Conference on Electronics, Circuits and Systems (ICECS2005), scheduled for December 11-14th, 2005 in Gammarth, Tunisia. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works, must be obtained from the IEEE. Contact: Manager, Copyrights and Permissions / IEEE Service Center / 445 Hoes Lane / P.O. Box 1331 / Piscataway, NJ 08855-1331, USA. Telephone: + Intl. 908-562-3966.

demand for their stratospheric balloon platform. The system operates today at 2 Mbit/s speed and at ranges up to 300 km using an omnidirectional antenna which gives an output of 10 W. The E-Link consists of transmitter and receiver for WLAN communication on the 2.45 GHz band with built in power stages and a command system. The system implements altered WLAN protocols to reduce bit degradation over long distances.

This paper describes the development of the previous system to a directional E-Link, called DE-Link, which is purely an *onboard* antenna pointing system. A replacement of the existing antenna with a directed antenna with a 10° aperture would improve the gain by a factor of 260. This improvement can be used both to increase the speed of the uplink as well as significantly reduce the weight of the system by the removal of batteries and heavy RF power amplifiers of the transmitter. To be able to determine the 6-dimensional pose of the gondola an attitude determination system and a position determination system is required. In addition, a mechanical system to point the antenna and a new antenna is needed.

The stratospheric balloons fly at an altitude of at least 27 km, which in practice means space conditions. These conditions put extraordinary demands on the design of an antenna pointing system, as well as additional requirements [2][3];

- *compatible with high radiation environment*
- *compatible with low pressure environment (< 20 mbar)*
- *compatible with low temperature environment ($< -40^\circ C$)*
- *rotation speed $> 53.5^\circ/s$*
- *tilt speed $> 29^\circ/s$*
- *low weight (< 5 kg, batteries included)*
- *low power consumption (< 10 W)*
- *low cost ($< \$10,000$)*
- *low error ($\pm 2^\circ$)*
- *high reliability*

Since flight times can easily reach weeks, all the position and attitude determination systems have to be absolute, i.e. if the system is rebooted during flight it should still be able to determine the 6 dimensional pose of the gondola, without calibration. This also means that no accumulative errors are allowed that would degrade the performance of the system with time.

2 System overview

A design flowchart of the system as a whole is shown in Fig. 1. The main processor is a PC/104+ board that contains software in ADA to provide a real-time platform for all calculations. The PC/104+ is installed with FreeBSD 4.10 (linux based OS) on a 512 MB Compact-Flash disk. One benefit of the use of ADA is the ability to create different

tasks that run independent from each other, creating a more stable environment and the possibility of running time critical tasks more often than noncritical tasks.

The position determination is done by an off the shelf GPS receiver from u-blox [4]. Communication between PC/104+ and the GPS modules is done by TCP/IP through an industrial grade switch. Attitude determination is achieved by a custom designed sensor board that contains a PIC-processor, accelerometers and magnetometers. The sensor board communicates by RS-232 with the PC/104+.

Figure 1: Overview of the system layout.

The pointing system is designed with a sturdy aluminum frame and uses two DC motors to turn the antenna in azimuth and elevation directions. The azimuth rotation means that a rotation joint had to be developed that can handle both RF and sensor signals with low loss in space conditions. To improve performance of the system, absolute

references of the current antenna direction are realized by angle sensors mounted on each rotation axis.

A sketch of what the physical system looks like can be seen in Fig. 4.

3 Attitude determination

3.1 GPS

To meet the demand of absolute determination of the gondola's 6-dimensional pose, it was decided to attempt to create an attitude determination system from low priced ($< \$100$) off the shelf GPS modules. A standard GPS receiver has an error of approximately 10-50 m during normal operating conditions. However, the errors in measurements of the pseudo range (estimated distance to satellite based on time differences between satellite and receiver) that degrade the accuracy to this level are common for receivers placed closely together and thus can be canceled out [5]. This implies that when three identical GPS receiver modules are placed at small distances from each other, the accuracy of the relative position in between the modules should improve vastly, to an error of a few mm.

Figure 2: Schematic picture of the GPS antenna mounting frame.

To meet the demand of small size of the system extremely short baselines were chosen (20 cm and 33 cm). The three GPS antennas were placed as seen in Fig. 2. To get the attitude of the gondola, the three different locations of the GPS modules need to be known. At first, an attempt was made to use the built-in algorithms of the u-blox receivers to retrieve these positions. However, this proved impossible as the received positions were extremely different from each other; they differed at 100-200 m levels. Instead, the standard algorithms described in the ICD-GPS-200C [5] document were implemented in the PC/104+ and used with raw data streams from the different receivers. This reduced the error to 50-80 m levels, which was still not sufficient.

One of the major calculation problems was discovered from an analysis of the Doppler shift measurements received from the GPS modules. As the test setup of the antennas

was stationary, the Doppler shift of each satellite should be equal between the three receivers. This was not the case, and it was soon discovered that the reference clocks on the GPS modules differed highly from each other. To solve this problem the clock signals were removed from the chips and replaced with a common high accuracy reference clock. This remedied most of the errors, and the error was reduced to 0.2-20 m levels. However, even with matched references, the receivers still produced a random discrepancy in the raw data that were $N \cdot 128$ (N is any integer) of the values of phase measurements of the L1 signal.

The difference in the raw data was deduced to arise from the time stamp that each GPS receiver put on the raw data. This time stamp is achieved internally in the modules as they solve their position and time in the GPS reference frame. This should be fine since the three receivers are spaced so closely together that all errors are common, thus the solution of the same matrix should produce the same result. However, this is not the case since each receiver chooses different sets of satellites, that are not user effectible, to solve the matrix. This only induces a time difference in the range of 50-100 ns, but that means an error in the phase measurements that yields > 15 m error in pseudo range calculations. This renders the phase measurements unusable for attitude determination.

Since the difference in Doppler shift between the receivers should be zero and these measurements also showed discrepancies at $N \cdot 128$ of the measurements, they could be used to remove the error by adjusting the time of the measurements to set the Doppler shift to zero. An unsuccessful attempt to correlate this mismatch was made as seen in Fig. 3. Without a clear correlation it proved impossible to remove this error from the phase measurements.

Figure 3: The graph shows no correlation between phase versus Doppler shift errors.

3.2 Accelerometers

In addition to the GPS attitude determination system, a sensor card with accelerometers and magnetometers was developed as a backup system. The accelerometers are cheap ($< \$15$) off the shelf components that can measure both static and dynamic accelerations. With a model of how the balloon moves in flight, it is possible to calculate the static component of acceleration that arises from Earth's gravity, which then can be used as a good reference for tilt in both roll and pitch axis. When dynamic accelerations are small ($< 0.1g$) the error of tilt is $\sim 0.1^\circ$.

To get yaw information as well, a magnetic compass was incorporated on the sensor card and the World Magnetic Model (WMM) [6] was implemented in the PC/104+. The accuracy of the electronic compass is highly dependent on local magnetic conditions, both from local ore deposits in the ground and internal magnetic fields inside the gondola. The achieved inaccuracy is $\pm 2^\circ$.

4 Pointing system

A number of different alternatives for the pointing system for the antenna were investigated. The final alternative was chosen based on a combination of cost, weight and accuracy. As seen in Fig. 4 the antenna is mounted below a base plane in a frame that can rotate unlimited in azimuthal direction. An elevation motor is mounted on the frame to provide full half-dome coverage of the antenna pointing range by turning the antenna $\pm 115^\circ$ from "straight down" in the gondola reference frame. The main problem with a design that utilizes unlimited rotation is to transfer signals at the rotation joint.

Since the rotating frame contains a motor, an angle sensor and the actual antenna element, a combination of RF and low-level signals must be transferred to the frame. For this a number of solutions were investigated, of which many were very expensive ($> \$5000$). The solution that was finally chosen consists of two separate parts, one RF-rotation joint to transfer the RF-signal to the antenna and a 6-way slip ring that is fit over the RF-rotation joint to provide low-level signal transfer. This combined solution proved to be a lot cheaper ($< \$1200$) than combined rotation joints and both parts were classified for vacuum and extreme cold.

For actuation small sized DC motors with high gearbox ratios were chosen over stepping motors to save power and cost. A gearbox with a ratio of 75:1 or larger is self-impeding, which removes the need to hold the motors when the antenna is stationary. The motors are 12 V DC motors with a maximum efficiency of 61% and can rotate and tilt the antenna at $244^\circ/\text{s}$ and $712^\circ/\text{s}$ respectively. This cover the requirements for the antenna speed with margin. The motors are controlled with Pulse Width Modulation (PWM) to improve efficiency since the motors rarely will run at full speed. To be able to control the antenna with a PID-controller it was decided to use absolute angle sensors to provide immediate knowledge of the current antenna direction. The sensors continuously provide a voltage output that is linear to the rotation angle of the sensor.

Figure 4: Schematic picture of the mechanical antenna pointing system. The outline dimension of the box is 36 x 23 x 10 cm.

4.1 Control hardware

Since PWM was needed to control the motors, a PIC-processor with built-in PWM capability was chosen to contain the actual control. The PIC also has A/D conversion capabilities and uses these to acquire the current direction of the antenna. The PIC continuously receives desired orientation of the antenna in both azimuth and elevation via RS-232 from the PC/104+ that calculates these values from the 6-dimensional pose of the gondola. PID-control is then done discretely in the PIC and PWM-signals are sent directly to the motors via an H-bridge driving stage.

4.2 Control software

The actual PID-controller was implemented discretely in C in the PIC18F2331. Timers and interrupt routines are used to prevent loss of control of the motors at any time, and the orientation of the antenna is continuously compared to the required orientation. The discrete controller of increment-type is shown in Eq. 1. This type of controller is used to prevent integrator wind-up [7].

$$u(k) = K_c \left(\left(1 + \frac{h}{2T_i} \right) e(k) + \frac{h}{T_i} e(k-1) - \frac{2T_D}{h} (y(k) - 2y(k-1) + y(k-2)) - \left(1 - \frac{h}{2T_i} \right) e(k-2) \right) + u(k-2), \quad (1)$$

where u is the output, y is the input and e is the error. Discrete steps are represented by k ($k-1$ means previous cycle) and h is the time between each step. To adjust the variables in the controller, i.e. K_c (proportional factor), T_i (integral time factor) and T_D (derivative time factor), the Ziegler-Nichols method was used.

5 Results and discussion

The final assembly of the pointing system can be seen in Fig. 5. The antenna pointing is fast and accurate, and weight-, power- and financial budgets were all fulfilled. Further tests must be completed before first flight-test, such as vacuum and heat distribution tests.

The prototype that was built has been tested for pointing speed and accuracy. The tests showed that the required values were met. The angular sensors that acquire the current antenna orientation were tested and they proved to be working with high accuracy. The GPS position was tested and the accelerometers proved to give accurate read-outs of the tilt in both roll and pitch. The electronic compass was not tested due to limited time of the project. PID-control was also tested and worked nicely with a small self-oscillation at magnitudes of no more than 0.5° . This oscillation is probably due to play in the gears.

The use of low-cost off the shelf GPS modules for extremely short baseline GPS attitude determination system proved difficult to do, and impossible with the GPS module used in DE-Link. Demands that need to be fulfilled by the GPS modules in such a system are;

1. *Common frequency reference*
2. *Common clock reference*
3. *Possibility to choose which satellites to use*
4. *Phase measurement of the L1 carrier frequency*

These demands are to the authors knowledge not available on low-cost ($< \$100$) modules today. An alternative to three GPS modules is to use three front-end IC's and one DSP (Digital Signal Processor) that does all of the correlation and calculation for all three antennas. With this setup the first three of the four demands are solved instantly. This

will not be cheap to develop, but once done the production cost of an GPS attitude system should be relatively small compared to the use of expensive ($> \$4000$ each) GPS modules that meet the demands above.

The use of accelerometers as a backup for roll and pitch measurements works well and is easily implemented in any system. The use of magnetoresistive circuits to measure Earth's magnetic field is also a good backup, but depending on accuracy demands, might not be good enough on its own.

6 Conclusions

This paper has described the construction of a small antenna pointing system for use onboard stratospheric balloons. The system is capable of pointing an antenna with an error of less than $\pm 2^\circ$ under near space conditions which improves the capabilities of a WLAN communication system already in use at the Esrange facility in Sweden. The attempt to use low cost, of the shelf, GPS modules for attitude determination failed. However, it should be possible to create a relative low cost GPS attitude determination system built on a DSP as mentioned above.

Figure 5: Photo of the actual mechanical antenna pointing system.

References

- [1] A. Hertzog, C. Basdevant, and C. M. F. Vial, “The accuracy of stratospheric analyses in the northern hemisphere inferred from long-duration balloon flights,” *Q. J. R. Meteorol. Soc. (UK)*, vol. 130, pp. 607–626, January 2004.
- [2] M. Fulchignoni, A. Aboudan, F. Angrilli, M. Antonello, S. Bastianello, C. Bettanini, G. Bianchini, G. Colombatti, F. Ferri, E. Flamini, V. Gaborit, N. Ghafoor, B. Hathi, A.-M. Harri, A. Lehto, P. L. Stoppato, M. Patel, and J. Zarnecki, “A stratospheric balloon experiment to test the Huygens atmospheric structure instrument (HASI),” *Planet. Space Sci. (UK)*, vol. 52, pp. 867–880, August 2004.
- [3] G. Johansson and J. Selinder, “Directional E-Link, a position and attitude determination- and directional system for WLAN communication antennas onboard stratospheric balloons.” Master’s thesis, Luleå University of Technology, 2005.
- [4] (2004, December) www.u-blox.com. [Online]. Available: <http://www.u-blox.ch>
- [5] *Navstar GPS Space Segment / Navigation User Interfaces*, 004th ed., Arinc Research Corporation, 2250 E. Imperial Highway, Suite 450 El Segundo, CA 90245-3509, October 1993.
- [6] (2005, February) www.ngdc.noaa.gov/seg/wmm/dodwmm.shtml. [Online]. Available: <http://www.ngdc.noaa.gov/seg/WMM/DoDWMM.shtml>
- [7] D. Clarke, “PID algorithms and their computer implementation,” *Transactions of the Institute of Measurement and Control*, vol. OUEL-1482, pp. 39 –, 1983.