Verification of Microwave Air-Bridging for Sky-Net

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***Abstract*—The Sky Net project proposes a mobile base transceiver station (BTS) for mobile communication service from airborne. In the preliminary study, a Microwave Air-Bridging (MAB) system is established on an Ultra-Light Aircraft (ULA) to offer relay mobile communication. In order to maintain sufficient Quality of Service (QoS) data-link, microwave system needs to establish critical Line-of-Sight (LoS) antenna alignment between airborne to ground to assure polarization matching. The proposed GPS-to-GPS tracking algorithm uses GPS and barometric data by considering earth curvature to estimate azimuth and elevation angles for the ground dual-axis tracking mechanism. With high accuracy demand in tracking, all sensor data are pre-calibrated by determining their covariance. An additional Data Variance Filter (DVF) is applied to eliminate the sudden data error and white noise from sensors to avoid mechanism vibration and maintain accurate tracking response to match with ULA flight path. The goal tries to reduce the Bit Error Rate (BER) of MAB to accomplish accurate antenna alignment for microwave transmission in Sky-Net application.**

Keywords-Antenna Alignment; Microwave Air Bridging; Dynamic Filter; Dual Axis Motor Control.

I. INTRODUCTION

Microwave Air Bridging (MAB) has been widely used in telecommunication relaying recently. Without hardware limitations, MAB can easily be implemented to establish communication links from remote areas. Antenna alignment in MAB is the fundamental issue to solve before minimum Quality-of-Service (QoS) can be made for communication link. Most remote Base Transceiver Stations (BTSs) apply MAB application to connect wide spread mobile communication service network.

In disaster situation, some mobile BTSs might be flooded or destroyed to disable from communication services. A draft idea of Sky Net was proposed to create a BTS carrying on a high altitude Unmanned Aerial Vehicle (UAV) for mobile communication services. After some preliminary surveys, the first proposal using repeater is abandoned. Since both donor and service antennas use the same frequency, it is not able to eliminate antenna isolation problem on a UAV. A second proposal arose to use microwave link from airborne to ground.

The High Altitude Platform (HAP) or Remote Airborne Platform (RAP) for communication relay have been introduced and widely studied in the past few years. The concept of relaying the communication signal, basically, has two kinds of system architectures, such as Direct Relay (P2P) and Multi-Node Relay. In the Line-of-Sight (LOS) field, Unmanned Aerial Vehicle (UAV) can carry airborne transceiver or repeater to establish the P2P communication link between UAV and ground base [1] [2]. However, in general condition, the area needs telecommunication service, usually, has obstacle between the region and ground base. Using multi-UAV flying around the specific area to establish the communication link network is one of the ways to overcome this problem. Also, even the signal transmission range and the UAV collision problem can be well avoided [3] [4], the multi-UAV relay system still has some problem to overcome such as signal transmission latency after the multi-node network and the uncertainty of wireless link quality due to each UAV's actual flight path and real-time altitude.

The airborne BTS concept was introduced and accomplished by Wypych et al. [5]; however, the service was limited by MS-to-MS communication in service area, which means the user cannot get contact with people far away still. In this paper, the goal is establishing a microwave link system between airborne BTS and ground BTS, which connect to the backbone network of the telecom company.

With proper antenna alignment tracking, the exchange of telecommunication signal between terminals should meet the minimal acceptable BER in mobile BTS. In this phase of study, the airborne terminal is mounted on a ULA carrying the microwave bridge working at 5.8 GHz frequency band in Multiple Input and Multiple Output (MIMO) system with adaptive modulation. The proposed MAB system configuration is shown in Figure 1, as the preliminary idea.

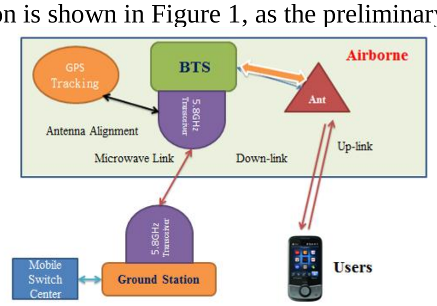

Figure 1. Microwave Air-Bridging system configuration for Sky-Net.

In general, in wireless applications, like UAV surveillance with real-time image or video [6], the transceiver, usually, works simply in one way transmission.

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However, the microwave bridge needs both terminals to maintain a good signal strength and steady data-link quality in order to achieve high bandwidth data transmission. Once the Received Signal Strength Indicator (RSSI) drops below the threshold of transceiver specification, the link is disconnected. Antenna tracking control may be deterministic if the main lobe on both side terminal antennas is aligned or not. In general, -3dB is set from the pick of antenna pattern to define the Vertical Beamwidth Angle (VBA) and Horizontal Beamwidth Angle (HBA). This shows critical constraint of the antenna's directional characteristic. Usually, the threshold is carefully monitored such that the antenna can work normally.

Antenna misalignment will cause high bit error rate and make microwave bridge crash. The keys to maintain well antenna alignment are twofold: antenna polarization keeps perfect matching and both VBA and HBA of two side terminal antennas maintain overlapping. The theoretical foundation of antenna characteristic is used to describe further automatic tracking system design for antennas. To accomplish the antenna alignment, the microcontroller tracking mechanism and control algorithm are designed using the Cortex-M3 32-bit microcontroller and implemented on a dual axis mechanism for precision control.

In this paper, the concept of the antenna tracking system is introduced in Section II, part A. The GPS-to-GPS tracking method and the whole hardware architecture are well describe and also the data filter that is designed according to data variance is explained in part B. Section III shows how the stepper motor control strategy works to eliminate the platform vibration which could lead to antenna misalignment. Dynamic tests of tracking algorithm for antenna alignment are presented for microwave air bridging verification by open field flight experiments in Section IV.

II. TRACKING ALGORITHM

A. GPS-to-GPS Tracking Method

The existing microwave automatic antenna tracking device generally uses signal strength gradient to aiming at the target. The device will rotate azimuth angle to get the Received Signal Level (RSL) as high as possible and make signal gradient close to zero when it is aiming at the target. The elevation angle tracking works correspondingly. When the airborne terminal is relatively far away from the ground terminal, the signal will be diluted because of space propagation and signal multi-path effect to RSL simultaneously. The tracking performance worsens to result in lost alignment between the MAB terminals. Based on the Global Positioning System (GPS), a simple but effective method termed as GPS-to-GPS (G2G) tracking algorithm is proposed. The proposed G2G method receives GPS position information from two sites, i.e., airborne and ground, and transforms them into a specific coordinate system for alignment. For GPS information, both airborne and ground terminals will receive their latitude, longitude and altitude in Mean Sea Level (MSL), continually. The algorithm in the control core will compare their differences on each side and calculate the appropriate geometric azimuth and elevation angels between the airborne terminal and the ground terminal.

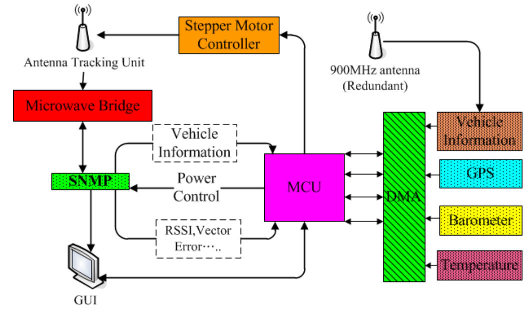


Figure 2. Backbone antenna tracking control system.

The backbone of antenna tracking control is shown in Figure 2. A dual-core mother board is fabricated to control the 2-axis rotation platform. The vehicle information of the airborne terminal is transmitted via microwave data link and Simple Network Management Protocol (SNMP) into MCU. A 900MHz wireless module is used as redundant link to ensure the integrity and reliability of the tracking control. All the data and command are transmitted by Direct Memory Access (DMA) to reduce CPU burden.

Coordinate transform plays a key part in the tracking control. The first step calculates and transforms the Longitude-Latitude-Altitude (LLA) information into an appropriate coordinate system to offer user with distance of East-to-West and North-to-South direction. The coordinate transform of LLA in WGS84 [7] into TM2 in TWD97 [8] can be rewritten by latitude and longitude in degree into East-North direction distance in meters. For the azimuth angle, as long as North and East direction can be obtained, the arctangent calculation can be applied to get a correct value. But for elevation angle, the situation is quite different. On the microwave transmission, the most concern on the VBA of both sides lies on their well overlap or not. Therefore, the elevation angle accuracy of mechanism unit becomes much important and sensitive than the azimuth angle. Figure 3 shows the difference between the calculations of two methods. The first method simply assumes the Cartesian coordinate system to ground terminal as the origin. The second method considers the Earth curvature error into calculation.

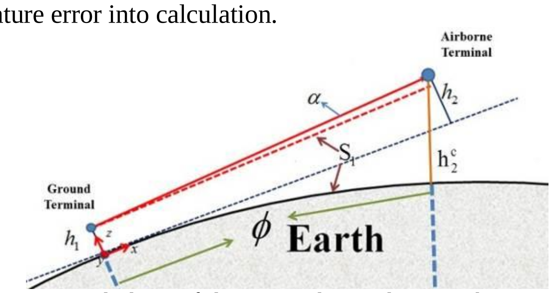


Figure 3. Calculation of elevation angle considering Earth curvature.

In Figure 3, if the airborne terminal and ground terminal are close enough, then the calculation can be simplified into a 3-axis Cartesian coordinate plane. As the coordinate being transformed into TM2 in TWD97 system, the distance S_1 between ground and airborne terminal can be obtained.

Meanwhile, using MSL for altitudes on both terminals as h_1 and h_2, the elevation angle α from the ground terminal can be expressed as:

$$\alpha = \arctan(\frac{h_2 - h_1}{S_1}) \tag{1}$$

However, as S_1 is far from both terminals, the curvature of earth will evidently affect the accuracy of elevation angle α. Figure 3 also shows how the curvature makes the error bigger as S_1 increasing. In TWD97 datum, the Earth model is an ellipsoid and the Earth radius scale is relatively huge comparing to ULA flight path. Within a small region, the Earth is reasonably assumed as a sphere not an ellipsoid. Therefore in figure 3, between the ground and the airborne terminals, the Earth radius is R and the incline angle between them toward Earth center is ϕ. The elevation angle α of the ground terminal can be recalculated as:

$$d_1 = R^2 + (h_2^c + R)^2 - 2R(h_2^c + R)\phi \tag{2}$$

$$d_2 = (h_1 + R)^2 + (h_2^c + R)^2 - 2(h_1 + R)(h_2^c + R)\cos\phi \tag{3}$$

$$\alpha = \cos^{-1}(\frac{h_1^2 + d_1^2 - d_2^2}{2 - h_1 d_1}) \tag{4}$$

B. *Data Variance Filter*

All the data from sensors should be filtered to eliminate noise or interference to cause unpredictable data error. Generally, software for Low-Pass Filter (LPF) or Complementary Filter [9, 10, 11, 12] can easily be adopted to compensate the unreasonable error or eliminate the sensor white noise. However, the time constant value or weight of the applied filter considerably affects the system response. In this paper, the Data Variance Filter (DVF) is adopted to add the variance of each sensor into the filter to generate the variable weight for LPF and avoid the internal data disturbance effect on the control output. The covariance values of GPS and barometric altitudes are also included to determine the time constant in complementary filter to get better altitude resolution.

DVF uses a simple equation to get the processed data at time y_t with data from t-1 and the data x acquired at time t. The weight is calculated by function ***Varf* (*α, β*)** and variance gain *kv*.

$$y_t = Varf(\alpha,\beta) y_{t-1} + kvx \tag{5}$$

The pre-calibrated step of DVF is getting the individual variance σ of sensors. Assuming that data have a Gaussian distribution, the sensor is implemented steady. The three variance derivations, α, β, and γ are generated as below:

$$\beta = 2\int_0^{\alpha} \frac{1}{\sqrt{2\pi}} \exp(-\frac{\tau^2}{2}) d\tau \tag{6}$$

$$\gamma = \left| \frac{x - y_{t-1}}{y_{t-1}} \right| \tag{7}$$

$$\alpha = \left| \frac{x - y_{t-1}}{\sigma} \right| \tag{8}$$

Equations (6) and (7) are determining data probability of each time data update. For Gaussian distribution, 99.73% of data will fall into the region of 3σ. Since the data sampling rate is 50 Hz in the proposed system, it is assumed that barometric and GPS data between two sampling times will not changing drastically. In order to reduce the calculation load on microcontroller, the 3σ data difference is set as the threshold to generate appropriate ***Varf(α, β)*** value from the following equation.

$$Varf(\alpha,\beta) = \beta - u(\alpha - 3)\{\beta - kv\} \tag{9}$$

The variance deviation will be calculated in each computation loop, and the variance gain (*kv*) will be automatically changed in each iteration.

$$kv = \gamma - u(\alpha - 1)\{\gamma - 1\} \tag{10}$$

The important part of using DVF falls into how to get the correct variance for each sensor. As the sampling frequency is relatively higher than system characteristic, the static data can be used to get the variance to fit for the real condition. Figure 4 shows how the variance affects the result of DVF.

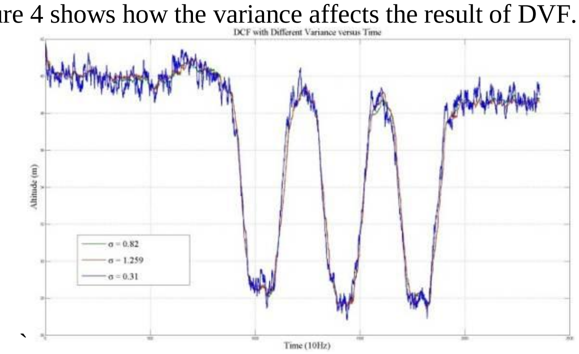


Figure 4. DVF for altimeter with different variance versus time.

For the blue line data, the variance is relatively small and therefore the DVF cannot eliminate the small noise and easily cause data overshoot. For bigger variance, such as red line data, the response will be too slow to reach the actual condition.

III. STEPPER MOTOR TRACKING CONTROL

The ground tracking system is a two-axis rotating mechanism, where the 23 dBi directional antenna is mounted with good alignment to mechanism axis, as shown in Figure 5. Limited by the GPS data update rate, the tracking algorithm has to be capable for estimating the position at the airborne terminal using the moving rate to achieve adjustable control frequency. The microcontroller outputs a digital signal, which is rapid enough to drive rotors to rotate to the desired angle displacement.

Figure 5. Two-axis Stepper Motor Rotation Platform.

However, as the rotor might be in rest state, the starting inertia of each axis will make the mechanism in sudden shock and cause damage to the mechanism. Besides, as the gear backlash increases, the tracking effect will make observable error in the perfect alignment. G. Hilton et al. [13] did the comparison about the terminal's Receiving Sgnal Strength (RSS) change due to different tilt and rotation angle of antenna. The result indicate that as the terminal's antenna polirization is match to transmitter side, terminal can get the maximum RSS. Therefore, the control strategy of two-axis platform become the main issue to avoid the antenna misaligment, which cause high BER in microwave link [14,15]. In order to control the platform smoothly, an appropriate signal output frequency has to be carefully designed. In this paper, a control loop to allow adjustable signal output interval and the unit rotation step for rotors are designed into the tracking control system for MAB.

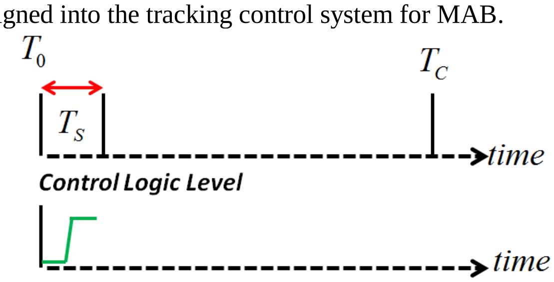


Figure 6. Control sequence.

Figure 6 represents the control sequence, where T_c is the control loop interval and T_s is the control signal output period. For each time after calculation, 2-axis mechanism has the target rotation displacement θ_d, so the adjusted unit step θ_c can be represented as:

$$\theta_c = (\frac{\theta_d}{T_C})T_S \qquad (11)$$

With appropriate calculation for each time control core to drive the platform, the adjustable unit step can make each control loop well engaged with less mechanical shaking by decreasing the times of acceleration and deceleration.

However, the adjustable unit step control can smooth the mechanism rotation only. When the airborne terminal has the fast movement in azimuth angle, the rate controller inside control core should be added to avoid the large phase delay of tracking result. The control function can be accomplished by changing the control interval T_c. It should be the function of moving rate, distance and the heading of the airborne terminal. The proposed concept of adaptive control interval is based on that the airborne terminal is moving on ULA or UAV. Its heading information can be used to determine the direction, like North or East, to change faster in the next instants. For example, in azimuth angle tracking, if the heading in T_0 is ψ_1, then, the velocity of the airborne terminal is V_1, the mechanism tracking angle is θ_T. By trigonometric function, the velocity vector of the radial and tangent direction of the airborne terminal with respect to the ground terminal can be estimated as:

$$V_t = V_1 \cos(90 - \theta_T + \psi_1) \qquad (12)$$

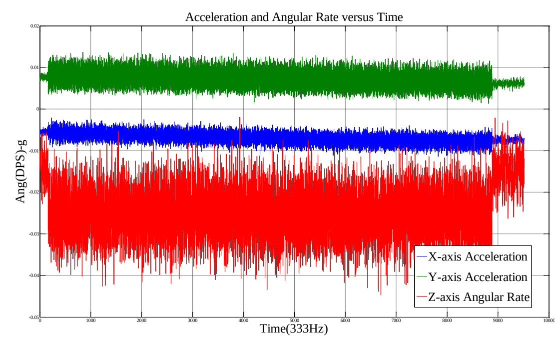
$$V_r = V_1 \sin(90 - \theta_T + \psi_1) \qquad (13)$$

Therefore, from (12) and (13), the tracking unit rotation speed in azimuth angle has positive relation with the tangent speed of the airborne terminal. Meanwhile, as its speed increases, the control interval should be decrease to avoid tracking delay. The relation of T_c and tuning gain K_a can be represented as below:

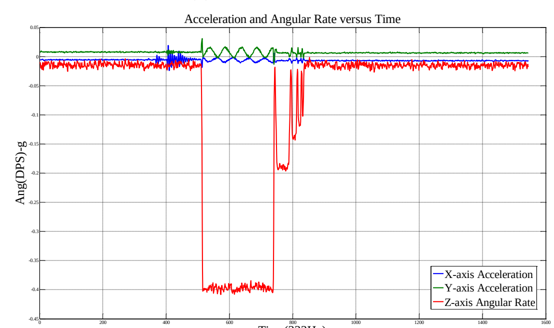
$$T_C(\psi, V, \theta_T) = T_{C0} - \left|\frac{K_a}{V_t}\right| \qquad (14)$$

T_{c0} is the default control interval and the optimized motor controller will be the combination of adjustable unit step and rate controller.

In the motor controller tests, the angle displacements are setting at 50.72°, 15.84°, and 0.86°, separately. The figures show the difference of using motor controller or not. The MCU sends 1000Hz control signal to drive the motor directly at unit step equal to 0.02°. Without motor controller, the vibration is large as Figure 7(a). While with motor controller, the vibration appears much reduced in Figure 7(b). In Figure 7(b), when the controller changes the motor's speed, the response drops abruptly, and returns to convergence shortly. Their scales refer to per unit of response. Likewise, Figuress 8 and 9 shows the control results by different angle displacements with changing speed.

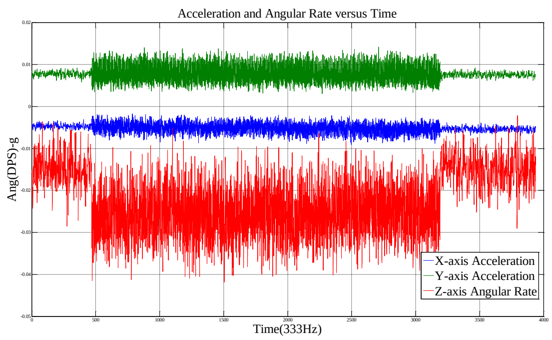


(a) Without controller

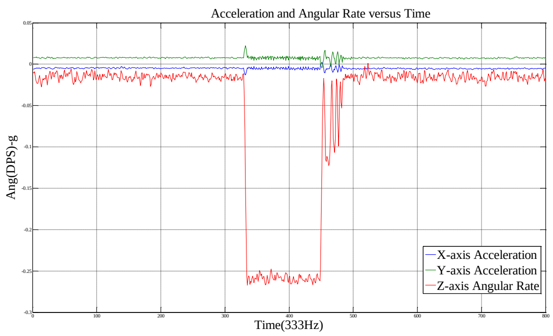


(b) With controller

Figure 7. 50.72° displacement without and with motor controller.

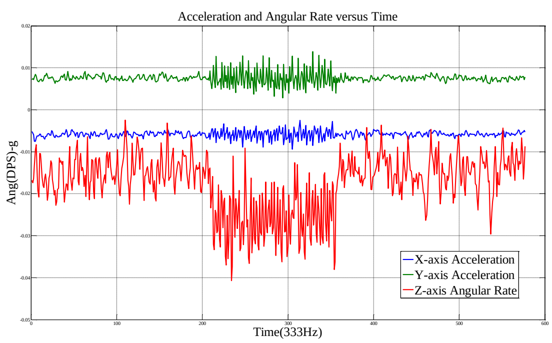


(a) Without controller

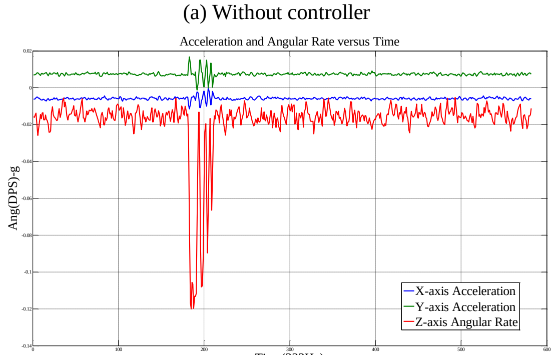


(b) With controller

Figure 8. 15.84° displacement without and with motor controller.



(a) Without controller



(b) With controller

Figure 9. 0.86° displacement without and with motor controller.

Comparing these three results, as the tracking system without motor controller, the mechanism shaking occurs continuously while the motor is rotating. The time constant of the whole rotation is longer than that with motor controller, especially when the rotation displacement is large.

IV. FLIGHT TEST VERIFICATION

The verification microwave module is installed on unmanned ULA JJ2710, on its wing top, as shown in Figure 10. Two 12 dBi omni-directional antennas were installed perpendicularly to fit the MIMO system. The ground terminal tracking unit was implemented as shown in Figure 11, both azimuth and elevation axis are well balanced to reduce the redundant loading of stepper motor.

Figure 10. Airborne terminal antenna on unmanned ULA JJ2710 for test.

Figure 11. Ground terminal tracking unit with microwave module.

The ground terminal tracking system is calibrated with laser to assure that the rotation original point has no offset, as shown in Figure 12.

Figure 12. Stepper motor platform calibration with laser.

Flight path was designed to ensure both side of microwave module antenna pattern can be overlapped. Therefore, the ground terminal is located at the mountain side at altitude 468 m (MSL) in southern Taiwan. In this

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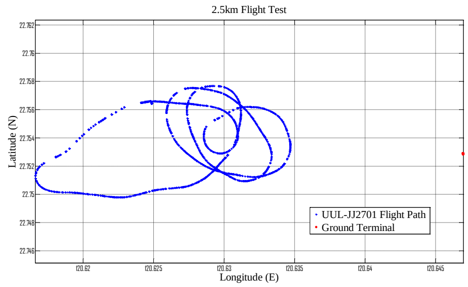
resting phase, the ULA is flying to approximate the same altitude to track the ground terminal. To verify that the tracking system is capable to maintain constant microwave link, the fight paths and distances are predetermined to check the microwave link. The test distances are 2.5 km and 6 km, respectively, as shown with flight path in Figure 13.



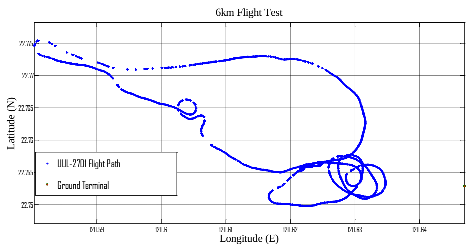
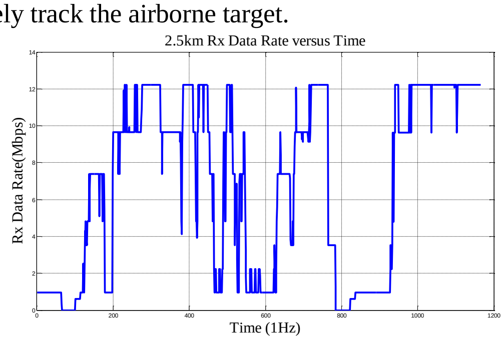
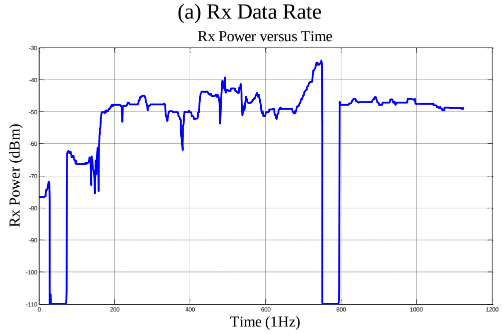


Figure 13. Flight test paths from 2.5 km and 6 km.

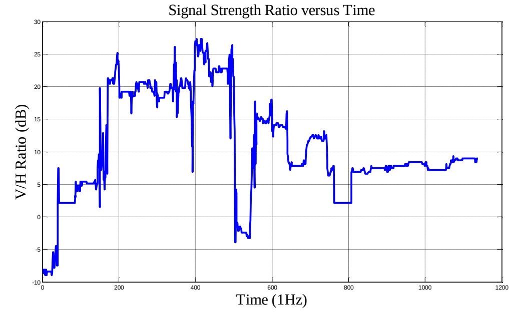
The preliminary flight test results are shown in Figures 14 to 17, for tracking mechanism without or with optimized motor controller. The tracking steps are threefold by take-off, searching, and link up. The tracking mechanism is capable for auto-interval tuning and unit step changing function to precisely track the airborne target.



(a) Rx Data Rate

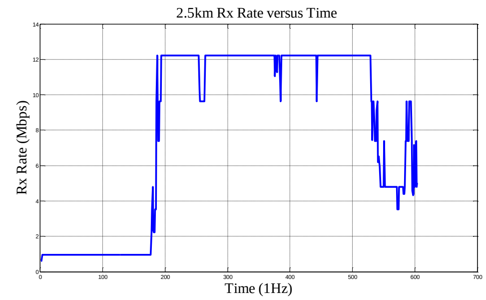


(b) Rx Power

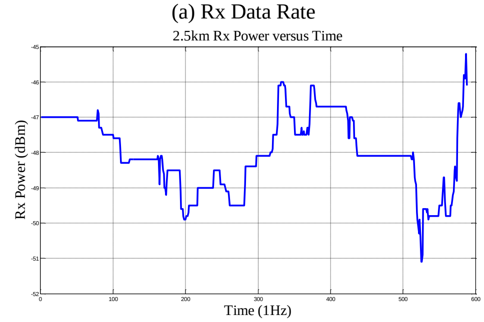


(c) Signal Strength Ratio

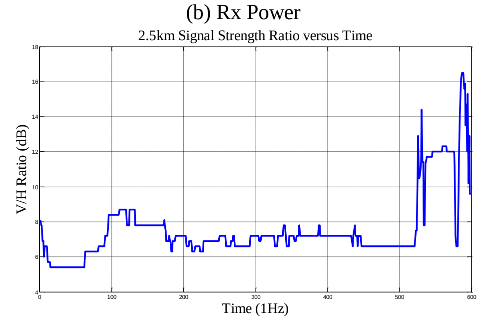
Figure 14. Tracking results to 2.5 km without optimized motor controller



(a) Rx Data Rate

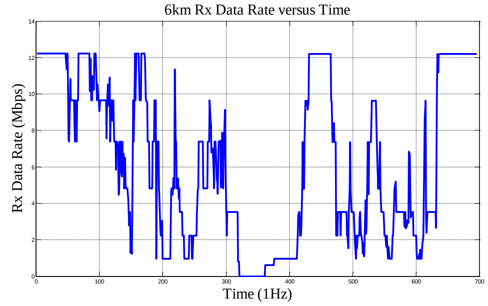


(b) Rx Power

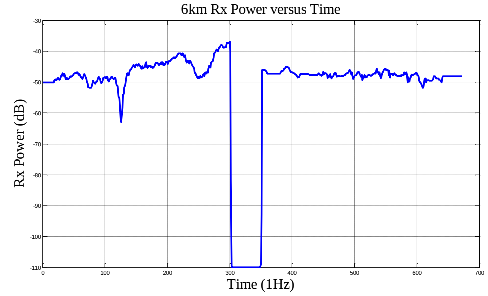


(c) Signal Strength Ratio

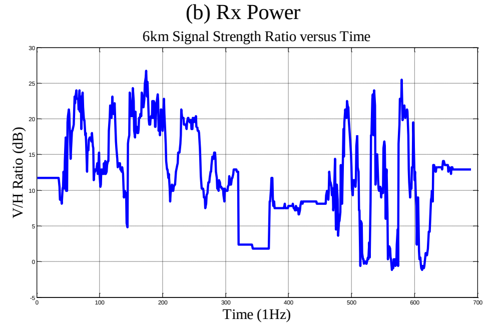
Figure 15. Tracking results to 2.5 km with optimized motor controller



(a) Rx Data Rate



(b) Rx Power

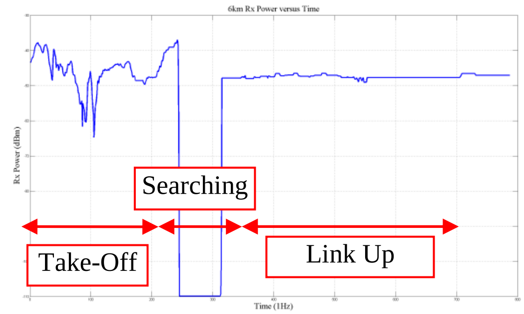


(c) Signal Strength Ratio

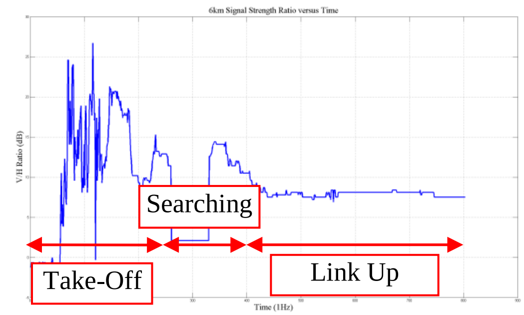
Figure 16. Tracking results to 6 km without optimized motor controller

Figure 17 marks the connection steps from ULA take-off to cruise. During take-off to searching, communication link cannot be made until the UAV turns into stable cruise maneuvering.

(a) Rx Data Rate



(b) Rx Power



(c) Signal Strength Ratio

Figure 17. Tracking results to 6 km with optimized motor controller.

It can be noticed that for longer distance between the airborne terminal and the ground terminal, the overall tracking performance appears better than the closer tests. As the controller core has optimized control algorithm, not only the data rate becomes relatively steady but also the signal strength ratio gets much improved. It is evident that the tracking result is more accurate. The signal strength ratios from both terminals present that the vertical and horizontal polarization antennas are aiming correctly to each other.

V. CONCLUSION

In this paper, a precision antenna alignment tracking system was designed and implemented to Sky Net Project. By considering Earth curvature, a corrective target tracking algorithm is formulated for the vertical and horizontal polarization antennas. Flight tests are carried with a prescheduled flight path to establish microwave link from the airborne terminal to the ground terminal. With optimized dual-axis motor controller, the tracking antenna alignment is proven with feasible results. The alignment problem for microwave transmission can be overcome by the proposed two-axis tracking unit with DVF to filter out the sensor's white noise and unpredicted data error. The test result shows that the tracking unit and antenna implementation can be used to provide the microwave application. It is found of high possibility to establish microwave air-bridging from airborne for mobile communication relaying.

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