

## **A PORTABLE MONOPULSE TRACKING ANTENNA FOR UAV COMMUNICATIONS**

Stewart Jenvey\*, Jonas Gustafsson<sup>+</sup> and Fredrik Henriksson<sup>#</sup>

\* [stewart.jenvey@eng.monash.edu.au](mailto:stewart.jenvey@eng.monash.edu.au), Department of Electrical and Computer Systems Engineering, Monash University, Melbourne, Australia.

<sup>+</sup> [jonas.u.gustafsson@ltu.se](mailto:jonas.u.gustafsson@ltu.se), System Teknik, Luleå University of Technology, Luleå Sweden.

<sup>#</sup> [fredrik.henriksson@ltu.se](mailto:fredrik.henriksson@ltu.se), System Teknik, Luleå University of Technology, Luleå, Sweden.

### **Abstract**

*This paper describes a portable tracking antenna system that is used for line of sight communications with the small UAVs being developed by Monash University. The antenna is a wire-frame parabolic antenna that is mechanically rotated in an elevation over azimuth mode in response to tracking signals derived from the UAV video link transmissions. The antenna feed system is arranged in a four channel monopulse format to derive the steering signals for the tracking and a single bore sight channel for the data reception.*

### **Biography**

Stewart Jenvey worked for ten years in the avionics, antennas and mobile radio communications industries in the United Kingdom and Australia. He joined Monash University in 1990 where he pursues his main areas of interests of antenna systems and indoor radio propagation. Over the past eight years he has taught several courses in these fields as a visiting lecturer to Luleå University of Technology.

Jonas Gustafsson was born in Skellefteå, Sweden (in 1980). He attended at Luleå University of Technology (2000 – 2005) and graduated with a Master of Science in Electrical Engineering in November 2005. He is currently working on a PhD program at Luleå University of Technology.

Fredrik Heriksson was born in Hudiksvall, Sweden. He attended at Luleå University of Technology (2000 – 2005) and graduated with a Master of Science in Electrical Engineering in March 2006. He is currently working for Boliden AB and he runs his own engineering consultancy.

## Introduction

Monash University has a UAV development program for small electric powered aircraft. These are research aircraft in their own right but they are also used for practical applications such as aerial survey work. When doing aerial survey work a video link between the UAV and a ground station is utilized to download survey data. In order to maximize the quality of this video data link a high gain tracking antenna has been developed for use as part of the ground station. This tracking antenna has been designed to be rugged, portable and to be readily disassembled and packed into the boot of car to enable rapid transportation to and from the survey sites.

The paper discusses the specification for the tracking antenna, the design and construction of the antenna and preliminary results of testing the antenna and video link to the UAV.

## Monash UAVs

Monash University has a UAV development program for small electric powered aircraft [1]. These aircraft weigh between 2 and 5 kg (including up to 1 kg of batteries) and have payloads up to about 1.5 kg (Fig. 1). They typically have an endurance of about 2 hours.



Figure 1. A Monash University UAV

The aircraft are either remotely controlled via a 36 MHz radio link or are autonomously flown by an autopilot and GPS navigation along routes specified by a series of way-points. Figure 2 shows the route of a typical flight where the aircraft is launched under remote radio control and then once in the air control is handed over to the autopilot which flies the aircraft around a route specified by the way points (octagons on the figure). The aircraft is then returned to remote control for landing.

The way-points can be either loaded into the autopilot before the flight begins or updated via a 920 MHz radio data link during flight. The 920

MHz radio link with the UAV is also used for data logging the aircraft's position (GPS determined) and performance parameters.



Figure 2. An autopilot controlled UAV flight path between way-points (octagons) plus associated instrument displays.

The UAVs are often used for aerial survey work and so they can be fitted with onboard still cameras that store the images (Figure. 3 shows the an image of the creek over-flown in the flight depicted in Figure 2), or video cameras that transmit the data in real time to a ground station via a 2.45 GHz radio link. (See accompanying video clip).



Figure 3. An Aerial Survey Photograph of Dandenong Creek in Melbourne.

## Tracking Antenna Specifications

A ground based tracking antenna is used to follow the UAV as it flies on its route. The antenna has to keep its main beam pointing at the in-flight UAV in order to maintain a strong video link from the UAV to the ground station. The main beam of such a tracking antenna can be made to change the direction in which it is pointing by two main methods

- By mechanically rotating the antenna in space.
- Or, if the antenna is a phased array, by electronically changing the relative phasing of the array elements.

In this study a mechanically rotated antenna is used. An electronically steered phased array antenna is planned for a future study.

The mechanically rotated tracking antenna is capable of being rotated 360° in azimuth and 180° in elevation to give hemispherical coverage above and around the ground station. A monopulse tracking system is used to determine the steering signals for the azimuth and elevation drive systems of the mechanically rotated antenna.

### Monopulse Tracking

If a UAV moves in azimuth or elevation relative to a ground station antenna that had been pointing at the UAV then the ground station antenna signal received from the UAV will become weaker as the UAV moves away from the centre of the antenna beam. Movement is thus detected but the direction of movement is unknown. In a monopulse system, in addition to the main antenna beam, there are additional beams connected to separate ports on the antenna and the signals received from these additional beams through their ports are used to determine the direction of UAV movement.

For example in figure 4, for the azimuth plane, an aircraft centred in the main beam (Beam A) of a monopulse antenna will produce equal amplitude signals from ports B and C if they are connected respectively to beams B and C (and provided Beams B and C are mirror images of each other about the main beam axis).

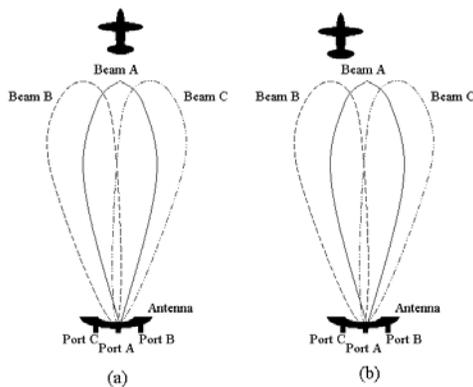


Figure 4. Monopulse Tracking

If the aircraft moves off the main beam axis it will move more into one of the off axis beams (Beam B in the diagram) and out of the other off axis beam (Beam C). Hence the signal will increase at one port (Port B) and decrease at the other (Port C), indicating the direction the antenna must be

rotated to re-centre the aircraft in the antenna's main beam and thereby equalize the signals from the ports (B and C). A similar arrangement of offset beams in the elevation plane enables elevation tracking.

### Tracking Antenna Performance Requirements

In current usage the Monash UAVs are kept at altitudes below 120 m and above about 30 m (other than during launching or landing), and they fly over unpopulated areas. This allows the UAVs to be flown without lodging flight plans and obtaining a flight permit from CASA (The Australian "Civil Aviation Safety Authority"). The aircraft have cruising speeds of between 35 kmph and 75 kmph.

The range over which the aircraft is to be tracked was specified as 50 m to 1000 m from the ground station, which, combined with a maximum speed for the UAV of 75 kmph, meant that the antenna would need to be driven at speeds up to 4 rpm in both the azimuth and elevation planes.

The tracking antenna also had to be rugged enough to be repeatedly assembled/disassembled and unpacked/packed from/into a car boot. Additionally it had to be stable in an outdoor environment when exposed to gusty winds.

### Tracking Antenna Gain and Size

The 2.45 GHz video transmitter used on the UAV has a power output of 10 dBm into an essentially omni-directional circularly polarized antenna. The resultant EIRP (Effective Isotropic Radiated Power) satisfies ACMA radiated power requirements [2], and minimizes the UAV battery requirements.

In order to track the UAV, maintain a strong video data signal and to reject the in-band noise of other unlicensed transmitters, a directive (high gain) tracking antenna was required.

Given that the transmitter and receiver characteristics and the range requirements are

- Maximum range  $d=1$  km
- Radiated  $EIRP=10^{-2}$  W and  $EIRP=G_T P_T$  where  $G_T=1$  is the transmit antenna gain and  $P_T=10$  mW is the transmit power
- Sensitivity of the receiver  $P_R=3 \times 10^{-12}$  W (-85 dBm)
- Frequency  $f=2.45 \times 10^9$  Hz and thus the wavelength  $\lambda=0.122$  m

the figure for the minimum gain  $G_R$  required for the tracking antenna can be calculated from the Friis formula for free space radio propagation [3].

$$\frac{P_R}{P_T} = G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2$$

Thus  $G_R=3.5$  (5.4 dBi)

This figure was raised by

- 3 dB to allow for circular to linear polarisation loss.  
The UAV uses a circularly polarized patch antenna so that it cannot become cross polarized with the ground station linearly (vertically) polarized antenna. The ground station antenna was chosen to be linearly polarized so that a skeletal wire grid reflector with low wind load could be used.
- 3 dB for losses in the RF cables that run between the feed of the parabolic antenna, and the RF filters and power level detectors that, for noise isolation purposes, are mounted in a metal box on the rear of the reflector antenna.
- A nominal 12 dB to keep the received video at an adequate signal to noise ratio

hence the minimum required tracking antenna gain is about  $G=250$  (24 dBi).

The gain is related to the effective antenna aperture area  $A_e$  [3] by

$$A_e = \frac{\lambda^2}{4\pi} G_R \text{ and } A_e \approx 0.7A$$

(where  $A$  is the physical aperture area of the antenna)

and a gain of 250 means a minimum aperture area for the tracking antenna of  $A=0.43 \text{ m}^2$  is obtained. However the size of the antenna to be used was limited by the requirement that it had to be able to be packed easily into the boot of a car.

A commercial wire grid parabolic reflector antenna was selected for the tracking antenna because

- it satisfies the gain requirement with a gain of 26 dBi.
- it has a rectangular aperture of 870 mm×720 mm which means it fits easily into the boot of a car. (Its focal length is 350 mm.)
- It is rugged. It is made of a plastic coated, welded, steel wire frame.
- It has low wind-load due to its open wire construction (see Figure 5).

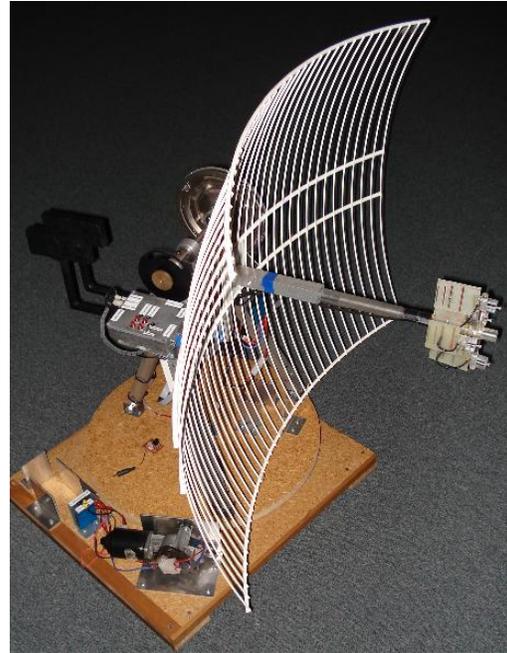


Figure 5. The high gain wire framed parabolic antenna with monopulse feed on its elevation over azimuth mount.

## Tracking Antenna Design

### **Tracking antenna feed and steering signal extraction**

The monopulse tracking antenna requires five separate antenna beams.

- The main “on axis” beam for receiving the video data
- Two beams, from which elevation steering data is obtained, squinted in the elevation plane either side of the main beam
- Two beams, from which azimuth steering data is obtained, squinted in the azimuth plane either side of the main beam.

A squinted beam is created by displacing a feed away from the central axis of the parabolic reflector, but keeping the feed in the focal plane as shown schematically in Figure 6.

The parabolic antenna used for the tracking antenna system came fitted with a Yagi feed located at the parabolic focal point, so to enable the antenna to operate in a monopulse mode, the single Yagi feed was replaced by a cluster of five printed Yagis centred on the focal point of the parabolic reflector, with four of the Yagis displaced from the focal point to create the squinted beams. (Figures 5 and 7). All the printed Yagis are spaced one focal

length from the parabolic reflector.

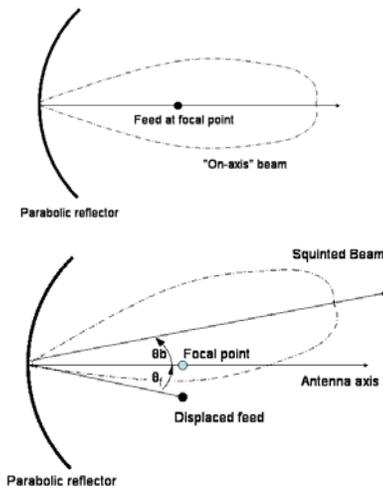


Figure 6. Beam squinting by feed displacement

The off-axis Yagis were each displaced laterally by 50 mm from the main beam axis in the focal plane as this gives a beam squint [4] to each off axis steering beam of 8°. The main beam has a beam width of 8° in the azimuth (H) plane (see Figure 8), and 10° in the elevation (E) plane.

With this beam arrangement there is a sensitivity of about four dB per degree of UAV movement relative to the tracking antenna main axis in each of the channels connected to the squinted beams. At the same time the signal from the main beam receiving the video data stream varies by about one dB for UAV movement of up to two degrees from the axis of the tracking antenna.

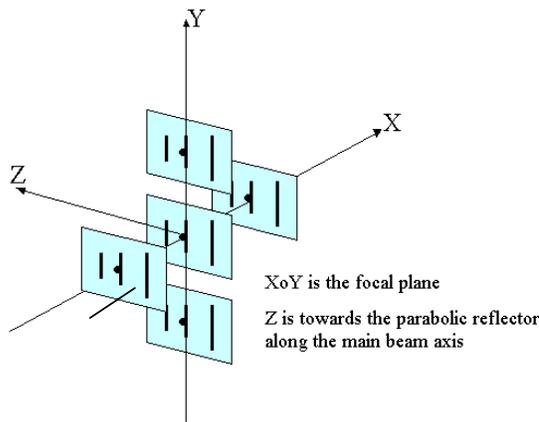


Figure 7. Printed Yagi monopulse feed elements Electrical design

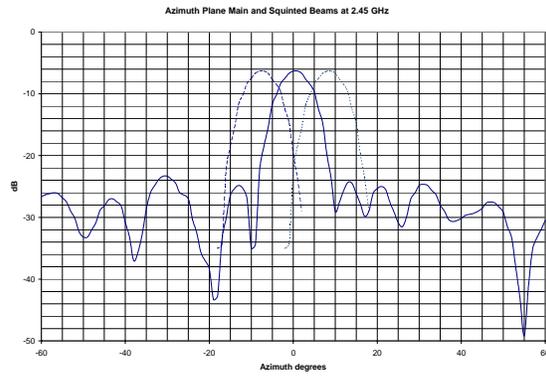


Figure 8

Tracking antenna main beam and squinted azimuth beams

The signals from the four Yagis associated with the squinted beams then become the inputs to the tracking antenna drive system.

### Tracking antenna drive electrical system

The electrical block diagram for the tracking antenna drive system is shown in Figure 9.

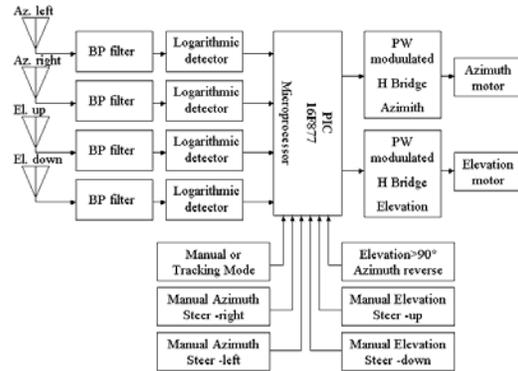


Figure 9. Tracking Antenna- Electrical block diagram

Each of the four tracking antenna steering signals from the monopulse feed is fed through a 2.45 GHz ceramic band-pass filter (100 MHz bandwidth) and into a logarithmic detector. The logarithmic detector (LT5534) outputs a DC signal with a voltage proportional to the RF power (in dB) going into the detector. This DC voltage is then clocked at 10 millisecond intervals into one of the A/D channels on a PIC microprocessor board for signal processing.

The microprocessor analyses the four incoming DC steering signal samples, comparing the voltages of the pair of azimuth steering signals then comparing the voltages of the two elevation steering signals.

The microprocessor generates pulse width modulated control signals for the H bridge motor speed/direction controllers (Marine SC50). If the voltages of the two signals derived from the squinted azimuth antenna beams are equal then the microprocessor outputs a 50 pulse per second train of 1.5 millisecond wide pulses to the speed controller for the azimuth motor. This produces no drive current to the motor. If there is an imbalance in the squinted beam signal voltages then the microprocessor varies the pulse width of the pulse train and the speed controller generates a current to drive the azimuth motor. Wider pulses cause the azimuth motor to turn the tracking antenna anti-clockwise and narrower pulses cause it to be driven clockwise. A comparison of the elevation squinted beam signal generates a similar pulse train to drive the speed controller for the elevation motor.

An optical sensor is used to detect when the antenna elevation angle exceeds  $90^\circ$ . This is used to signal that the azimuth rotation sense needs to be reversed in the software as the two squinted azimuth beams shift from left to right and vice versa when elevation angles exceed  $90^\circ$ . The control program also interacts with "out of range" micro-switches on the elevation control to stop it being driven to far in any direction.

The unit can also be switched to manual control for either or both azimuth and elevation scanning.

### Tracking antenna mechanical system

The parabolic reflector antenna is steered to point at a UAV by a servo driven elevation over azimuth mount system as shown in Figure 10.

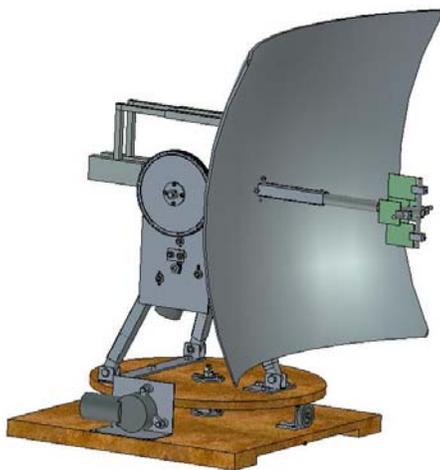
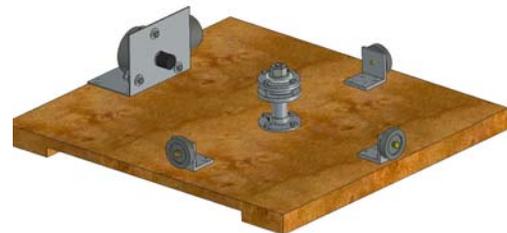


Figure 10 The tracking antenna on the assembled elevation over azimuth rotator mount system.

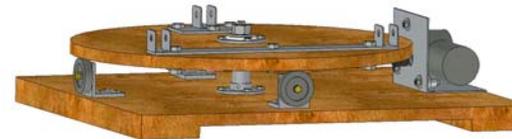
The system is designed to be readily

disassembled and packed it into the boot of a car. It comprises four major parts: the azimuth turntable, the tripod supporting the elevation scanner on the azimuth turntable, the parabolic reflector and Yagi feed cluster, plus a counterweight which is required to balance the antenna in the elevation scanning.

*The base plate and azimuth turntable:* The tracking antenna azimuth scan is achieved by driving a dc motor attached to the base plate of the azimuth turntable (Figures 11a and 11b) in response to the azimuth steering signals. The motor drives the turntable by a friction wheel that presses against the bottom of the turntable. The gearing ratio of the DC motor and the friction wheel to turntable have been selected along with the torque of the motor and the necessary current capacity of the speed controller to give the motor sufficient drive to permit the required azimuth rotation speed. The turntable and whatever is mounted on it rests on three idler wheels attached to the baseplate.



(a)



(b)

Figure 11 Tracking antenna azimuth turntable (a) the baseplate and (b) the complete azimuth turntable

Also mounted on the baseplate is the azimuth speed controller and the battery power supply for the azimuth drive (see Figure 5). Attached to the top of the azimuth turntable are the three mounts for the tripod that supports the elevation scanner and the tracking antenna.

*The tripod for the elevation mount:* A tripod is used to support the elevation scan mechanism on the azimuth turntable (Figure 12). It releases easily from the azimuth turntable by removing the three bolts securing it to the turntable.

On the side of the tripod is a mounting plate for the elevation motor, speed controller and battery.

On the top of the tripod are attached the bearings and axle connected of the elevation scanner. The elevation motor drives the scanner by a toothed belt and a wheel that is attached to the elevation scanner axle. The RF filters, the logarithmic detectors and the microprocessor board are all housed in an enclosed metal box that clips to the top plate of the tripod (Figure 5).



Figure 12 The elevation mounting on the tripod

*The parabolic reflector and feed:* The feed cluster of five printed Yagis readily disconnects from the feed boom of the tracking antenna by undoing one screw and unplugging the Yagis' RF feed lines. The parabolic reflector can then be detached (four screws) from the feed boom and slid off it leaving the boom and the counterweight connected to the elevation axle and elevation drive.

*The antenna counterweight:* The counterweight is removed from the elevation axle and drive by undoing two small bolts.

The four subsystems; turntable, tripod, reflector and counterweight, can then be easily stacked flat and packed into the boot of a car.

### **Testing the tracking Antenna**

A prototype tracking antenna has been used successfully to track UAVs flying under the range and height restrictions discussed previously. This has been very useful on dull days when visually picking up the UAV against grey cloud has been difficult.

The antenna lost lock on the UAV a few times when the UAV was at its extreme range. This was due to the signal strength received on the main beam from the video transmitter falling below the minimum signal level of the logarithmic detectors connected to the squinted antenna beams. The system is to be retro-fitted with RF amplifiers between the band-pass filters and the logarithmic

detectors to overcome this problem.

When the signal strength briefly fell below that required and the UAV/tracking antenna lock was disrupted, the tracking antenna relocked onto the UAV if the signal strength to the squinted beams was re-established whilst the UAV is still between the squinted beam peaks (about  $\pm 7^\circ$  from bore-sight). When the lock was not thus re-established the signaling to the azimuth and elevation drive motors had to be switched to manual to allow the antenna to be driven so as to realign the AUV and the antenna.

A testing program is currently in progress to correlate video signal dropouts with UAV position as determined from the GPS data, and the displacement of the UAV from the antenna bore-sight as determined by an antenna mounted video recording system with a high magnification lens.

### **Conclusions**

A monopulse tracking antenna has been built and tested that will track a UAV transmitting video from a 10 dBm transmitter over a 2.45 GHz radio link to a ground station. The tracking antenna maintains contact with, and reliably tracks the UAV over a range of 50m to about 700m from the ground station at altitudes between 30m and 120m. (see accompanying video). At ranges beyond 700 metres there have been occasions when the tracking failed. This reason for this is known to be weak signals in the logarithmic detectors and so the system is being upgraded to add RF amplifiers immediately after the squinted beam filters to raise the signal levels to that required for successful tracking of the UAVs.

### **Acknowledgements**

We wish to thank Luleå University of Technology and STINT (The Swedish Foundation for International Cooperation in Research and Education) for the financial support that enabled Master of Engineering students Gustafsson and Henriksson to come from Sweden to Monash University in Australia as exchange research students in order to develop this ground station with Monash staff (Jenvey)[5]. We also wish to thank Mr. Tony Brozinsky of Monash ECSE for his great help in the machining and construction of the tracking antenna system and Mr. Ray Cooper and Professor Greg Egan of the Monash UAV group for their help in testing the system and for providing the UAV photographs and survey data.

## **References**

- [1] Egan G.K., Cooper R.J. and Taylor B.  
“*Unmanned Aerial Vehicle Research at Monash University,*” AIAC-11 Eleventh Australian International Aerospace Congress, February 2005.
  
- [2] Radiocommunications Act 1992  
“*Radiocommunications (Low Interference Potential Devices) Class Licence 2000*”, Attorney-General’s Department, Canberra, Australia
  
- [3] Ramo S, Whinnery J R, and Van Duzer T.  
“*Fields and Waves in Communication Electronics*”, p717, Wiley International Ed.
  
- [4] Lo Y. T. “*On the Beam deviation Factor of a Parabolic Reflector*”, IRE Transactions on Antennas and Propagation., pp 347-349, 1960.
  
- [5] Gustafsson J. and Henriksson F., “UAV Tracking Device using a 2.4 GHz Video Transducer”, Luleå University of Technology, MSc Programmes in Engineering, 2005.