The flying classroom – a cost effective integrated approach to learning and teaching flight dynamics

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In the United Kingdom, the Royal Aeronautical Society recommends the inclusion of practical flight exercises for accredited undergraduate aerospace engineering programmes to enhance learning and student experience. The majority of academic institutions teaching aerospace in the UK separate the theory and practice of flight dynamics with students attending a series of lectures supplemented by an intensive one day flight exercise. Performance and/or Handling Qualities flight tests are performed in a dedicated aircraft fitted with specialist equipment for the recording and presentation of flight data. This paper describes an innovative approach to better integrate theory and practice and the use of portable Commercial-off-The-Shelf (COTS) technologies to enable a range of standard, unmodified aircraft to be used. The integration of theory and practice has enriched learning and teaching, improved coursework grades and the student experience. The use COTS and unmodified aircraft has reduced costs and enabled increased student participation.

Keywords: flight dynamics, learning & teaching, flight data recorder

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Nomenclature

AHRS	Attitude/Heading Referencing System
ALL	Activity Led Learning
AoA	Angle of Attack
AOC	Airline Operators Certificate
BEng.	Bachelor of Engineering
COTS	Commercial-off-the-Shelf
CRM	Crew Resource Management
CVR	Cockpit Voice Recorder
EASA	European Aviation Safety Agency
EFIS	Electronic Flight Information System
ETPS	Empire Test Pilot School
FDR	Flight Data Recorder
FTE	Flight Test Engineer
FTI	Flight Test Instrumentation
FTO	Flight Test Observer
GPSS	Global Positioning Satellite System
iFDR	Independent Flight Data Recorder
IRS	Inertial Reference System
LAT	Latitude (degrees:minutes:seconds)
L_p	Rolling moment due to roll rate
L_v	Rolling moment due to sideslip velocity
LON	Longitude (degrees:minutes:seconds)
LPO	Long Period Oscillation (Phugoid)
LSS	Longitudinal Static Stability
MEng.	Master of Engineering
MP3	Audio coding format for digital audio
PFR	Post Flight Report
QAA	Quality Assurance Agency
RAeS	Royal Aeronautical Society
SPO	Short Period Oscillation
STC	Supplemental Type Certificate
TP	Test Pilot
ζ	damping ratio

1 Introduction

Aeronautical and Aerospace Engineering programmes at Bachelor (BEng.) and Master's (MEng.) levels in the United Kingdom are accredited by the Royal Aeronautical Society. Accreditation is a positive indicator that such programmes are likely to comply with QAA standards. These programmes are expected to have a practical flight test course, supplemented (but not replaced) by flight simulation (RAeS 2013). The RAeS recognise that practical flight tests and associated flight briefings provide experience that is not attainable solely by flight simulation. All students on accredited programmes are therefore encouraged to participate in a practical flight test although this may be shortened by supplementary use of flight simulation. The RAeS also encourage innovative alternative approaches to achieve the desired learning outcomes.

The majority of UK aeronautical universities enrol students on a short course in flight testing; this is usually one day, intensive flight experience. The course consists of pre-flight brief, flight exercises and post-flight brief with a pilot and flight test instructor (Lewis, Potts and Gautrey 2016). The course is appended to university undergraduate modules in flight mechanics/flight dynamics or aircraft design and although the experience is generally well received by students, it lacks integration with courses/modules and is relatively costly as a dedicated, instrumented aircraft is required with flight data presented using LABVIEW.

With respect to alternative approaches, the University of Strathclyde for reasons of cost, has in the past used two seat gliders to address the practical flight test requirements (Scanlon and Stickland 2004). This approach using gliders is highly dependent on favourable meteorological conditions and tow launches. The gliders were installed with limited instrumentation and test methods therefore were predominantly manual. Gliders were also utilised extensively within the aircraft design course. The flight test course was run as a 3-4 day residential course in association with a gliding. Tests conducted in this programme were limited to basic performance, stability tests and stall characteristics with no assessment of handling qualities.

The University of Tennessee Space Institute (UTSI) has implemented low cost COTS for inflight data acquisition, post-flight analysis & pre-flight predictions to support their flight test engineering Masters' Programme (Muratore, Moonan and Young 2010). The system uses LABVIEW based data acquisition and a kneeboard/tablet PC computer user interface. One hundred and fifty parameters are measured at 20 Hz and the data acquisition system is interfaced to custom-installed sensors on a single, dedicated aircraft (Piper PA-31 Navajo). The system links to aircraft 28V power bus and each tablet PC requires a wired Ethernet connection. This custom-developed system requires specialist support and is not portable between aircraft. UTSI use X-Plane to practice flight test procedures pre-flight and to predict flight test data. The introduction of the Apple iPad in 2010 has seen rapid adoption by young people, especially undergraduate and postgraduate students. In the learning environment iPads have been found to enhance learning but not necessarily improve learning outcomes (Nguyen, Barton and Nguyen 2015). It has not been clear how to integrate these devices into an academic teaching and learning programme, a useful application is required. This type of new technology may address the limitations of the UTSI solution and could be applicable to the flying classroom environment when used in conjunction with portable, wireless flight data sensors.

Liverpool University in the UK, use a FLIGHTLAB based, engineering flight simulator to support flight dynamics teaching and problem-based learning of handling qualities (Padfield 2006). Students work in small teams on ‘whole aircraft’ handling qualities problems focusing on aircraft/system deficiencies. Each team is given one of 5 mission task environments to solve, using one aircraft type with different apparent problems. They are required to identify required upgrades, implement the upgrades then re-test using Matlab for flight data analysis. The aircraft models are accepted as representative of the real aircraft and students are not required to validate the models against flight test data. Specialist, commercial flight simulation software or full-flight/engineering flight simulators are not readily available to most academic institutions.

California Polytechnic University in the USA use a desktop flight simulation package X-Plane as a, low cost alternative. X-Plane uses blade element theory to model aerodynamic characteristics of an aircraft based upon physical geometry and mass properties and does not require pre-defined stability & control derivatives to determine aircraft handling characteristics (Babka 2011). The benefits of using X-Plane are that it is also scalable from desktop to full flight simulator, using UDP protocol for interface development.

TU Delft has been using flight testing to enhance learning since the early 1950s (Slingerland & Melkert 2005). Flight exercises are used to support learning about lift, drag and performance, steep turns and parabolic flight using a Cessna Citation II. Report writing skills are also developed. The aircraft is fitted with dedicated equipment and limited to 6 students in the cabin area. Although the study states the positive benefits of undertaking such practical flying, there is a lack of quantitative and qualitative feedback from participants.

The Politecnico di Milano (Trainelli & Rolando et al 2014) has been using light aircraft for education and flight testing since 1998. Purchasing their own Tecnam P92 Echo aircraft, they have developed an in-house flight test instrumentation system to record flight test data. The FTI uses nine data collection nodes to collect air data, inertial measurements, GPS data, flight control force and position, engine data and support data logging and presentation. The use of nodes for control force and position measurement as well as engine measurement offers opportunities to evaluate a wide range of flight tests related to handling qualities and performance. During the early 2000s this proved a cost effective option when compared to larger dedicated aircraft. Pass rates are 95% but quantitative assessment of learning is not stated. With rapid advancements in COTS technologies and associated cost reduction, this type of solution is no longer as cost effective. The use of small light aircraft means low student numbers and testing is limited to one aircraft type.

The Politecnica de Madrid (Orio, Blanco & Aragon 2013) delivers an MSc level programme in flight testing and has proposed a low cost flight test instrumentation platform in support of education. The flight test instrumentation is to be used in combination with installed Garmin 1000 Electronic Flight Instrumentation on a Cessna 172 light aircraft. The approach requires the customised installation of hardware at significant cost to sense and record up to 21 data parameters at rates varying from 1 to 10 Hz in support of a comprehensive range of performance and handling qualities flight testing.

The Technical University of Munich (Höhndorf 2016) provides a practical flight test experience in a single engine piston light aircraft to Masters' level students to consolidate learning of flight systems dynamics. Students prepare their own test cards in pairs and flight measurements are taken directly from aircraft instruments, a stopwatch and an inertial measurement unit. Seating is usually restricted to a pilot in command plus up to 3 passengers when light aircraft are used for such purposes. Flight instruments are not always visible to all participants and parallax errors may occur when reading them. The test results are consolidated and distributed in a common database and each group produces a report and presents to the whole cohort for critique and discussion.

Figure 1, Percival P40 Prentice T1 (Test Aircraft)

Figure 2, De Havilland DH104 Dove 6 (Test Aircraft)

2 Integrating theory & practice

To address the limitations of previous approaches, a practical flight test experience has been developed and this has been integrated with a flight dynamics lecture programme and supporting tutorials. The approach has been developed using a revised version of Bloom's learning taxonomy (Anderson and Krathwohl 2001) and recognises that there are several developmental stages to the learning experience from recalling facts (e.g. critical speeds) to creating a flight test report to an industry standard (Figure 3). Following this principle, the learning outcomes of the flight dynamics & practical flight test module are:-

- To <u>understand & apply</u> for a given aeroplane:-
  - flight test methods
  - performance & handling qualities assessment
- To <u>analyse and evaluate</u>
  - performance & handling qualities data
  - assess against certification criteria
- To <u>create</u> a flight test plan, test cards & post flight report using industry standards

At each stage of learning, feedback is sought to confirm the level of progression in the module. Formative assessment is provided for class tutorials and summative assessment is provided by coursework and the end of the module. Students are required to complete sections of a Post Flight Report to industry standards using the '7-part paragraph' method, in preparation for the future workplace (ETPS 1996). Prior to the practical flight exercises, students are exposed to modelling & flight simulation in a class and laboratory environment to prepare them for the real-world flying environment. A 'flying classroom' has been created using portable, low cost 'COTS' technologies. Standard, unmodified aircraft can be operated from a local aerodrome (subject to aircraft operating limitations) and this offers a highly cost effective practical flight test experience.

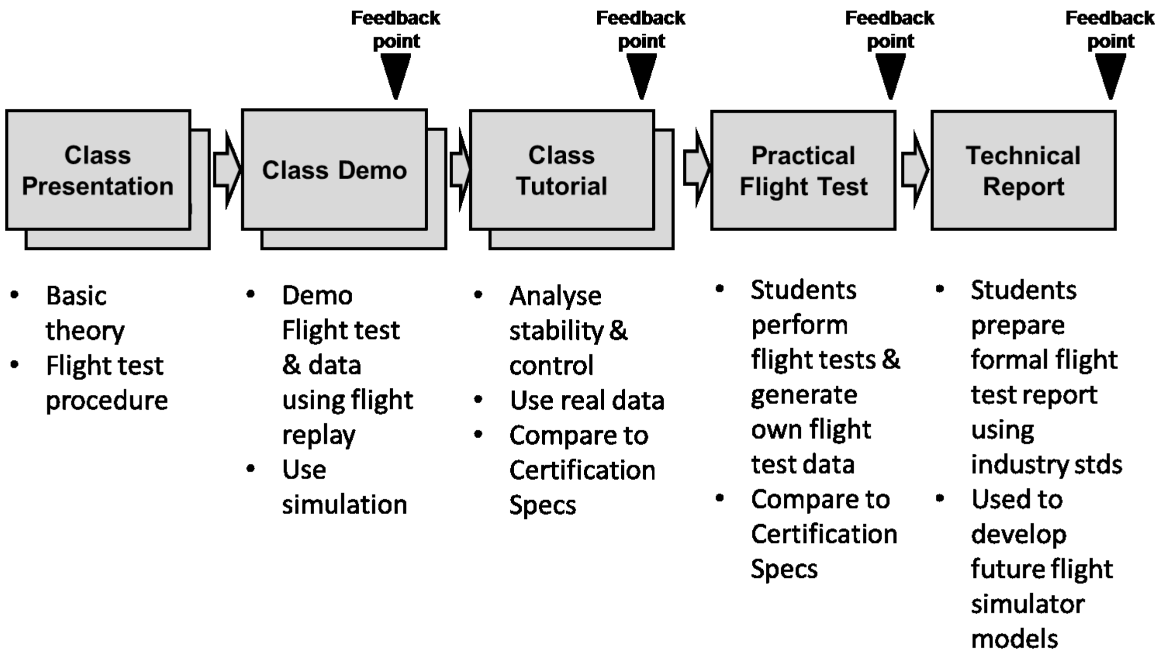

Figure 3, Learning & Teaching Approach

Basic theory of flight dynamics is delivered in class using presentations supported by the use of 3D and 2D simulations of the same flight tests conducted by the previous cohort. In addition, actual flight test video using multiple cameras is also used to further illustrate longitudinal static & dynamic modes and lateral/directional dynamic modes. Classical flight test methods are described and explained in class using physical aircraft models.

Following the class presentations and demonstrations, tutorial sessions are conducted to enable students to analyse the performance & handling qualities of a given aircraft using real flight data gathered from previous flight tests. Students work individually or in groups, depending on the level of learning, and they are required to reduce the data, analyse the results and compare to relevant certification specification criteria for the given aircraft and stability modes.

For a given aircraft project students and student groups may be required to:-

- Prepare flight test plan, test cards;
- Observe flight tests & generate own flight test data;
- Extract data;
- Analyse results;
- Compare to certification specifications;
- Write a partial/complete Post Flight Report (PFR) using industry standards.

Flight testing requires a formal, detailed flight test plan, test objectives and risk assessment which are followed during the exercises (‘plan to test’ and ‘test to plan’). The test plan is used to prepare individual test cards and these define the test to be completed (e.g. climb performance), test conditions required (e.g. starting height, desired airspeed etc.), test method and include customised tables for the collection of manual data. During the flight exercises, students observe and record manual data as required by each test. Selected automated data (e.g. groundspeed) is collected using portable flight data recorder systems running continuously in the background.

On completion of the flight exercises (time permitting on the day) these data are plotted and analysed using spreadsheets and flight test data plotting tools (Datplot 2016). For selected tests, students compare these to current design certification requirements for the type of aircraft being evaluated (EASA 2016). Within one to two weeks of the exercise, selected students are required to write a formal Post Flight Report as part of their final year project assessment.

3 Flight test method & equipment

The flight test instrumentation used in the flight test programme was portable and secured during the take-off and landing. Each device used it's own internal or independent power source and aerial so as not to affect aircraft certification (no STCs or Minor modifications were required). All equipment had to be capable of being installed and removed safely within a limited time period, usually 15~20 minutes. Additional handheld equipment was used for manual data capture for selected tests (tape measure, spring balance force gauge, stopwatch, pilot's kneeboard with mounted test cards). Cockpit, cabin and over wing video was provided using lightweight wide-angle lens, self-contained video cameras capable of recording up to 2 hours of video onto a 4 Gigabyte SD memory card. This was useful for de-briefs and used in the classroom for demonstration of the flight exercises.

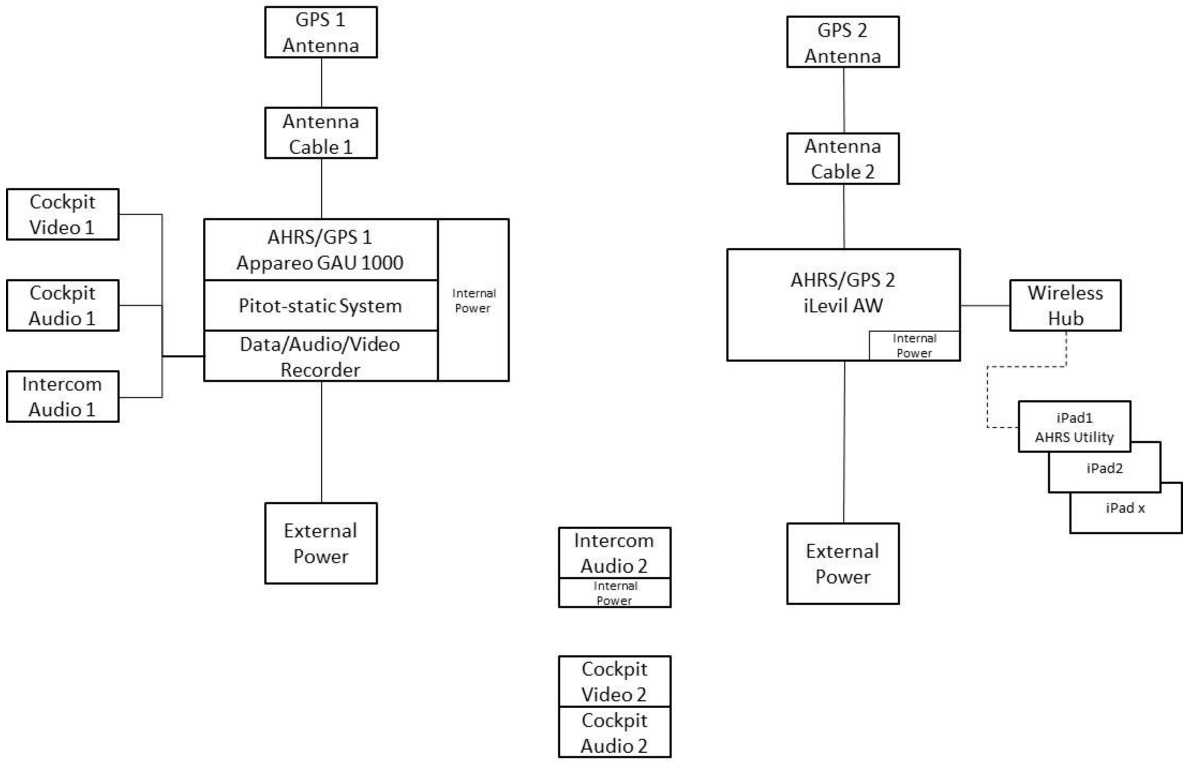

Figure 4, Flight Test Data Acquisition System

Figure 5, Flight Test Data Acquisition System Installation (AHRS/GPS 2)

For automated data collection, a stand-alone, self-powered Appareo GAU 1000 Independent Flight Data Recorder (iFDR) was used in conjunction with Appareo AS Flight Analyzer software (Bromfield & Gratton 2012). The software enabled export of the flight data in an open format (comma separated file format) for analysis using Microsoft Excel & Matlab. For presentation of the flight data to the Flight Test Coordinator and students acting as Flight Test Observers (FTOs), an iLevil AW self-powered Attitude Heading & Referencing System/Global Positioning Satellite System (AHRS/GPS) with integral wireless network was used. A simulated flight instrument display (Figure 4) using the iLevil AHRS Utility iPad application was used to present real-time flight data to the students in the form of an Electronic Flight Instrumentation System (EFIS). A digital voice recorder (MP3), connected to a microphone inserted in the crew's headsets provided adequate cockpit voice recording quality and this was later synchronised with video from the onboard video cameras recording flight data for post-flight review/analysis.

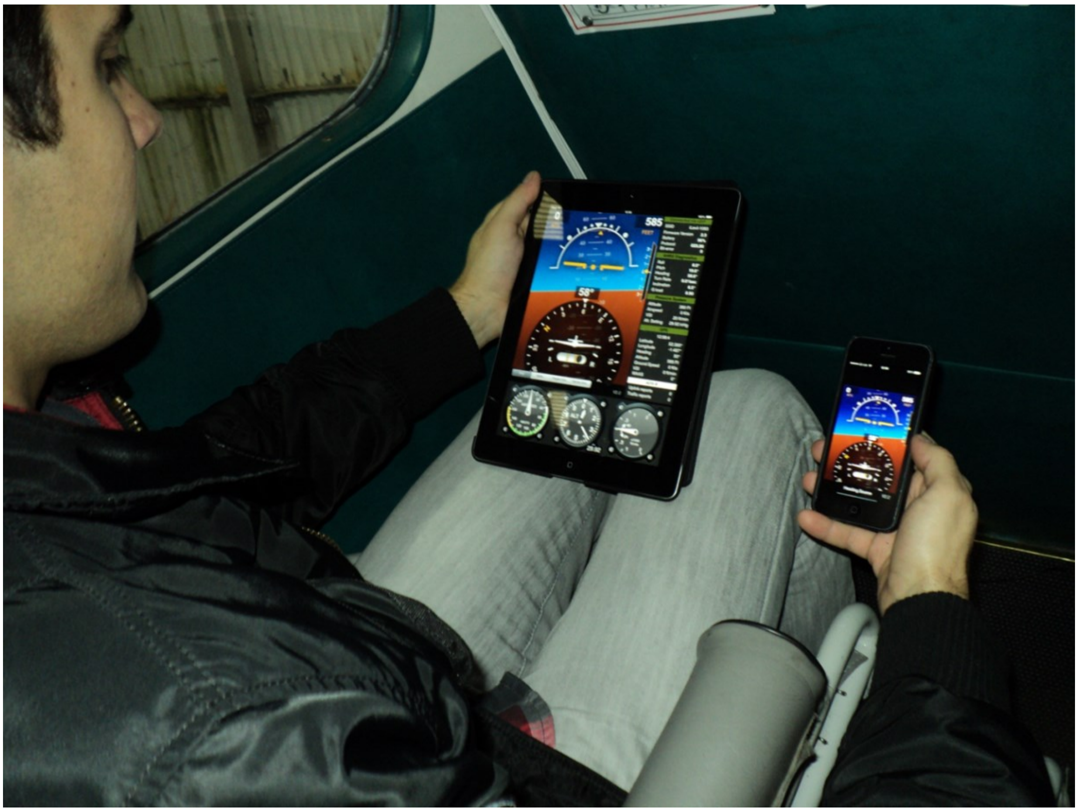

Figure 6, iPad & iPhone Running AHRS Utility App

Figure 7, iPad AHRS Utility for Simulated (EFIS) Cockpit Instruments

3.1. Cross-calibration

The independent flight data recorder unit was cross-calibrated with a known reference system (IRS) installed on an aerial platform. Five in-flight tests were conducted to compare data sensing and recording capabilities of the iFDR. Longitudinal and lateral/directional dynamic stability tests were used to generate flight data for comparison. Sixteen data parameters (Appendix A, Table A-1) were recorded by the iFDR at a sampling frequency of 4 Hz for a selection of dynamic modes (Appendix A, Table A-2) then plotted and compared to on-board systems using time series plots (Appendix A, Figure A-1).

The portable iFDR unit was mounted forward of the aircraft's calculated longitudinal CG position and the on-board IRS was mounted aft of the CG. The iFDR was switched on and calibrated prior to take-off and continuously recorded data (4 Hz) for the duration of the flight. The IRS/Labview data recording system was switched on at the beginning and end of each dynamic mode test to conserve data storage (10-25 Hz sampling rates). Pilot audio cues were used to start the recording prior to commencement of each manoeuvre. A digital voice recorder was used throughout the flight to capture ATC and cockpit/cabin communications.

Ignoring position differences of the units and considering differences in sampling rates, barometric pressure setting and wind speed/direction, the iFDR showed good correlation with the LabView/IRS system for all modes. Rapid manoeuvring resulted in a degradation of data quality for linear accelerations and angular rates since the effective sampling rate of the Appareo unit is only 4 Hz. The iFDR proved suitable for steady-state and slow aircraft dynamics (2 Hz or less). For comparison of true airspeed, further development of a calibration method is required taking into consideration position error corrections, compressibility effects, density ratio, horizontal and vertical winds. However, maintaining a constant height/rate of climb and heading showed that groundspeed (iFDR) could be used as an alternative to indicated airspeed.

3.2. Flight test approach

The flight test programme was developed over a 3-year period using three different aircraft types operating under an Airline Operators Certificate (Bromfield 2013) to ensure adequate safety and to comply with university requirements. Each year, the flight tests were used to evaluate different types of hardware for flight data collection including the use of new digital multi-media devices (iPads & iPhones) in the cabin environment. The availability of both manual and automated data (Table 1) for analysis and reporting provided additional learning experiences to the student. For example, students were able to assess the phugoid mode in the cruise climb by recording GPS groundspeed and geo-potential altitude at 30 second intervals. Manual test cards were used to record manual data presented on iPad/iPhone(s) using a software application for simulated EFIS presentation.

Table 1, Flight Test Schedule

			MANUAL DATA		AUTO MATED DATA	
Test No.	**Description**	**Test Objectives**	**Recorded on Test Cards**	**Obser-vations**	**Recorded @ 4Hz**	**Required Parameters (time)**
1	Performance - Cruise Climb	Estimate Climb Performance	X		X	• height • speed
2	Longitudinal Dynamic Stability: Short Period Oscillation (SPO)	Estimate SPO		X	X	• speed • height • pitch angle • pitch rate
3	Longitudinal Dynamic Stability: Phugoid	Estimate LPO	X	X	X	• height • speed • pitch angle
4	Apparent Longitudinal Static Stability - Stick-fixed/free: Cruise	Estimate Stick-fixed/free Neutral Point	X		N/A	• stick force • stick displacement • speed
3	Stall Characteristics – Flap Zero	Evaluate Stall Characteristics & compare to Certification Specifications	X	X	X	• height • speed • rate of descent • pitch angle • roll angle • normal acceleration
6	Lateral/Directional Stability – Spiral Mode	Estimate time to double/half amplitude & compare to Cert. Specs.		X	X	• height • speed • bank angle
7	Lateral/Directional Stability – Dutch Roll	Estimate No. cycles to damp out & compare to Cert. Specs	X	X	X	• roll rate • yaw rate • lateral acceleration
8	Lateral/Directional Stability – Roll Mode	Estimate Roll Mode Time Constant & compare to Cert. Specs.		X	X	• bank angle • roll rate

3.3. Post-flight analysis

Post-flight, the automated data (4 Hz) was extracted from the FDR using the SD Card and loaded into flight analysis package for verification using flight visualisation tools (Figure 8). Using the analysis tool export facilities, data was exported in *.CSV format for further analysis as required using Microsoft Excel, Matlab and/or Datplot. This flexibility enabled manual and automated data to be compared. This exercise improved students' knowledge and understanding of flight test methods, data collection errors, sampling rates and data anti-aliasing.

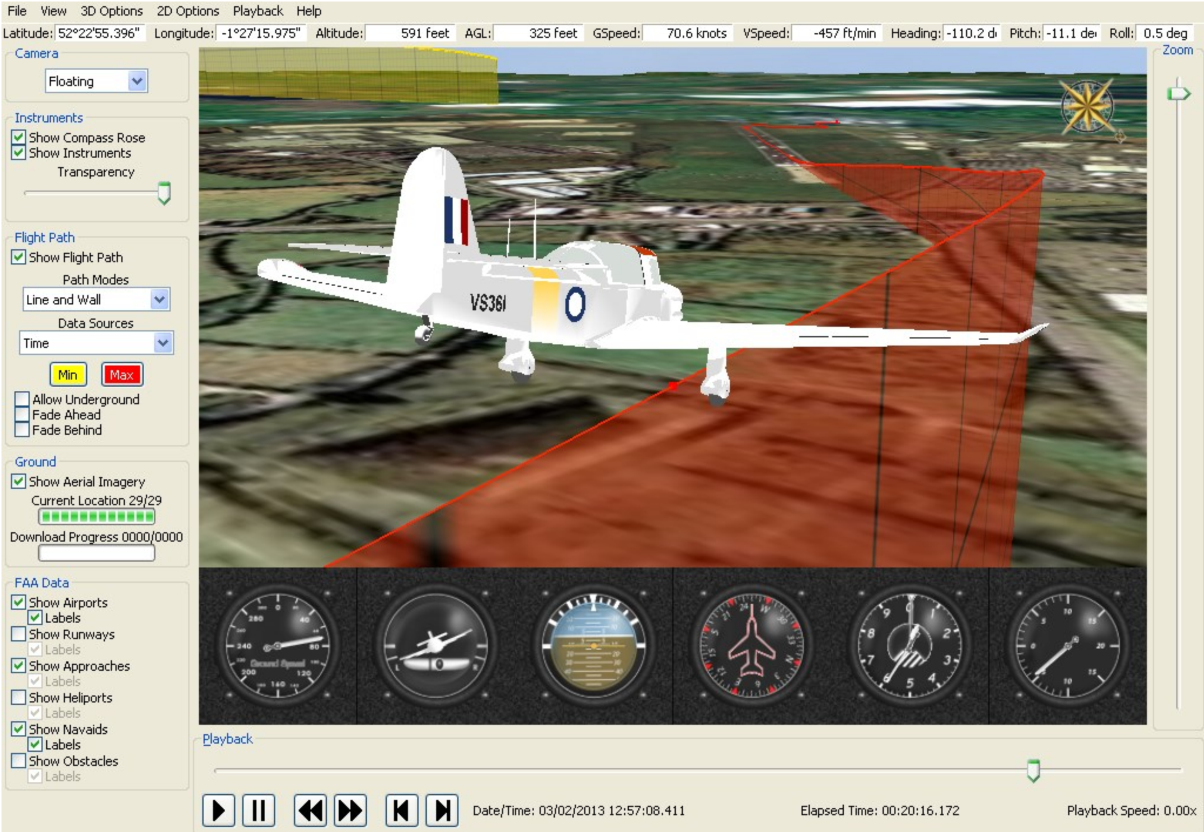

Figure 8, 3D Visualisation of Approach (Prentice Model)

4 Flight test results

Using the recorded flight data it was possible to replay the entire flight using visualisation software in 'real-time' (Figure 8) in 2D data time series and 3D flightpath formats. To add realism to the flight replay, a 3D CAD model of the aircraft was created and added to the library of aircraft available within the flight visualisation software. The data review in 2D format enabled key tests/events to be confirmed and cross-checked with manual timings. All times were recorded in GPS/UTC in the format 'hh:mm:ss.000' for all portable flight data collection devices on-board the aircraft. Manual event timings also used the same GPS/UTC times visible using the iPad EFIS application and separate portable GPS. After confirming the timing of all flight tests/events using the flight visualisation tool, the data was exported to Datplot – a freeware software utility for plotting flight test data (Datplot 2016) for further validation. Examples of flight test data results generated during the Performance and Handling Qualities Evaluation of one aircraft – the Percival P40 Prentice T1 (Figure 1) are shown below (Figure 9 to Figure 17 inclusive). All flight tests for these examples were conducted with a take-off mass of 1761 kg and CG at 0.94 m aft of datum. The iFDR (AHRS/GPS 1) was positioned in line with longitudinal (OX) CG position approximately 0.3 m above the CG (-OZ), on aircraft centreline (OY = 0). All data was sampled at a frequency of 4 Hz.

4.1 Flight summary

In order to validate overall flight data a summary of key flight data (elevation, groundspeed vs. time) is first presented. The flight summary data (Figure 9 & Figure 11) shows the start time and LAT/LON positions for the start of the flight recording at 12:39:54.783 and the finish at 12:59:32.303. All eight flight exercises (as defined in Table 1) were complete within 20 minutes. Test conditions and test sequences were optimised through a series of shakedown flights to enable time compression (hence cost reduction). GPS groundspeed was used for flight tests requiring airspeed measurement. Estimates of wind speed and wind direction were obtained during the initial part of the flight and where required, this could be used to convert from groundspeed recorded by the GPS to indicated/calibrated/true airspeed as required. A steady heading was maintained for all tests to simplify any necessary corrections.

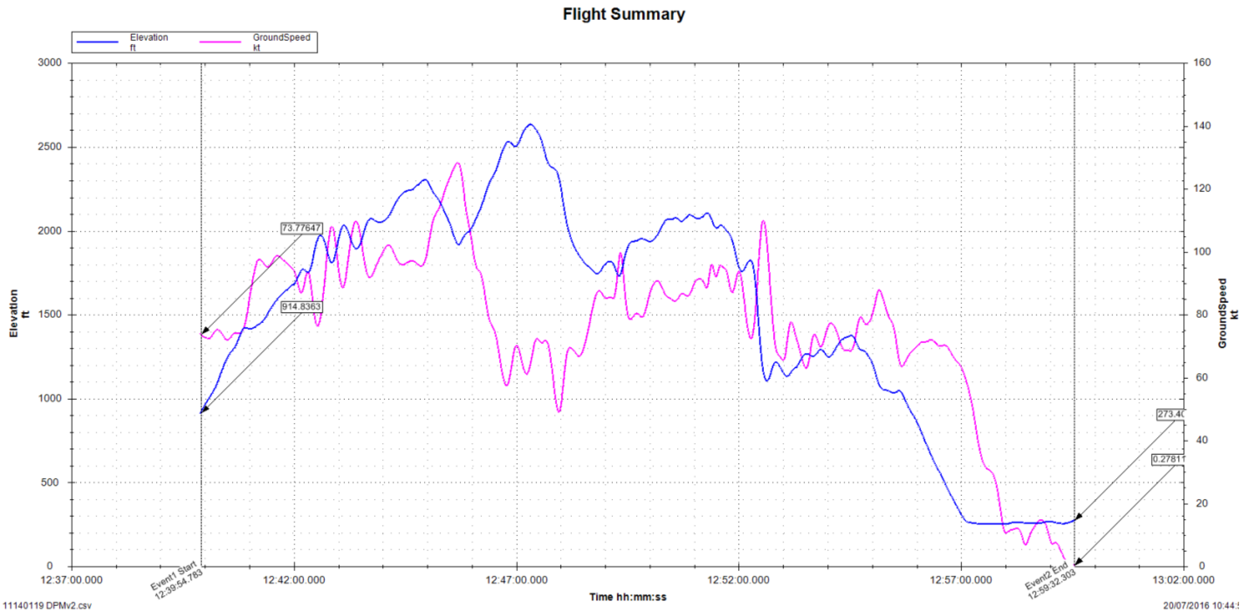

Figure 9, Flight Summary – Height & Groundspeed vs. Time

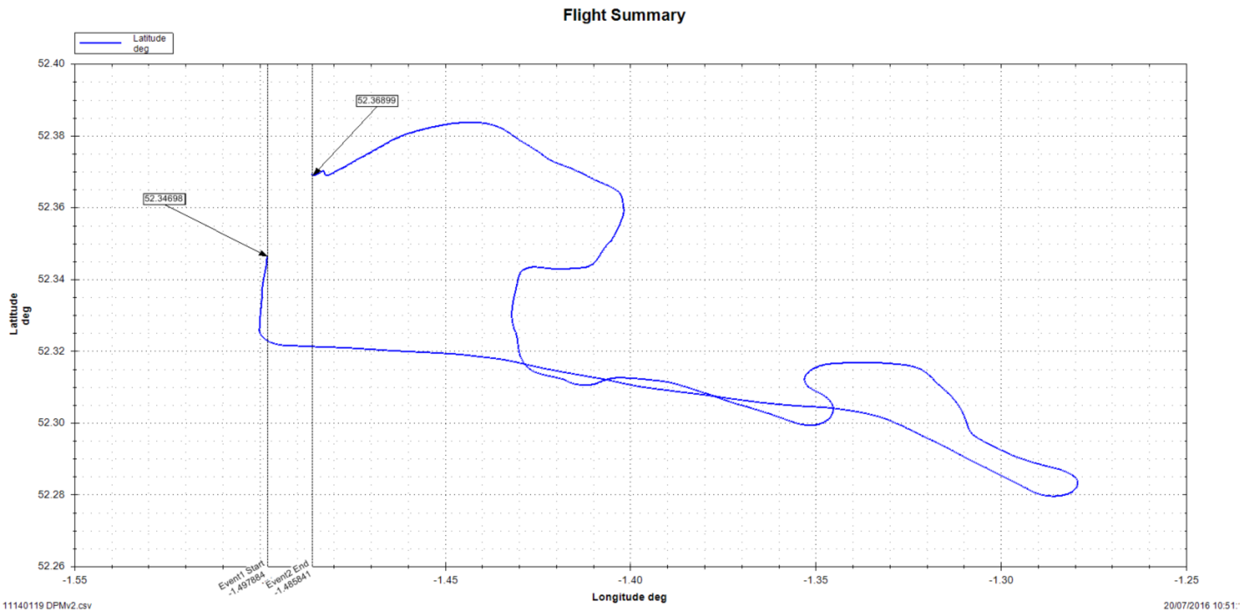

Figure 10, Flight Summary – Track Latitude vs. Longitude

4.2. Cruise climb performance

For cruise climb performance, the vertical rate of climb of the aircraft was assessed. AHRS/GPS 1 was used to automatically record geo-potential height (ft) versus GPS/UTC time. Students were also required to manually record the time, height and airspeed at the start, mid-point and end of the climb using the iPad EFIS application, using GPS data generated by AHRS/GPS 2. Using a linear approximation, students estimated the rate of climb of the aircraft from manually recorded data and compare this with automated data from AHRS/GPS 1. During flight tests at the given loading conditions, the aircraft achieved a climb rate of approximately 514 ft per minute whilst the manually recorded data indicated a climb rate of approximately 494 ft per minute.

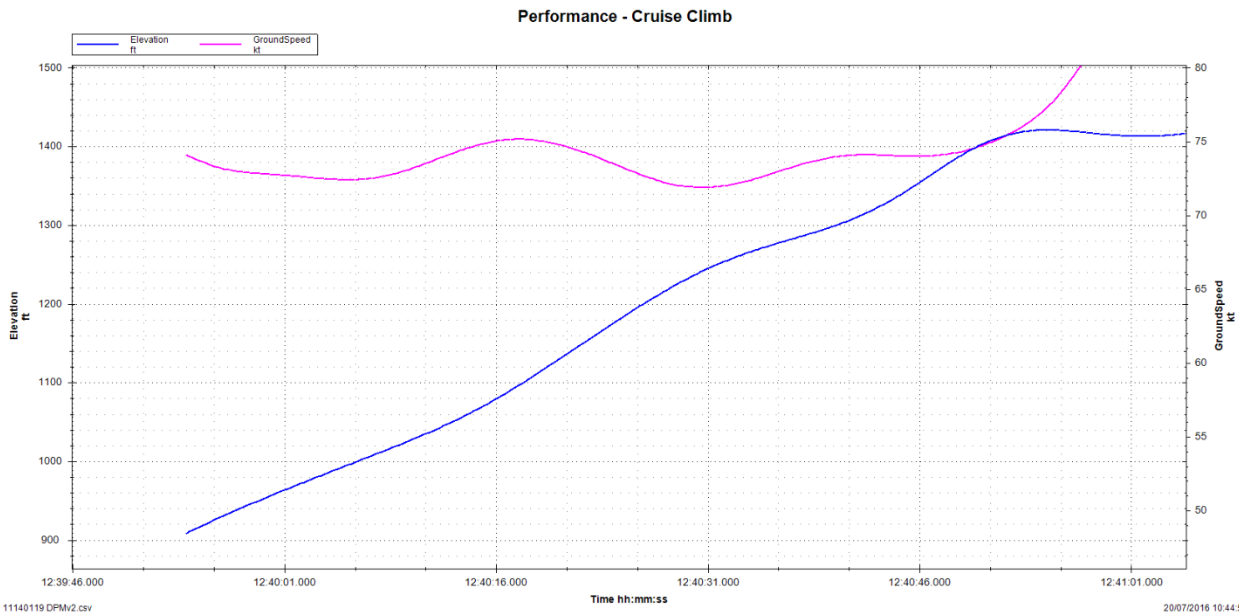

Figure 11, Performance – Cruise Climb

4.3. Longitudinal dynamic stability: SPO mode

The Short Period Mode is the most important longitudinal dynamic mode and is used to simulate the response of the aircraft to a gust, hence it is also known as the 'gust response'. It consists of a damped oscillation about the pitch axis when disturbed and the principle variables are pitch rate and angle of attack. The typical frequency response is between 0.5 to 2 Hz (within the natural frequency response range of a human pilot) for acceptable flying qualities. The mode must be well damped or handling problems arise. The AoA recovers to its trim value sufficiently quickly for the speed to remain constant throughout.

For this test the aircraft was set in trimmed, level cruising flight at 90 KIAS, approximately 94 kt groundspeed with a 4 kt headwind. The short period mode was excited by using a rapid pitch doublet with elevator backwards then forwards before returning to the neutral position near to the trimmed flight condition. A comparison of flight test and flight simulation data (Figure 12) show that no overshoots were present and that the aircraft response was 'deadbeat' as a result of heavy pitch damping. The results show that in the trimmed flight condition prior to commencement of the test, the pitch attitude was approximately -8 degrees nose down. An increase of 0.8g in normal acceleration was detected by the iFDR.

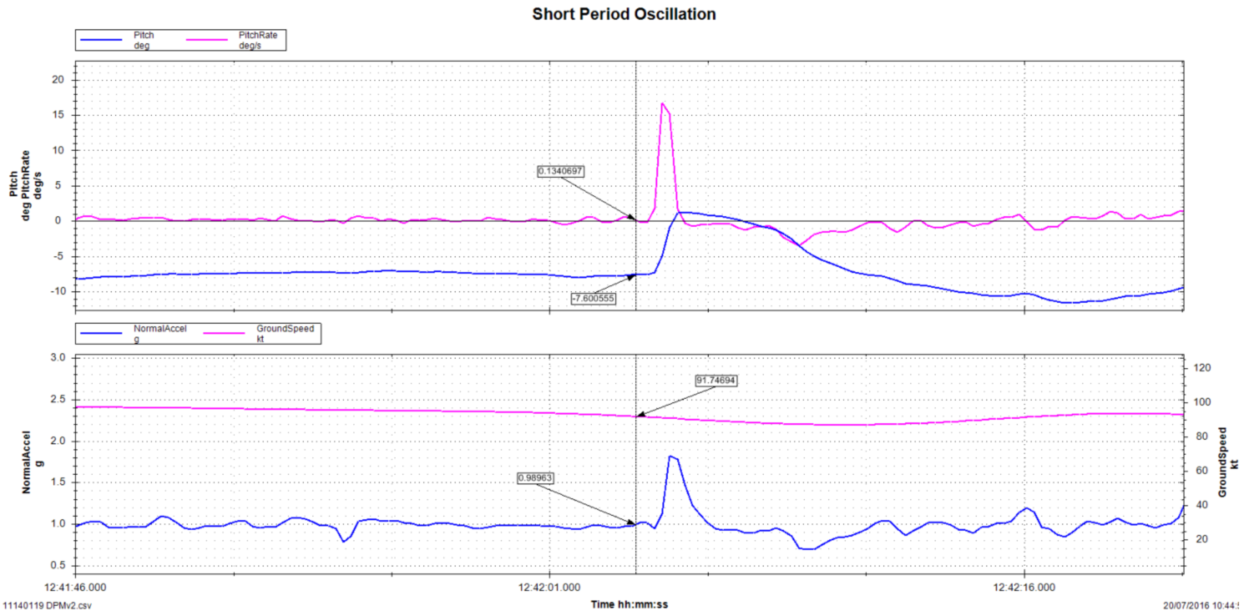

Figure 12, SPO

4.4. Longitudinal dynamic stability: LPO or Phugoid mode

The Long Period Oscillation or Phugoid Mode is a longitudinal dynamic mode and was originally (incorrectly) named by Frederick Lanchester. It is characterised by the interchange of kinetic & potential energy as a result of a major trim change due to flaps, gear, power or a combination of these factors. It is a lightly damped, low frequency oscillation in height & speed. When disturbed from trim, sinusoidal oscillation with variation of pitch attitude & airspeed occur but angle of attack remains largely constant. The change in pitch attitude results in a change in flight path.

The aircraft was established in the trimmed cruise climb condition at 90 KIAS. Whilst maintaining a constant heading, the phugoid mode was excited by using a pitch 'singlet'. The aircraft was slowed down by 10 knots from the trimmed flight condition by gently pulling back on the pitch control – then released with the pilots hands off the controls. The flight test data (Figure 13) sampled at 4 Hz shows the aircraft to be positively statically and dynamically stable (aircraft attempts to return to trimmed flight conditions and oscillations damp out). The estimated time period of the phugoid is 32 seconds. By inspection of graphical results, the damping ratio can be determined by using the Transient Peak Ratio method (NTPS, 2008) , yielding a value of $\zeta = 0.1$.

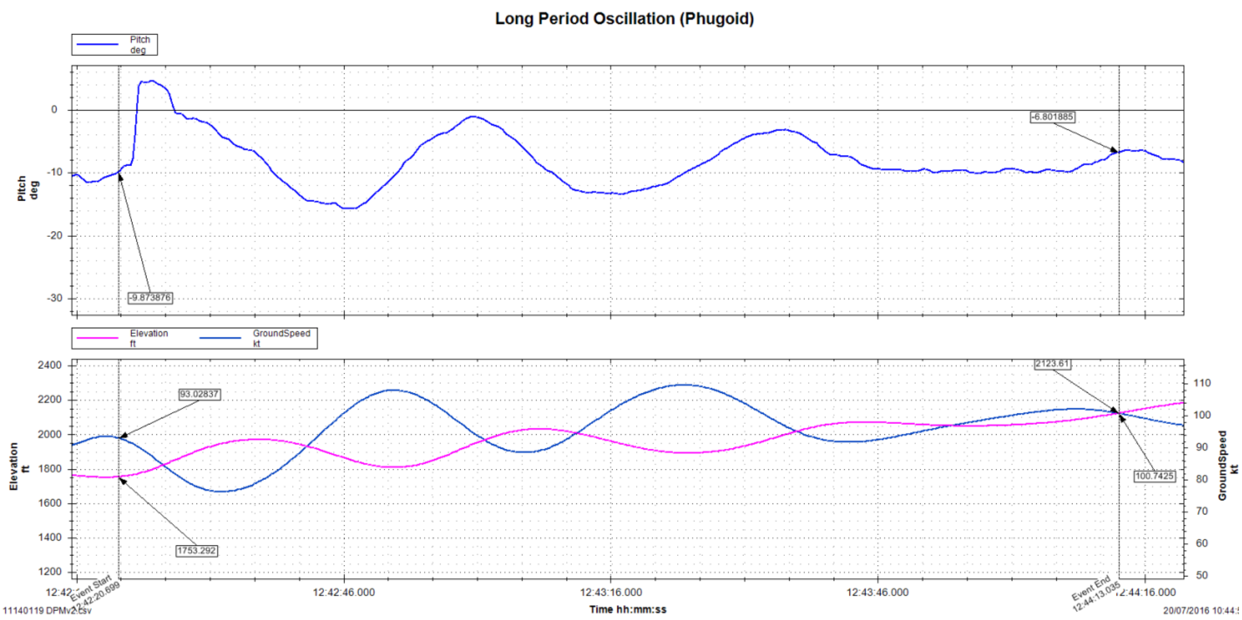

Figure 13, LPO (Phugoid)

4.5. Spiral mode

The Spiral Mode is a non-oscillatory lateral/directional dynamic stability mode and it manifests itself as an exponential convergence or divergence in roll attitude which, when unstable, results in a divergent spiral descent. It is a combination of yaw and roll motion controlled by relative magnitudes of L_v and N_v. As the time constant of the mode is relatively large (typically 40+ seconds for a light aircraft), the mode is slow to develop. Physically, when the roll attitude of aircraft is disturbed, lift vector will also rotate which has the potential for causing a small sideslip. If the sideslip is in the direction of the roll, any dihedral effect will produce a moment in a direction which will reduce the bank angle, but the vertical tail fin will produce a moment which will yaw the aircraft in the same direction as the roll.

The aircraft was established in a steady co-ordinated (ball centred) left hand turn to the left with a bank angle of 15 degrees and controls were released. The aircraft bank angle doubled to 30 degrees within 10 seconds, indicating that the aircraft is spirally unstable to the left. The test was repeated in a right hand turn and after a slow initial divergence, the aircraft halved bank angle within 30 seconds, indicating that it was spirally stable to the right.

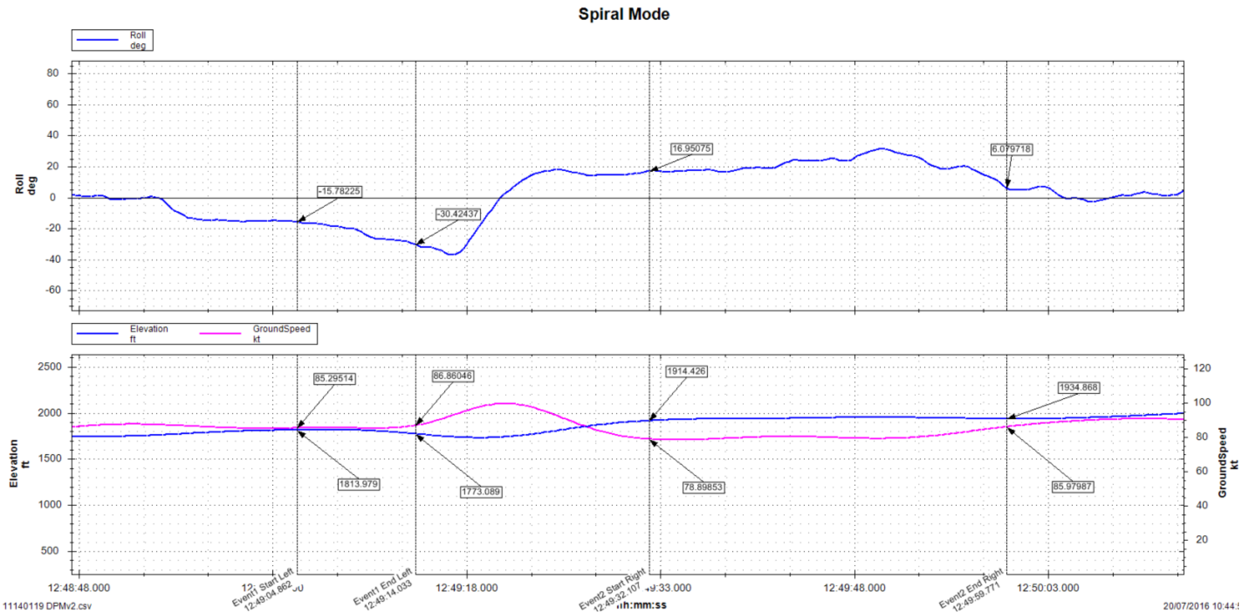

Figure 14, Spiral Mode

4.6. Lateral/directional stability – Dutch Roll mode

The Dutch Roll Mode is a lateral/directional stability mode characterised by an oscillation about the aircraft yaw axis. The principal variables are sideslip angle and yaw rate with the aircraft maintaining a straight flight path. It is the directional equivalent of longitudinal SPO with less damping. Sinusoidal changes in sideslip cause a similar change in rolling moment (via the "dihedral effect") and this causes the aircraft to oscillate in roll. There is phase shift between cause and effect, the forward going wing is low and the aft going wing high, with wing tips describing an elliptical or circular path when observed from the aircraft cabin.

The aircraft was setup in the trimmed cruising flight condition at 90 KIAS on a constant heading. The mode was excited by using a rudder doublet – approximately 50% deflection of the rudder pedals left-right-left-centre, the pilot removing both feet from the pedals. The coupled yawing and rolling motion was observed by movement of the wing tip (to assess the yaw to roll ratio). The results plotted with data points at an interval of 0.25 s (Figure 15) show that the aircraft is statically and dynamically stable tending to return to the trimmed flight condition with oscillations damping out within 4-5 cycles.

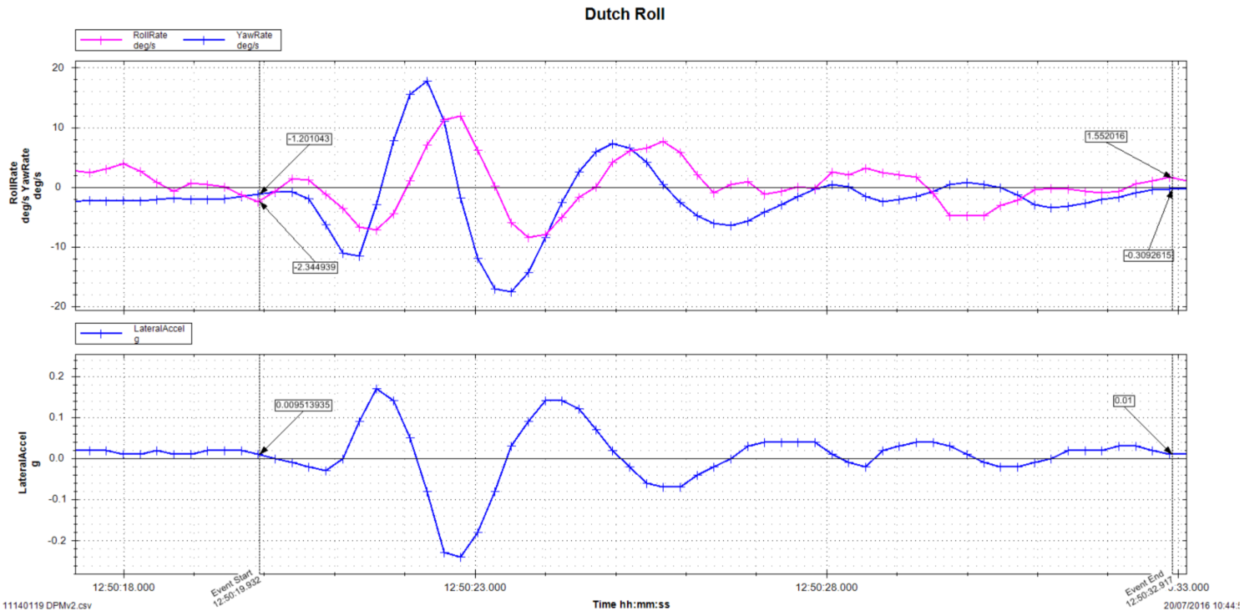

Figure 15, Dutch Roll Mode

4.7. Lateral/directional stability – Roll mode

This lateral/directional control mode is characterised by an exponential change in roll rate about the aircraft roll axis and is non-oscillatory. When the aircraft is disturbed in roll it will acquire a new roll rate exponentially, consequently all rolling motion (especially aileron response) has an exponential lag associated with it. The mode characteristic is almost entirely due to the viscous 'paddle' damping effect of the wings when the aircraft is disturbed in roll, is always present and has a stabilising effect.

The aircraft was setup in the trimmed cruising flight condition at 90 KIAS on a constant heading. The mode was assessed by setting up the aircraft in a 30 degree banked turn to the left, using rudder pedals to co-ordinate the turn and avoid slipping. Using a 50% stick/roll input the pilot rolled the aircraft to 30 degrees angle of bank to the right, holding the bank angle momentarily, before repeating the roll to left again, then returning to wings level flight. The results, plotted with data points at an interval of 0.25 s (Figure 16) indicate that the aircraft has a maximum roll rate of 40 degrees per second with a Roll Mode time constant (time taken to reach 2/3 of maximum roll rate) of 0.50-0.75 seconds.

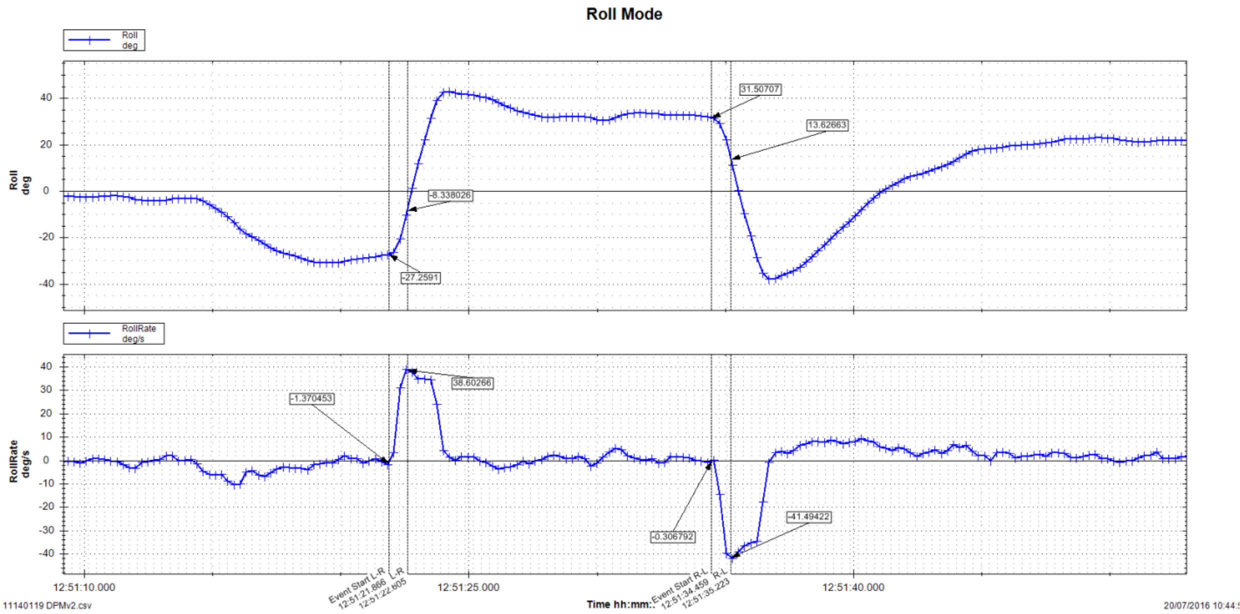

Figure 16, Roll Mode

4.8. Stall characteristics

The aircraft was setup at V_{REF} of 65 KIAS with flaps up and decelerated at a rate of 1 kt per second until uncommanded nose down pitching motion was observed (full aerodynamic stall). The results (Figure 17) show that the aircraft pitches down at 12:47:58.543 with a slight oscillation in pitch rate ('nose bobbing'). The stall speed is therefore approximately 49 kts groundspeed or 53 KIAS using wind correction and conversion to indicated airspeed. The normal acceleration or 'g-break' is less well defined but results are in broad agreement with manually recorded flight data and stall characteristics observed. The aircraft is fitted with a stall warning system comprised of stall (vane) sensor fitted to the leading edge of the right hand wing connected to a stick-shaker fitted to each control column.

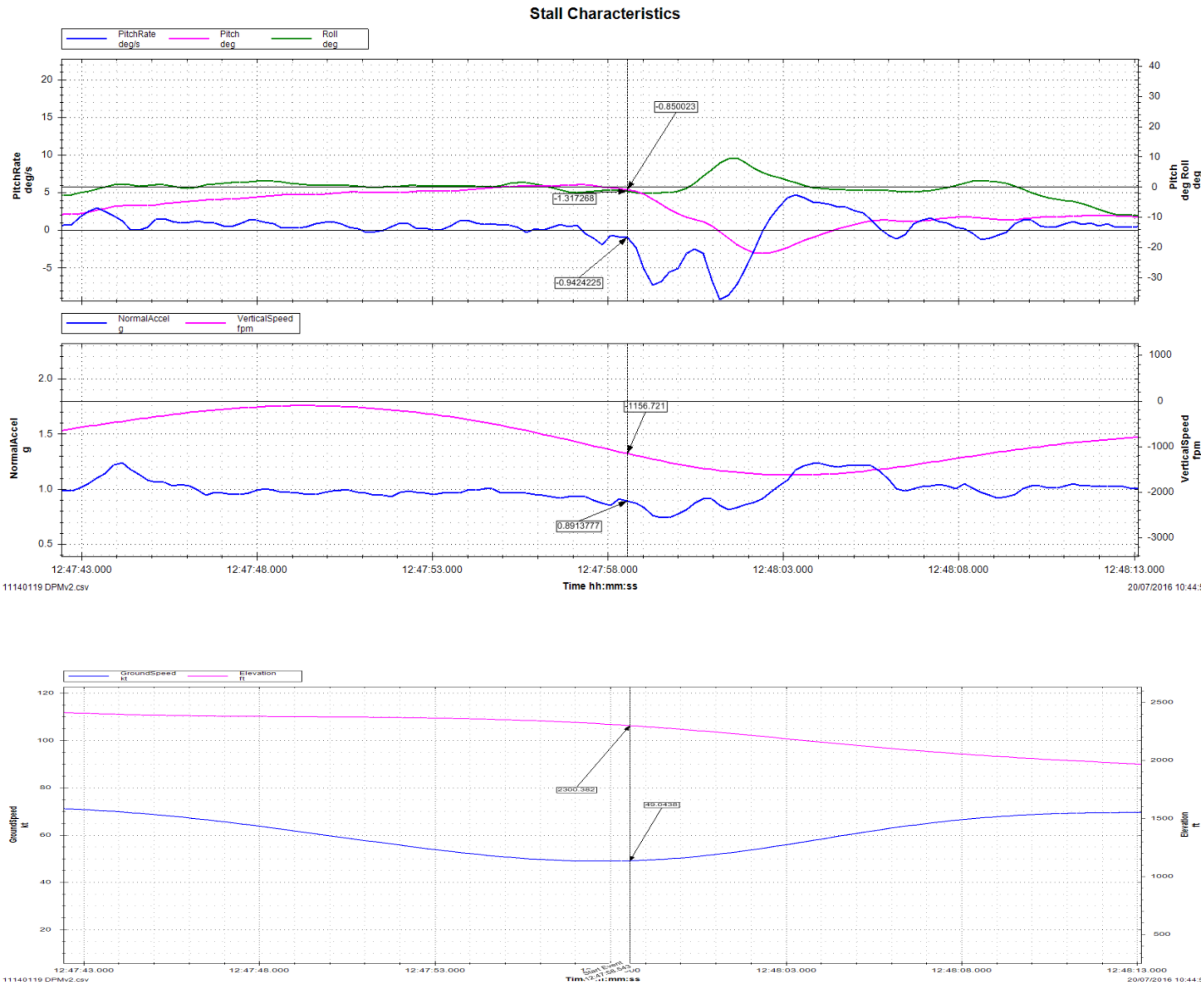

Figure 17, Stall Characteristics

4.9. Analysis and Evaluation of Test Results

Students completed the flight exercises in groups of 2 to 8, depending on the size and seating configuration of the aircraft used. On completion of all flights at the end of the flying day, a combined post-flight de-brief was conducted with all student participants, the test coordinator (a trained flight test engineer), test pilot and supporting academic staff. During the de-brief, the recorded flight data was re-played using 3D flight visualisation software as the test pilot described the flight test technique employed. Student participants were asked in an open forum to comment on the observed performance and handling qualities of the aircraft being tested. On completion of the review of all tests, there was an open question and answer session. Selected final-year undergraduate students had the opportunity for a wider learning experience by opting to complete final year projects related to the flight test exercises. Example projects included the design and development of a flight test plan to post-flight report, the functional and technical evaluation of portable flight data recording devices and the development and evaluation of flight simulation models of aircraft utilised. These project students were required to complete a formal technical flight test report to summarise the test results and compare to the aircraft certification requirements and the published pilot operating handbook where relevant.

Table 2, Example of Key Flight Test Results (Prentice Aircraft)

Test No.	Description	Test Objectives	Example Results
1	Performance - Cruise Climb	Estimate Climb Performance	• Climb rate = 514 fpm (W= 3,884 lb @ 37.1")
2	Longitudinal Dynamic Stability: Short Period Oscillation (SPO)	Estimate SPO	• SPO Time Period = 1s • Frequency = 1 Hz • Deadbeat
3	Longitudinal Dynamic Stability: Phugoid	Estimate LPO	• LPO Time Period = 32s • Frequency = 0.03 Hz • Damping Ratio = 0.1 • Oscillations damped within 3-4 cycles
4	Apparent Longitudinal Static Stability - Stick-fixed/free: Cruise	Estimate Stick-fixed/free Neutral Point	• No automated data (Manual)
3	Stall Characteristics – Flap Zero	Evaluate Stall Characteristics & compare to Certification Specifications	• Stall speed (Flap 0) = 53 KIAS (49 kt GND)
6	Lateral/Directional Stability – Spiral Mode	Estimate time to double/half amplitude & compare to Cert. Specs.	• Divergent to Left with time to double amplitude = 30s • Convergent to Right time to half amplitude = 10s
7	Lateral/Directional Stability – Dutch Roll	Estimate No. cycles to damp out & compare to Cert. Specs	• Oscillations damped within 5 cycles
8	Lateral/Directional Stability – Roll Mode	Estimate Roll Mode Time Constant & compare to Cert. Specs.	• Roll rate 40 deg/s • Roll Mode Time Constant 0.50-0.75 s

4.10. Measurement of Learning Outcomes

Learning outcomes were measured qualitatively by means of a student participant survey and quantitatively by comparing summative assessment grades before and after the introduction of integrated theory and practice.

Coursework Results

On completion of the flight dynamics module and flight test experience, module learning outcomes were assessed by coursework. Students were required to complete selected performance and handling qualities assessments with given data. During the first year of the introduction of flight test experience (*Group 1*, $n = 48$) theory and practice were not integrated and were delivered separately. During the second year (*Group 2*, $n = 62$) theory and practice were integrated as outlined in Section 2, resulting in mean coursework grades increasing by +9.22% and standard deviation decreasing by -3.45%. Using a statistical analysis (Coolican 2004) between subjects, independent samples *t*-test (Table 3) showed that differences in mean coursework grades were statistically significant ($p<0.01$).

Table 3, Independent Samples *t* Test for Equality of Means

		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
							Lower	Upper
Grade	**Equal variances assumed**	-3.195	108	.002	-9.22312	2.88712	-14.94589	-3.50034
	Equal variances not assumed	-3.104	88.104	.003	-9.22312	2.97146	-15.12817	-3.31807

Student Survey

A survey of the student experience was conducted (21 respondents) on completion of the flight exercises and post-flight data reduction and analysis. The survey showed that 71% 'strongly agreed' or 'mostly agreed' that the flight exercises helped them to 'better understand and apply principles and theory studied in the classroom'. It also showed that 84% of students 'strongly agreed' or 'mostly agreed' that the overall quality of the flight test experience was satisfactory. Individual comments from students were:-

"The flight was an advantage to the coursework."

"I understood flight dynamics from a practical point of view and understood the behaviour of an aircraft. Getting the chance to talk to one of the best test pilots in the UK and getting feedback from him about the aircraft was valuable."

"The experience of performing the tests in an actual aircraft makes things real and you can see the difficulties in the testing and anomalies of actual test flights. The iPad shows in flight data at a high accuracy level. It made me smile all day and got me excited about the subject again."

5 Conclusions

The inclusion of practical flight exercises within undergraduate aerospace engineering courses is recommended by the RAeS in the UK to enhance learning and student experience. Most institutions separate theory and practice, with theory being taught in class and practical exercises being done using a one day intensive programme using a separate syllabus. With the increasing size of cohorts this can be cost prohibitive.

By applying a revised learning & teaching taxonomy, flight test and flight simulation has been integrated with the classroom environment to enhance learning as evidenced by 9% improvements in coursework assessment grades. The student experience has also been enhanced as evidenced by positive, qualitative feedback. Flight tests are replayed in 'real-time' to demonstrate the flight exercises that support the theory. Flight test data generated by the flight exercises has been used in tutorial sessions and related to real-world situations. Test data has also been used to support the evaluation of aircraft performance and handling qualities and it is now possible to use a validated flight simulation model (with known limitations) to practice flight test exercises before the actual flight tests to generate simulated flight test data independently. The development of flight test methods and flight simulation models has also generated a number of undergraduate and postgraduate student projects.

The cross-calibration of a portable flight data recording system with a known reference system demonstrated the accuracy, precision and limitations of COTS technologies. The flight test results show that COTS technologies can generate useful data for determining aircraft performance and handling qualities in support of learning and teaching flight dynamics. The range of frequencies measured during the dynamic stability tests (approximately 0.03 Hz to 1 Hz) are within the capability of the recording devices and results were acceptable, without correction for environmental factors or sensor location. The use of portable flight data recorders provided the opportunity for students to work with new, familiar technologies (iPads/iPhones etc.) and develop a critical appreciation of instrument sensing, precision, accuracy and correction factors. Methods could be refined in the future by the inclusion of correction factors to enhance data quality and student learning.

The ability to apply this new approach and portable technology to any standard, un-modified aircraft has enabled flight test data to be generated for classic and modern aircraft. The use of classic aircraft has helped to further engage students and the flight data may contribute to aviation heritage. For example, only 4 Percival Prentice airframes remain in airworthy condition on the UK register at present and published flight test data for this aircraft is limited.

The survey of the student experience has suggested that flight exercises and use of familiar technologies have helped students to better understand and apply principles and theory studied in the classroom. As in all flight activities, safety cannot be compromised and the flight test programme was delivered by trained flight test professionals (Test Pilot & Flight Test Engineer) using an aircraft operating under an Airline Operators Certificate.

In conclusion, the authors believe that the combination of integrated theory and practice and novel use of available COTS technologies has simultaneously:-

- Increased student participation by reducing operating costs (using standard, un-modified aircraft and portable flight data recording and transmission equipment);
- Enhanced student learning by the integration of classroom theory and practical flight exercises (using revised Bloom's);
- Improved the student experience by using familiar and popular technologies (use of iPads, iPhones);
- Improved student achievement of the module learning objectives as evidenced by improvement in course work grades.

Development of the data analysis and the evaluation of flight test results would further enhance the experience for future student cohorts.

Figure 18, Coventry University Flight Test Team (De Havilland DH89a Rapide Test Aircraft in background)

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APPENDIX A

Table A-1, AHRS/GPS Data Parameters (Appareo 2009)

No	Parameters	Unit	Rate (Hz)	Resolution	Accuracy	Source
1	**Date**	**(Month/Day/Year)**	4	1 day	1 day	GPS
2	**Time**	**(Hour:Min:Sec:milli-sec)**	4	50 NS	1 us	GPS
3	**Latitude**	**(Degrees)**	4	1x10-7 deg	2.5 m CEP 2σ	GPS
4	**Longitude**	**(Degrees)**	4	1x10-7 deg	2.5 m CEP 2σ	GPS
5	**Geoptotential Altitude**	**(Metres)**	4	1 mm	5 m SEP 2σ	GPS
6	**Speed (Ground)**	**(Knots)**	4	**	< 5 knots ***	GPS
7	**VerticalSpeed**	**(Ft/Min)**	4	**	< 50 Ft/Min ***	GPS
8	***Course (Track/derived)**	**(Degrees)**	4			GPS
9	**Heading**	**(Degrees)**	4	**	< 2 deg 1σ	COMPASS
10	**Pitch**	**(Degrees)**	4	**	< 1.5 deg 1σ	GYRO
11	**Roll**	**(Degrees)**	4	**	< 1.5 deg 1σ	GYRO
12	**RollRate**	**(Degrees/Sec)**	4	0.01 deg/sec	0.1 deg/sec/sqrt(Hz)	GYRO
13	**PitchRate**	**(Degrees/Sec)**	4	0.01 deg/sec	0.1 deg/sec/sqrt(Hz)	GYRO
14	**YawRate**	**(Degrees/Sec)**	4	0.01 deg/sec	0.1 deg/sec/sqrt(Hz)	GYRO
15	**Normal Accel**	**(g)**	4	0.3 ug	10 mg 2σ	ACCEL
16	**Longit. Accel**	**(g)**	4	0.3 ug	10 mg 2σ	ACCEL
17	**LateralAccel**	**(g)**	4	0.3 ug	10 mg 2σ	ACCEL

Notes

* Internally sampled at higher rate

**These parameters are derived as part of a post processing algorithm - resolution is limited by the double precision floating point calculation

***Approximate engineering estimates

CEP - Circular Error Probability, radius of a horizontal circle centred at the true position containing 50% of fixes

SEP - Spherical Error Probability, radius of a sphere centred at the position containing 50% of fixes

Table A-2, Cross-calibration Flight Tests & IRS Recorded Parameters

Test No.	Dynamic Mode	Time UTC	Duration (s)	Freq (Hz)	Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
1	Short Period	13:39:57	22.602	23.980	Time	Elevator	Alpha	Pitch Rate	Norm Acc
2	Phugoid	13:42:12	115.817	10.007	Time	Elevator	Pitch angle	Speed	Altitude
3	Dutch Roll	13:43:07	35.120	23.576	Time	Rudder	Beta	Yaw rate	Roll Rate
4	Roll Mode	13:44:45	30.965	23.058	Time	Aileron	Roll Rate	Roll angle	
5	Spiral Mode	13:46:07	62.220	10.013	Time	Roll angle	Height	Speed	Aileron

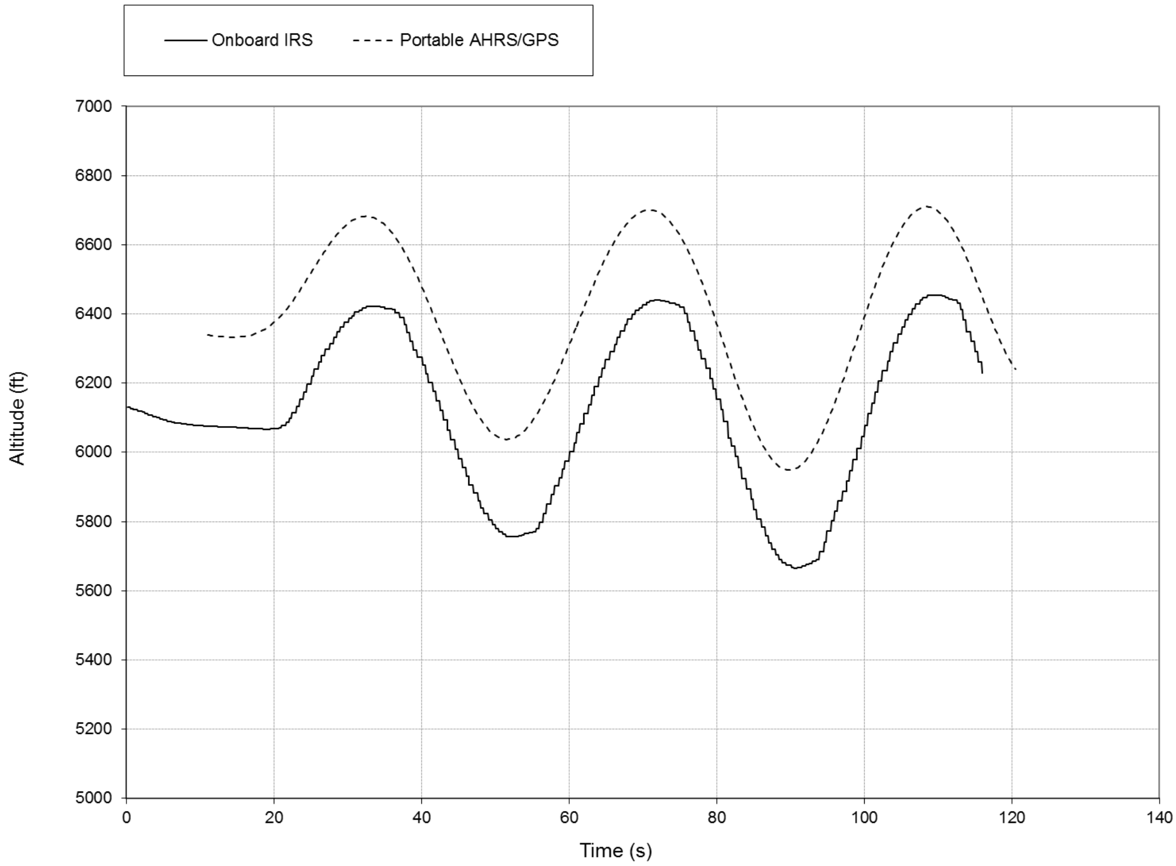

Figure A-1, Example of Cross-calibration Data for the Phugoid Mode

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