Defence
Safety
Authority

Service Inquiry

Watchkeeper 006

2 Nov 15

Defence Accident
Investigation Branch

PART 1.1 – COVERING NOTE

4 Aug 16

DG DSA

SERVICE INQUIRY INTO AN ACCIDENT INVOLVING A WATCHKEEPER UNMANNED AIRCRAFT (UA) WK006 AT MoD BOSCOMBE DOWN (BDN), WILTSHIRE ON 2 NOV 15

1. The Service Inquiry Panel assembled at BDN, on the 10 Nov 15 by order of the DG DSA (ex MAA) for the purpose of investigating the accident involving Watchkeeper UA WK006 on 2 Nov 15 and to make recommendations in order to prevent recurrence. The Panel has concluded its inquiries and submits the Provisional Report for the Convening Authority's consideration.

PRESIDENT

[redacted]
Squadron Leader
President
WK006 SI

MEMBERS

[redacted]
Flight Lieutenant
Aircrew Member
WK006 SI

[redacted]
Lieutenant Royal Navy
Aircrew Member
WK006 SI

2. The following inquiry papers are enclosed:

Part 1 (The Report)
Part 1.1 Covering Note
Part 1.2 Preliminaries
Part 1.3 Narrative of Events
Part 1.4 Findings
Part 1.5 Recommendations
Part 1.6 Convening Authority Comments

Part 2 (The Record of Proceedings)
Part 2.1 Diary of Events
Part 2.2 List of Witnesses

PART 1.2 – PRELIMINARIES

CONVENING ORDER

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Defence Safety Authority

Service Inquiry Convening Order

09 Nov 15

SI President
SI Members

Hd Defence AIB
DSA Legad

Copy to:

COS/SofS	NA/CNS	MA/D MAA
PS/PUS	MA/CGS	MA/Comd JHC
MA/Min(DPV)	PSO/CAS	
DPSO/CDS	PSO/Comd JFC	
MA/VCDS	MA/CJO	

DSA DG/SI/06/15 – CONVENING ORDER FOR THE SERVICE INQUIRY INTO THE AIRCRAFT ACCIDENT INVOLVING WATCHKEEPER WK006 ON 02 NOV 15 AT BOSCOMBE DOWN AERODROME.

1. A Service Inquiry (SI) is to be held under Section 343 of Armed Forces Act 2006 and in accordance with JSP 832 – Guide to Service Inquiries (Issue 1.0 Oct 08).

2. The purpose of this SI is to investigate the circumstances surrounding the subject aircraft accident and to make recommendations in order to prevent recurrence.

3. The SI Panel is to assemble at the Defence Safety Authority (Rm 6.1.3), Ministry of Defence, Main Building on Mon 09 Nov 15 at 1030.

4. The SI Panel comprises:

President: [redacted]

Members: [redacted]

5. The legal advisor to the SI is [redacted] **(DSA Legad)** and technical investigation/inquiry assistance is to be provided by the Defence Accident Investigation Branch (Defence AIB).

6. The SI is to investigate and report on the facts relating to the matters specified in its Terms of Reference (TOR) and otherwise to comply with those TOR (at Annex). It is to record all evidence and express opinions as directed in the TOR.

7. Attendance at the SI by advisors/observers is limited to the following:

Head Defence AIB – Unrestricted Attendance.

1
OFFICIAL SENSITIVE

Defence AIB investigators in their capacity as advisors to the SI Panel – Unrestricted Attendance[1].

8. The SI Panel will work initially from the Defence Accident Investigation Branch facilities at Farnborough and Boscombe Down. Permanent working accommodation, equipment and assistance suitable for the nature and duration of the SI will be requested by the SI President in due course.

9. Reasonable costs will be borne by DG DSA under UIN D0456A.

Original Signed

R F Garwood
AM
DG DSA – Convening Authority

Annex:

A. Terms of Reference for the SI into aircraft accident involving Watchkeeper WK006 on 02 Nov 15 at Boscombe Down Aerodrome.

[1] On a case by case basis as authorised by Hd Defence AIB.

ANNEX A TO
WATCHKEEPER WK006
SI Convening Order
Dated 09 Nov 15

TERMS OF REFERENCE FOR THE SERVICE INQUIRY INTO THE AIRCRAFT ACCIDENT INVOLVING WATCHKEEPER WK006 ON 02 NOV 15 AT BOSCOMBE DOWN AERODROME.

As the nominated Inquiry Panel for the subject SI, you are to:

1. Investigate and determine the cause of the occurrence, together with any contributory, aggravating and other factors and observations.

   a. Specifically to establish whether there are any significant similarities to the causes identified in the loss of WK 031 at West Wales Airport on 16 Oct 14, but not to further investigate known issues.

   b. To identify and investigate any key differences between the two accidents that may have contributed to the loss of Watchkeeper WK006.

2. Examine the policies, orders and instructions that were applicable and whether they are appropriate and were complied with to include:

   a. The level of awareness and application of the information contained within the Safety Advice[2] issued by the DG MAA on 10 Feb 15.

   b. The environmental limitations for the operation of the system, with specific reference to the recovery and landing phase regarding precipitation and visibility.

   c. The Aircraft Document Set to ensure sufficient information is available to crews to deal with emergency/unusual situations.

3. Determine the state of serviceability of the aircraft and relevant equipment.

4. Establish the level of training, relevant competencies, qualifications and currency of the individuals involved in the activity and its authorisation and supervision.

5. Identify if the levels of planning and preparation were commensurate with the activities' objectives.

6. Report and make appropriate recommendations to DG DSA within 3 months.

7. If at any stage the panel discover something they perceive to be a continuing hazard presenting a risk to the safety of personnel or equipment, the President should alert the DG DSA without delay; in order to initiate remedial actions immediately and consideration should be given to raising an Urgent Safety Advice note.

8. You are to ensure that any material provided to the Inquiry by any foreign state, is properly identified as such, and is marked and handled in accordance with MOD security guidance. This material continues to belong to those nations throughout the SI process. Before the SI report is released to a third party, authorization should be sought from the relevant authorities in those nations to release, whether in full or redacted form, any of their material included in the SI report,

[2] 20150210_WK031_SI_Safety Advice-CA Cover Note_OS SI

or amongst the documents supporting it. The relevant NATO European Policy (NEP) or International Policy and Plans (IPP) team should be informed early when dealing with any other foreign state material.

9. During the course of your investigations, should you identify a potential conflict of interest between the CA and the Inquiry, you are to pause work and take advice from DG DSA. Following that advice it may be necessary to reconvene reporting directly to MOD PUS.

ADDENDUM ONE TO THE CONVENING ORDER

Defence Safety Authority

Service Inquiry Convening Order

22 Feb 16

SI President
Hd Defence AIB

DSA Legad
DSA Legad 1

Copy to:

SI Members

DSA DG/SI/06/15 – ADDENDUM ONE TO THE CONVENING ORDER FOR THE SERVICE INQUIRY INTO THE AIRCRAFT ACCIDENT INVOLVING WATCHKEEPER WK006 ON 02 NOV 15 AT BOSCOMBE DOWN AERODROME.

1. A Defence Safety Authority (DSA) safety-related Service Inquiry (SI) was convened on Mon 09 Nov 15 under Section 343 of Armed Forces Act 2006 and in accordance with JSP 832 – Guide To Service Inquiries (Issue 1.0 Oct 08). The purpose of the SI is to investigate the safety-related circumstances surrounding the subject aircraft accident and to make recommendations in order to prevent recurrence.

2. Due to personnel changes and competing demand for legal support within the DSA legal team, in order to maintain the appropriate level of legal advice to the SI Panel, with effect from 22 Feb 16 the legal advisor assigned to this SI is [redacted]

Original Signed

R F Garwood
AM
DG DSA – Convening Authority

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GLOSSARY

1ISR Bde	1st Intelligence, Surveillance and Reconnaissance Brigade
43 Bty	43 Battery Royal Artillery
47 RA	47 Regiment Royal Artillery
ADH	Aviation Duty Holder
ADS	Aircraft Document Set
ADU	Air Data Unit
AGL	Above Ground Level
AM	Amplitude modulated
AMSL	Above Mean Sea Level
AO	Authorising Officer
AOA	Angle of Attack
AOS	Angle of Slip
APCM	Aircraft Post Crash Management
ASC	Air Safety Culture
ASMS	Air Safety Management System
ASRA	Air Safety Risk Assessment
ASSWG	Air System Safety Working Group
ATC	Air Traffic Control
ATOL	Automatic Take-off and Landing
ATOLS	Automatic Take-off and Landing System
ATZ	Air Traffic Zone
AUM	All up Mass
Auth Sheet	Authorisation Sheet
AVGAS	Aviation Gasoline
BDN	MoD Boscombe Down
BF	Before Flight
Bty Cdr	Battery Commander
C of G	Centre of Gravity
C to I	Competent to Instruct
CAS	Calculated Airspeed
CDCS	Capability Directorate Combat Support, now called Capability Combat Support
CP	Connect Point (also referred to as Connect Waypoint)
CQT	Certificate of Qualification on Type
CS	Client Server
Cs of C	Certificates of Competence
CTT	Conversion to Type Training
DA	Design Authority
DDH	Delivery Duty Holder
DE&S	Defence Equipment and Support
Defence AIB	Defence Accident Investigation Branch
DROPS	Demountable Rack Off-load and Pickup System
EAT	External Air Temperature
EOP	Electro-Optic Payload
EOP/IR	Electro-Optic Payload/Infrared
ERL	Emergency Recovery Point
ESL	Elbit Systems Limited

FAP	Final Approach Point
FCS	Flight Control Software
FLIR	Forward Looking Infrared
FLRC	Flight Line Reference Cards
FLSCU	Flight Line Section Control Unit
FM	Frequency Modulated
FMCW	Frequency Modulated Continuous Wave
FMV	Full Motion Video
FOB	Flying Order Book
FRC	Flight Reference Cards
FRF	Flying Record Folder
FRS	Functional Requirements Specification
GAP	Go-Around Point
GBU	Ground Beacon Unit
GCS	Ground Control Station
GDT	Ground Data Terminal
GFCC	Ground Flight Control Computer
GMTI	Ground Moving Target Indication
GPS	Global Positioning System
GPS/INS	Global Positioning System /Inertial Navigation System
GRU	Ground Radar Unit
GT	Ground Touch
GTOL	GPS Take-off and landing
HCI	Human Computer Interface
IAS	Indicated Airspeed
IETP	Interactive Electronic Technical Publication
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
INS/GPS	Inertial Navigation System/Global Positioning System
ISA	Independent Safety Advisor
ISTAR	Intelligence, Surveillance, Target Acquisition and Reconnaissance
JARTS	Joint Aircraft Recovery and Transportation Squadron
JHC	Joint Helicopter Command
L&R	Launch and Recovery Detachment
LLP	Lost Link Procedure
LMAR	Lightweight Multimode Air Radio
LRDC	Launch and Recovery Detachment Commander
LRU	Line Replacement Unit
LSS	Land Site Survey
LS-S	Laser Sub-System
LTDRF	Laser Target Designator and Range Finder
MAA	Military Aviation Authority
MARC	Military Airworthiness Review Certificate
Met	Meteorology
MFTP	Military Flight Test Permit
MO	Master Override
NAS	Naval Air Squadron
NBLD	Narrow Band Data Link
ODH	Operating Duty Holder

OCU	Operational Conversion Unit
Panel	The Service Inquiry Panel convened to investigate the loss of WK006
PATE	Portable Aircraft Test Equipment
PCDU	Power Control Distribution Unit
PCM	Post-Crash Management
PCMO	Prime Contractor Management Organisation
Pilot	The Handling Pilot of the Unmanned Aircraft
PO	Payload Operator
RPM	Rotations per Minute
RSA	Royal School of Artillery
RtS	Release to Service
RVT	Remote Viewing Terminal
RVTIU	Remote Viewing Terminal Interface Unit
RWY	Runway
SA	Safety Advice
SAR	Synthetic Aperture Radar
SATCO	Senior Air Traffic Control Officer
SI	Service Inquiry
SMA	Safety Management Arrangements
SOP	Standard Operating Procedure
SPTA	Salisbury Plain Training Area
SQEP	Suitably Qualified and Experienced Personnel
SRO	Senior Responsible Owner
TAA	Type Airworthiness Authority
TAF	Terminal Aerodrome Forecast
TAS	True Air Speed
TD	Touchdown Point
TOL site	Take-off and landing site
TRF	Training Record Folder
TUAS	Tactical Unmanned Air System
UA	Unmanned Aircraft (formerly referred to as UAV)
UAS	Unmanned Air System
UAST	Unmanned Air Systems Team
UAV	Unmanned Air Vehicle (now referred to as UA)
UR	Under-run Point/Area
UTacS	UAV Tactical System Ltd
V/UHF	Very/Ultra High Frequency
VHF	Very High Frequency
VMS	Vehicle Management System
VMSC	Vehicle Management System Computer
WBDL	Wide Band Data Link
WK	Watchkeeper
WoW	Weight on Wheels
WTS	Watchkeeper Training School
WWA	West Wales Airport

WATCHKEEPER SYSTEM DESCRIPTION

Introduction

1. The following paragraphs have been written to provide background information on the Watchkeeper (WK) system in order to assist the reader in understanding the technical content of this Service Inquiry (SI) report. With this aim in mind, after a brief system overview, emphasis is placed on describing the landing phase of flight, abort conditions and overrides. The information provided represents the SI Panel's understanding of the system and is based on a documentation review with the support of the DE&S Unmanned Air Systems Team (UAST), the WK Training School (WTS), the WK031 SI Panel President and Defence Accident Investigation Branch (AIB) investigators[1] and various Design Approved Organisation Scheme (DAOS) approved organisations associated with WK.

System Overview

2. WK is an Unmanned Air System (UAS) which provides a network enabled Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) capability. The WK UAS consists of a number of separate system components and support equipment that enable Unmanned Aircraft (UA) pre-flight preparation, launch, operation and recovery, controlled from a Ground Control Station (GCS). There are also associated ground elements to enable transportation, storage and maintenance. The major UAS components can be broken down as follows:

a. GCS.

b. Ground Data Terminal (GDT).

c. Automatic Take-Off and Landing System (ATOLS) comprising of:

(1) Ground Beacon Unit (GBU).

(2) Ground Radar Unit (GRU).

(3) Airborne Beacon Unit (ABU).

d. Arrestor System.

e. Portable Aircraft Test Equipment (PATE).

f. UA.

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[1] Some of the text and photographs in the following paragraphs is taken from the WK031 Service Inquiry report and other MOD sources without further acknowledgement.

Figure 1 – Watchkeeper UA external features

3. **UA**. The UA is the airborne element of the Watchkeeper ISTAR capability. Externally it comprises a cylindrical fuselage, main wing, V-Tails, rear-mounted engine and propeller, a tricycle undercarriage and an Electro-Optic Payload (EOP) and a Radar Payload, as shown in Figure 1. The UA has a length of 6.50m, a wingspan of 10.95m and an overall height of 2.18m and a maximum all up mass of 500kg. Further details of the UA are as follows:

a. **Fuselage**. The fuselage is a carbon composite monocoque design. The majority of the avionic components are packaged inside the fuselage, with the payloads, undercarriage and antennae protruding outside.

b. **Undercarriage**. The UA has a non-retractable tricycle undercarriage and is able to take-off and land on paved and semi-prepared airstrips. It has a steerable nose landing gear assembly. There are no wheel brakes; on landing, the UA is halted by a fixed arrestor hook system.

c. **Propulsion, fuel, lubrication and cooling system**. The UA is powered by a Wankel rotary engine, produced by UAV Engines Ltd in the UK, which runs on aviation gasoline (AVGAS) and drives a pusher type propeller. The fuel system comprises an integral fuel tank and collector tank designed to ensure that the engine will not run dry at low fuel levels or whilst manoeuvring. The engine is water cooled and has a total loss oil system, using Mobil Pegasus 1 oil, which is indirectly heated by the coolant system.

d. **Vehicle Management System (VMS)**. The VMS is an all-encompassing term used to describe the essential electronic installations within the UA and the associated top level tasks it carries out. It is an amalgamation of Line Replacement Units (LRUs) designed to fully prioritise and task the semi-autonomous UA in providing monitoring and control, automated flight, instrument / sensor feedback and navigation throughout all phases of flight. The VMS is controlled directly by software within the Vehicle Management System Computer (VMSC), which is mounted in the forward section of the fuselage. The VMS has full authoritative control of the UA flying controls, utilising information derived from the UA navigation instrumentation and sensors. The operators in the GCS, therefore, only have indirect control of the flight controls via commands sent to the UA. The VMS monitors and controls the various systems on the UA where real time information is relayed via the data links to the GCS for display on the client server Human Computer Interface (HCI).

e. **VMSC**. The VMSC is a single Line Replaceable Unit (LRU); it houses dual redundant computers primarily responsible for controlling the VMS. An in-built VMS monitor compares the health status of the two computers (Side A and B) and will determine which side to utilise, with Side A having primacy in normal operation. The VMSC is a software based system, which interfaces with other LRUs in the VMS to monitor and control the UA. A simplified diagram of VMSC interfaces is shown in Figure 2. The VMSC responds to the pre-programmed flight mission plan and reacts dynamically to real time commands received from the GCS via the data links. It is designed to automate routine tasks, through all phases of flight from Engine Start to Engine cut, including Automated Take Off and Landing.

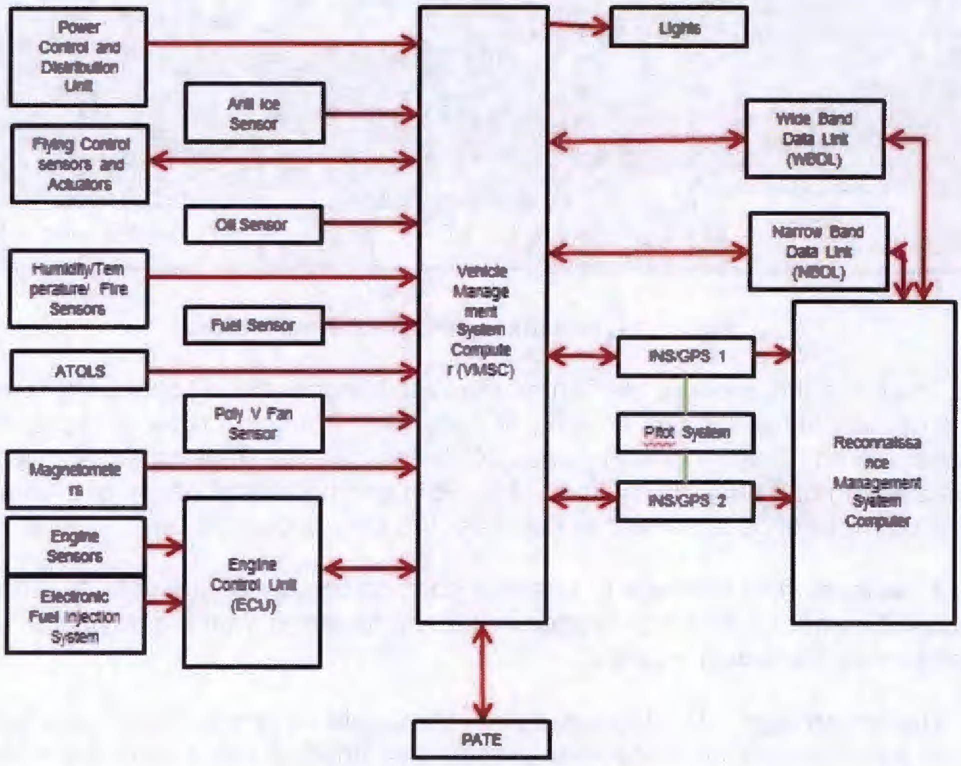

Figure 2 – VMSC interfaces (simplified)

f. **VMSC Software**. The software within the VMSC is programmed to control power switching, redundancy, failure management and status monitoring for all LRUs. Its primary role is to calculate all changes in atmospherics and aerodynamics to maintain the UA in a safe and controlled flight attitude by applying the correct control surface error corrections. The VMSC contains all of the logic 'state machines', algorithms and coding designed to calculate flight paths, loiters, take-offs and landings, glide slopes and predicted landing points and utilises the integral Flight Control Software (FCS) to achieve this. The VMSC software is designated as Software Integrity Level (SIL) 3.

g. **Control**. The flight control surfaces include ailerons and flaps, installed in the main wing and moving V-Tails that serve as a combined rudder and elevator. All flight control surfaces are moved by dual electrically redundant single linkage electro-mechanical actuators located in the wings and rear fuselage, under the control of the VMSC; this forms a closed loop positional feedback control system. The nose landing gear steering system and engine throttle controls are also electrically dual-redundant. The FCS within the VMSC maintains the UA flight within a pre-designated operational envelope providing a safety margin against structural and flight limitations. In normal flight the VMSC FCS is programmed to protect against operation outside of the flight envelope design limitations.

h. **Communications systems and datalinks**. The UA can utilise the following communication systems and datalinks:

(1) **Lightweight Multiband Airborne Radio (LMAR)**. The LMAR is a VHF/UHF rebroadcast station that allows the UAS to communicate with external entities[2] from the UA itself.

(2) **Wide-Band Data Link (WBDL)**. The WBDL is a Ku Band datalink providing the primary means of communication between the GCS and the UA. It is used to transmit and receive command/control and status data and Full Motion Video (FMV). It can also be used to pass voice and data between ground elements of the system and the UA and external systems (via the LMAR). The WBDL is used to provide positional information to the UA during take-off and landing from the ATOLS system.

(3) **Narrow-Band Data Link (NBDL)**. The NBDL is an S-band data link, which provides a secondary means of command and control of the UA from the GCS (via the GDT and ADT). It also provides positional information to the UA during take-off and landing from the ATOLS system. The NBDL can also be used for distributing imagery from the GCS to Tac Parties[3].

(4) **Remote viewing terminal interface unit (RVTIU)**. The UA can transmit data directly to a RVTIU, which is a portable device for viewing imagery from the UA designed to give situational awareness to an operational unit.

(5) **Identify Friend of Foe (IFF)**. The UA is fitted with a Mk XII Mode 4 IFF transponder. It is controlled and monitored within the GCS.

i. **Navigation systems and sensors**. The main navigation systems and sensors are:

(1) **Inertial Navigation System and Global Positioning System (INS/GPS)**. The UA is fitted with 2 dual redundant Athena GS-411 integrated INS/GPS units manufactured by Rockwell Collins in the USA. In the event of dual INS/GPS failure (or GPS denial) the UA calculates its position by range and azimuth data from the data link. In the event of both GPS and data link failure the UA reverts to 'dead reckoning' based on the last known good position using the INS. These modules integrate solid-state gyros and accelerometers, magnetometer, GPS receiver and the air data sensors to provide the VMSC with data such as position, heading, attitude, airspeed, velocity, accelerations, angular rates and rate of climb.

(2) **Pitot systems**. There are 2 dual redundant pitot systems fitted to the UA; a Kollsman pitot probe and a Space Age pitot probe (shown in Figure 3). Both supply static and total pressure to each Athena unit, which feed dual redundant Air Data Units (ADU). Static and Total pressure measurements are then differenced to provide dynamic pressure which is used by the VMSC. Angle of Attack (AOA) and Angle of Slip (AOS) are supplied by the Kollsman pitot probe only.

[2] Non-Watchkeeper, such as Air Traffic Control (ATC), Attack Helicopter, Close Air Support. At the time of writing the Panel understand that in practice the crew communicate directly with ATC via a radio in the GCS.

[3] The datalink at the Tac Party operates in receive only mode. It is intended that the Tac Party will provide an interface between the supported HQ and the Watchkeeper system. The Tac party data link is not part of the OCU Build standard.

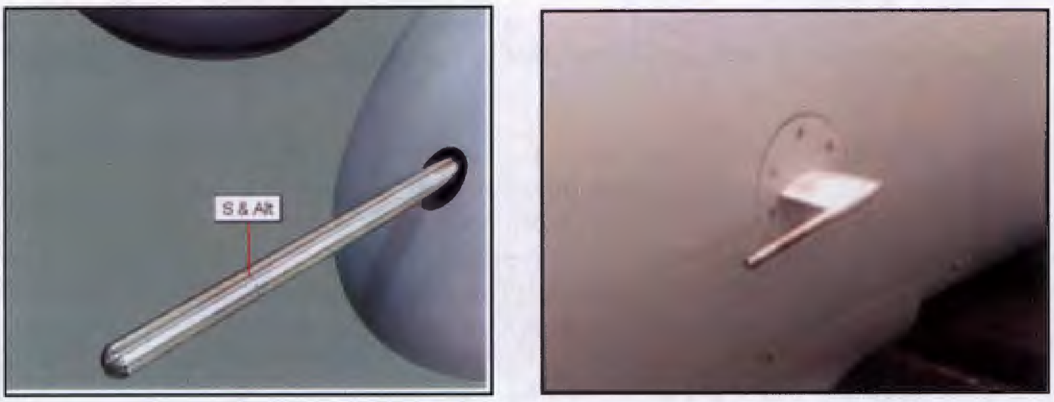

Figure 3 – Kollsman (left) and Space Age pitot probes.

(3) **Weight on Wheels (WoW) Systems**. There are 2 separate WoW systems in the UA. The first, hereinafter referred to as WoW1, is a pseudo WoW system[4] which determines whether the UA is *On-ground* or *In-air* by determining *Ground Touch* and *Air Jump* based on measured accelerations and rotation rate. The logic conditions used to determine *Ground Touch* and *Air Jump* are discussed in the findings of the of the SI (Part 1.4), however, in essence to sense a *Ground Touch*:

(a) The UA needs to be in an Automatic Take-Off and Landing (ATOL) *landing mode* and cannot be in *ATOL stand-by* mode, therefore it is assumed to have reached the *Connect Point* (see landing description below). WoW1 is reset to *In-air* if an ATOL landing is aborted for any reason.

(b) A *Ground Touch identification window* needs to be open. This time window is opened by a height measurement of less than 1m by the laser altimeters. Therefore, the UA should be within both a height and a time window in order to sense a *Ground Touch*.

(c) There needs to be a difference between pitch rate and vertical acceleration above a set threshold value. The rationale for this is that during a landing, positive 'g' momentarily increases when the main wheels touch the ground; at the same time a negative pitch rate is induced as the nose wheel comes down to touch the ground[5].

Once a *Ground Touch* has been sensed the WoW1 can either declare the UA to be in *Air Jump*, if vertical acceleration meets a set threshold, or on-ground. Once vertical acceleration meets a second threshold value for a period of time, *Air jump* ends and the UA is declared to be on the ground. A different set of WoW1 parameters are used to declare the UA airborne on take-off. There is also a mechanical, hereinafter referred to as WoW2, safety switch on the Nose Landing Gear which prevents inadvertent operation of the high powered Laser and transmission by the Radar Payload whilst the UA is on the ground. Of note, the WoW2 switch is not used by the VMSC to determine whether the UA is on the ground.

[4] It is understood that during the development of Watchkeeper, a prototype UA had a physical WoW device attached to the main landing gear to indicate ground contact. This was the same mechanical WoW switch that had been fitted to the Hermes 450 platform, the forerunner of Watchkeeper. Thales UK indicated that there had been some failures of the mechanical WoW system when fitted to the Hermes 450 UAV. Thales UK also highlighted that one of the operational requirements for the Watchkeeper design specification was that the UA needed to be able to operate from unprepared take-off and landing strips, which made it more likely for this particular design of mechanical WoW system to be damaged. It was this over-arching requirement which led Thales UK to favour the software based pseudo WoW algorithm embedded within the VMSC and remove the mechanical WoW system.

[5] A large positive acceleration coupled with a negative pitch rate is seldom encountered during normal flight conditions, however, of note, to sense a *Ground Touch*, vertical acceleration does not necessarily have to be positive provided pitch rate is sufficiently negative to meet the threshold difference between the 2 parameters.

(4) **Laser Altimeters**. The UA contains 2 laser altimeters situated just forward of the fuel tank under the fuselage. They are designed to supply accurate height measurements to the VMSC when the UA is close to the ground on landing. This additional accuracy ensures the UA lands smoothly and helps it to account for imperfections in landing strip elevation that the system would otherwise be unaware of. The laser altimeter readings are only used during recovery phase and are switched on and off automatically by the Power Control Distribution Unit (PCDU). It is understood by the Panel that they do not operate during any other part of normal flight.

(5) **Height reference**. Height reference is provided by:

(a) Barometric pressure supplied via the pitot system to the Athena units.

(b) GPS altitude provided by the Athena units.

(c) Altitude provided by the Ground Radar Unit within ATOLS.

(d) The laser altimeters.

During route flight conditions the UA uses barometric altitude as its primary height reference within the INS. Data from the GPS is then used to calibrate the INS positional solution due to its tendency to drift over time. During the landing phase ATOLS and laser altimeter height reference is used as described for a 'Normal Landing' in Paragraph 13 below.

j. **Payloads**. The UA can carry any combination of two of the following Payloads:

(1) **I-Master Radar**. Fitted to the forward payload bay, The I-Master Radar payload is an airborne surveillance radar, which can operate as a Synthetic Aperture Radar (SAR) or a Ground Moving Target Indicator (GMTI).

(2) **Electro-Optic Payload (EOP)**. One of the following EOPs can be fitted to the aft payload bay:

(a) EOP/IR. This system has optical and infrared capabilities including a solid state optical camera and an infrared camera.

(b) EOP/Laser Sub-System (LS-S). This system has optical and infrared capabilities, plus a Laser Target Designator and Range Finder (LTDRF) and laser pointer.

(3) **Dummy Payload**. A dummy payload can be fitted to either the forward or aft position and has the same shape and approximate mass of the above payloads.

4. **GCS**. The GCS is a 20ft long, specifically designed, ISO-type container used by the crew for planning missions, command and control of the UA and its sensor payloads during missions (Figure 4). Each GCS can accommodate a Pilot, a Payload Operator (PO), a Mission Commander (the Captain), a Signaller and an Image Analyst. The GCS is fitted for BOWMAN secure military tactical Communications (Comms). It also houses a V/UHF ground radio for direct Comms with Air Traffic Control (ATC). Ground crew outside the GCS generally use handheld VHF radios to communicate with the ATC tower and the GCS.

Figure 4 – GCS

6. **Ground Flight Control Computer (GFCC)**. All flight command instructions for the UA are processed by the GFCC, which checks the validity and Safety of commands including; terrain clearance, air-space compliance and glide ranges to Emergency Recovery Locations (ERLs). The design of the Dual Redundant GFCC components is judged to have the integrity properties and characteristics that will be commensurate with 00-55 SIL2[6]. The GFCC HCI consists of Dual Redundant Air Vehicle Display Components (AVDCs) through which all flight commands can be selected and Dual Redundant Hard Keys for Safety Critical Functions including ATOL Aborts, Engine Cut and Laser Arming. Although the GFCC forms part of the end-to-end Flight Control System, in the absence of an input from the GFCC, the UA is designed to follow an Emergency Lost Link Procedure (LLP) that would, if communication cannot be restored, ultimately result in the recovery of the UA to an appropriate ERL. The UA is protected from erroneous inputs from the GFCC as the UA's higher integrity VMSC will only accept valid commands from the GFCC.

7. **Ground Mission Control Computer (GMCC)**. The GMCC provides the monitoring and control function to the UA payloads and the data links. It also acts as a conduit for data flowing from the data links to the Client Server (CS) and for communication between the CS and the GFCC. The Operators interface directly with the GMCC through Dual Redundant Hard Keys and Joysticks, and indirectly through a keyboard, mouse and monitors.

8. **Client Server (CS)**. The CS provides the interface for operators and is used for mission planning. With the exception of take-off and landing commands and some safety-related functions, the UA is routinely commanded by the CS interface (the GFCC ensures operators commands are valid, prior to uploading to the UA). The mission monitoring function of the CS monitors and displays the UA status and can display the UA position, airspace and route information on a moving map, or imposed on satellite imagery.

9. **Ground Data Terminal (GDT).** The GDT is a collection of external ground equipment (Figure 5) which can be located up to 1 km from the GCS, connected by multi-core optical cable. It comprises antennae, control units and modems for both the Wide Band Data Link and Narrow Band Data Link. Both Data Links receive and transmit encrypted command, control and UA status data and the WBDL has the facility to relay imagery back to the GCS.

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[6] Safety Integrity level (SIL) is a quantified level of safety system performance, with SIL4 being the highest and SIL1 the lowest.

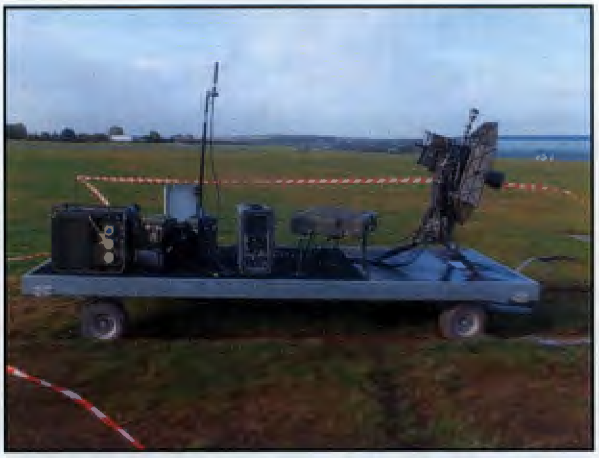

Figure 5 - GDT

10. **ATOLS**. ATOLS is a system which allows the UA to perform Automatic Take-Off and Landing (ATOL). It comprises a GRU and a GBU (Figure 6) next to the runway at accurately surveyed points and an ABU in the UA itself. Based on initial position data passed from the GCS, it tracks the position of the UA and provides steering information to the vehicle via the GCS and datalinks using the GBU as a surveyed reference to enable accurate target positioning. In the event of a failure or malfunction of the ATOLS, the UA can still perform an ATOL using the GPS Take-Off and Landing System (GTOLS). The VMSC will select the more accurate of ATOLS or GTOLS during the landing phase. Therefore, the Watchkeeper UAS can perform an ATOL using either ATOLS or GTOLS.

Figure 6 – ATOLS ground components. GBU (left) and GRU (right)

11. **Arrestor System**. The arrestor system is used to bring the UA to a smooth stop following a landing or aborted take-off. The arresting hook on the UA catches the arresting cable laid across the runway. Adjustable braking drums hold the cable taught and provide tension and hence a braking force when the UA 'takes the cable'.

12. **PATE**. The PATE is normally housed within the Flight Line Support Control Unit, a modified Pinzgauer vehicle (Figure 7) that is also used to tow the UA during airfield /strip operations. The PATE performs:

a. UA functional system tests.

b. Pre-flight checks.

c. Engine start.

d. Data upload/ download.

e. Support to fault diagnostics to Line Replaceable Unit (LRU) level including payloads.

Figure 7 – PATE in a Pinzgauer vehicle

Normal approach and landing

13. **Normal ATOL approach**. The WK VMSC Flight Control Software automatically prioritizes aircraft attitude, speed, height and bearing depending on which phase of flight it is in. These phases are programmed and switched according to the pre-programmed flight plan based on pre-surveyed geographic points, specific heights and actions commanded by the operator. Only the downwind phase through the *Connect Point* (CP) and beyond as part of the landing sequence is discussed. The key phases of a 'normal' landing are described below and should be read with reference to Figure 8. Of note, these points remain the same whether the UA is carrying out an ATOLS or a GTOLS landing; the only difference being which sensor is providing UA height and position information to the VMSC.

a. **Downwind leg**. During this phase, the UA prioritizes True Air Speed (TAS). The VMSC Flight Control Software will attempt to maintain a stable TAS of 65kts by controlling engine throttle commands. Height is determined through pitot and static sensors and adjusted by altering the relevant control surfaces. Barometric pressure is used for height and the magnetometers for bearing. INS/GPS is cross referenced for location purposes. During this phase of flight the ATOL state is in *Standby*.

b. **Connect Point (CP)**. The CP represents the beginning of the landing phase and is the last waypoint in the recovery route. As part of the planning process, operators can design and manipulate the recovery circuit to plan the location of the last waypoint and therefore the CP. The CP has to be a distance equal or greater than 500 metres slant range from the *Final Approach Point* (FAP), described below. Once the UA has declared it has reached the CP, it will command flaps down to allow the TAS to reduce to approximately 55kts and both laser altimeters are energised and tested. The GPS World Geodetic System (WGS84) is used for height reference from the CP. The ATOL state changes to 'Intercept' and the UA corrects its height, if required, to attain a 3 deg GS. Once the UA is within 3 deg GS limits, the ATOL state will change to *Approach*. If ATOLS is available[7] the GRU will attempt to acquire the

[7] ATOLS is a Minimum Equipment List (MEL) requirement to get airborne, but it is possible for ATOLS to become unserviceable during a sortie, in which case it is accepted practice to land without ATOLS.

ABU. Once ATOLS has acquired and locked, it will provide azimuth and elevation steering data to align the UA on the correct landing approach path.

c. **FAP**. The FAP is a point in space determined by the system to be at least 1200m from the *Touchdown* point on runway centre-line and on a 3 deg GS to the semi-flare point (see below). At the FAP, the approach is prioritised and flight envelope protection is disabled; the UA control priority switches to establish and maintain a 3 deg GS through a combination of engine speed and control surface adjustments. If the UA departs horizontal or vertical approach limits, the landing will be automatically aborted.

d. **Underrun (UR)**. The UR point is positioned between 500m and 2000m from the TD point. The UR area starts at the UR point and ends at Threshold 1 (TH1). Once the UR point is reached and valid laser altimeter data is available, the VMSC applies a one-off bias correction to correct any GPS height error, for a GTOLS landing and to account for real life differences between the calculated and actual surface height. If both laser altimeter heights are within defined limits, then a mean of the two will be used, otherwise it will use only the valid laser altimeter reading. The VMSC continues to prioritise a 3 deg GS and calculates a landing point to confirm the UA will land in the vicinity of its operator pre-programmed TD point.

e. **At 7m Height – Semi-flare point**. At 7m (corrected height) above the runway, the ATOL state changes to *Semi-flare* and a *Semi-flare* is commanded by the VMSC to reduce the GS to 1.5 deg. The *Semi-flare* is followed immediately by a *De-Crab* manoeuvre to align the UA with the runway heading.

f. **At 1m Height AGL – Ground Touch Window**. At 1m above the runway the VMSC software will open the *Ground Touch identification window*, thereby activating the WoW1 logic to sense a *Ground Touch*.

g. **Post Ground Touch declaration**. Once *Ground Touch* has been sensed, the VMSC looks for *Air Jump* before declaring G*round Touch* equals *Ground* and setting WoW1 to *On-ground*. If *Air Jump* is declared, the *Semi-flare* and *De-crab* will be repeated before the UA touches down again. If the *Air Jump* vertical velocity is too great, the UA will abort the landing. Once the *On-ground* state of the UA has been established, the ATOL state changes to *Ground Contact* and the UA will move its v-tails to pitch the nose down to put positive traction on the nose wheel for steering. The engine is then commanded to idle and the ATOL state changes to *Free roll* after a 1 second pause. The WoW2 switch is mechanically activated, which isolates the EOP, SAR and Laser Altimeters.

h. **Arrestor Cable engagement**. The UA is captured by the arrestor cable and the VMSC declares a *Cable Stop* condition, using aircraft velocity as a trigger. If the UA passes Threshold 2 (TH2) by 100m, a *cable overrun* is declared after 2 seconds.

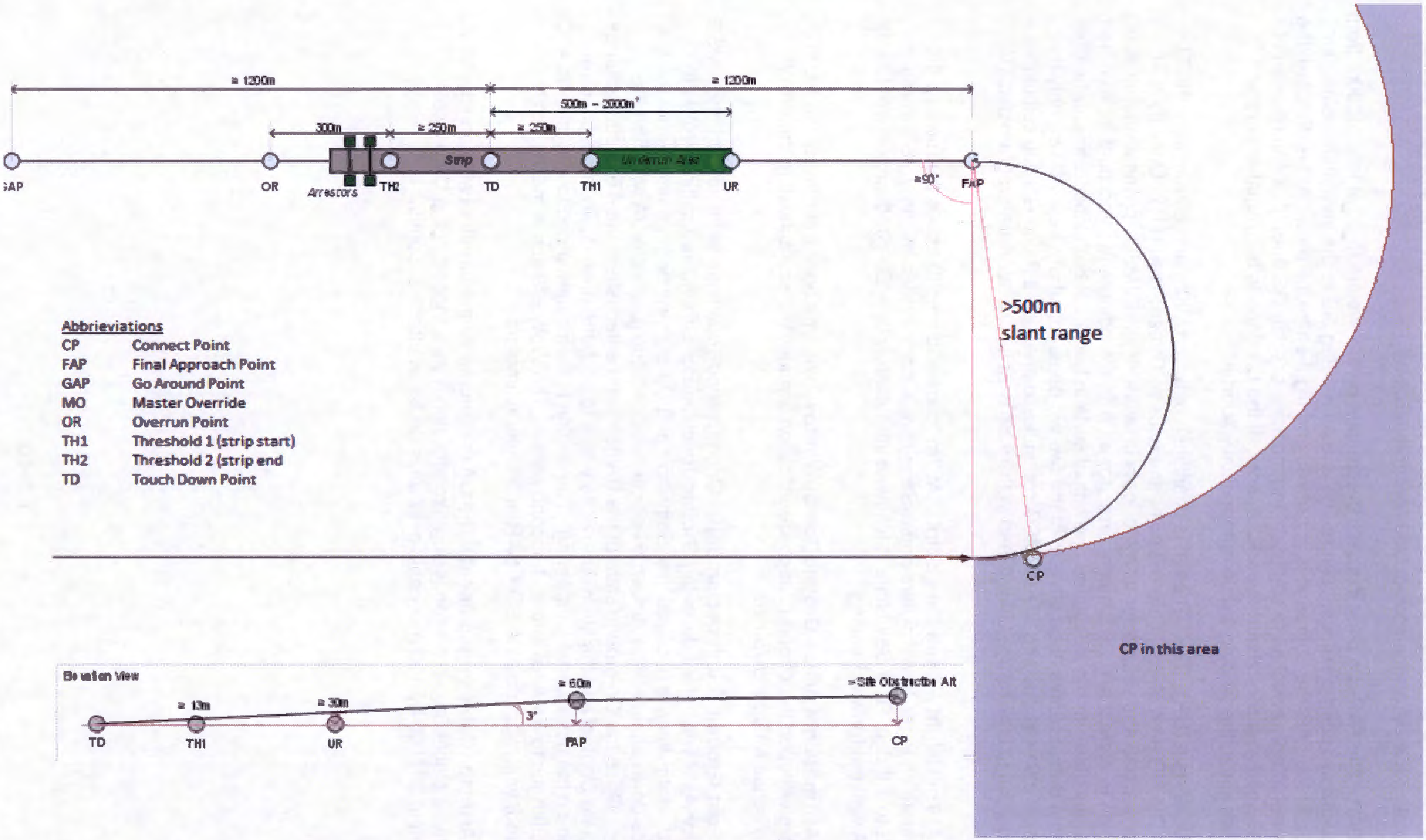

Figure 8 – ATOL Landing points.

ATOL aborts and overrides

14. During a normal approach, the VMSC will monitor a variety of flight parameters and will abort the landing if one or more of these goes out of limits, or if specific failures occur in the system. It is also possible for the crew to abort an approach manually, by pressing *ATOL_ABORT*.

15. If the ATOL abort is received before the CP, the UA will continue to fly the current route. If the ATOL abort is received when the UA is between the CP and the *Free roll* stage, the VMSC will change the flight mode to *Take-off*. The VMSC will perform the *Take-off* using the programmed landing site and route the UA to a *Go Around Point* (GAP). Subsequently, the operator within the GCS will be informed of the reason for the system abort in order to determine whether to re-fly the approach or if it may be appropriate to consider applying a system override for subsequent approaches. After the Free Roll stage the VMSC will continue with the landing roll until the UA has been stopped by the arrestor cable.

16. **Specific overrides.** It is possible for the crew to pre-emptively override a number of potential aborts using ATOL overrides. ATOL overrides only affect UA behaviour during the take-off and landing phases of flight and have no effect in any other phase of flight. They are set prior to recovery and allow the approach to continue when a parameter has been exceeded, hence potentially removing layers of safety. They are, however, designed to assist in landing the UA when conditions are sub-optimal and it is not possible to land without overriding the abort condition or where an emergency failure or condition exists. If a specific override is selected but conditions are such that the landing would otherwise have been aborted, the ATOL Landing Aborted message will be displayed to the crew, but the UA will continue with the landing. A list of ATOL abort causes and potential overrides is at Table 1.

ATOL Abort Cause	Description	Specific ATOL override
INS/GPS HOR Inaccuracy	VMSC detects INS/GPS horizontal accuracy outside allowed limits.	INS/GPS Horizontal
INS/GPS VER Inaccuracy	VMSC detects INS/GPS vertical accuracy outside allowed limits.	INS/GPS Vertical
Envelope Vertical	UA vertical position relative to glideslope outside allowed limits. Active during approach and semi-flare at ranges less than 1200m from the TD point (ie after the FAP).	Ground Proximity*
Envelope Horizontal	UA lateral position outside allowed limits. Active during approach at ranges less than 1200m from the TD point (ie after the FAP).	Lateral Deviation
Envelope Ground Proximity	VMSC detects UA too close to the ground between CP and UR.	Altitude Deviation*
No Comm	VMSC declares no communication with the GCS. UA will follow lost link logic after ATOL abort.	No Comm
Altimeter Fail	Failure of one laser altimeter or difference between them out of allowed limits. Operator can select one or other altimeter to override.	Altitude Difference
ATOLS Horizontal Inaccuracy	ATOLS ground radar horizontal (lat/lon) accuracy reported by GCS is out of allowed limits.	Radar Horizontal
ATOLS Vertical Inaccuracy	ATOLS radar vertical accuracy reported by GCS is out of allowed limits.	Radar Vertical
ATOLS Comm Rate	ATOLS ground radar data rate outside allowed limits.	Radar Data

ATOLS Comm Validity	ATOLS ground radar data invalid.	Radar Data
Faulty AB	ABU failure detected by VMSC.	Air Beacon
INS/GPS Fail	VMSC detects failure of GPS/INS.	None Landing at TOL site not advised in the event of a total loss of GPS
VMSC CPU Transition	VMSC Central Processing Unit (CPU) transition (side A to side B or vice versa).	None
Engine Cut	Engine failure detected by VMSC.	None UA will follow engine cut logic
Jump Vertical Velocity	Following first Ground Touch, the UA has bounced (experienced JUMP) with a vertical velocity higher than allowed limits.	None
Envelope Protection during Approach	Envelope protection manoeuvre has occurred. Active in approach mode prior to reaching the FAP.	None
Velocity Deviation during Approach	Instrumented Air Speed (IAS) is outside of allowed range. V_{stall} +5 < IAS < 1.6 V_{stall}. This can be cause by the UA picking up too much speed in descent to intercept glideslope after reaching the CP.	None. It may be possible to reduce the possibility of a velocity deviation abort by reducing height of the recovery route
Altimeter/WGS84 Contradiction	VMSC detects a contradiction between laser altimeter readings and WGS84 altitude during semi-flare.	None
Ground Touch Identification Timeout	ATOL state has not progressed to *Free roll* within the *Ground Touch identification time window.*	None
Operator Abort	UAV Operator has pressed ATOL Abort.	None

*It is a known problem that, ATOL Ground Proximity override and ATOL Altitude Deviation override are swapped.

Table 1 – ATOL abort causes and overrides[8].

17. **Master Override (MO)**. It is also possible to apply the MO to override all abort causes. When MO is applied, the system will continue with the approach and attempt to land regardless of any abort conditions that it may encounter, with the exception of an operator abort (manual abort). Use of MO is recommended to ensure that the UA lands where a 'go-around' would potentially result in increased risk to life[9]. MO does not change when the *Ground Touch identification time window* opens (at 1 m above the runway), unless after the UR the VMSC detects a laser altimeter fault, failure or height difference, in which case the *Ground Touch identification window* opens at 20m above the runway and both laser altimeters are disqualified. The increased height window takes into account a possible GPS height error in the event of a GTOLS landing.

[8] Table adapted from Watchkeeper TUAV System DAP: 101B-7900-1A Issue 8 Interactive Electronic Technical Publication, Document Reference WATCHKEEP0Mk1-ABA-DTF-22-50-1000-043A_001.

[9] Thales Presentation, WK031 Incident Use of Master Override, 26 Mar 15, presented at the WK031 Incident Post Safety Notice Action Meeting Held at Abbey Wood on 26 Mar 15 chaired by the DE&S Unmanned Air Systems Team TAA.

PART 1.3 – NARRATIVE OF EVENTS

All times ZULU.

Synopsis

1.3.1. At 1550 hrs on 2 Nov 15, a Watchkeeper (WK) Mk1Unmanned Aircraft (UA), registered as WK006 and operated by the Army, crashed on final approach to Runway 17 West at MoD Boscombe Down (BDN). Exhibit 1

1.3.2. Following 2 aborted landing attempts, on the third attempt at 23ft Above Ground Level[1](AGL), the UA pitched nose down, resulting in it impacting the ground at approximately 35-deg nose down, on the centreline, just over 100 metres short of the planned touchdown point. The UA nose and main undercarriage collapsed and the UA slid along the runway for approximately 120m before coming to rest just off the western side of the runway, as shown below in Figure 1. There was no post-crash fire or any injuries sustained to personnel. Exhibit 1 Exhibit 2

Figure 1 – WK006 Wreckage

Background

WK Programme

1.3.3. **WK Capability Overivew**. WK is a system of unmanned air vehicles, sensors, data links and ground control stations. The aim of WK is to deliver a flexible, 24-hour, all-weather Intelligence, Surveillance, Target Acquisition and Reconnaisance (ISTAR) capability. WK is employed primarily within the Land environment and contributes to Information Superiority. Exhibit 3

1.3.4. **WK Procurement Overview**. In 2005, Thales UK was awarded the contract for the development, manufacture and initial support phases of the WK programme. The system was originally intended to reach Initial Operating Capability by Jun 2010 and Full Operating Capability in 2013. However, the programme was delayed, partly due to more stringent software certification requirements than anticipated, the rectification of a small number of safety-critical deficiencies in the system's technical publications, and errors in the Exhibit 3

[1] During this report, for ease of reference, the Impact Point has been assumed as zero ft AGL.

training courseware. In Sep 13, the Military Aviation Authority (MAA) provided a Statement of Type Design Assurance for WK, confirming its airworthiness.

1.3.5. **WK Programme Organisation**. Thales UK are the Prime Contractor Management Organisation (PCMO) and Design Authority (DA) for the WK system. As PCMO, Thales UK leads an industry team consisting of Cubic Corporation (datalinks), Elbit Systems Limited (ESL) (UA air vehicles), Marshall SV (ground station shelters and ground vehicles), Praxis (programme safety), UAV Engines Ltd (UA engines) and Vega (training). UAV Tactical Systems Ltd (UTacS) is a joint venture company that was created by Thales UK and ESL to manufacture the WK system in the UK and provide crews for WK air operations at West Wales Airport (WWA).

1.3.6. **WK Military Flying**. The WK platform was issued with its initial Release to Service (RtS) on 28 Feb 14 and flying operations commenced at BDN shortly thereafter. In Aug 14, WK deployed to Afghanistan under Op HERRICK. Whilst the Army was flying WK from Afghanistan, Thales UK continued to conduct test flying at WWA. On 16 Oct 14, WK031 crashed whilst making an approach to land at WWA. The Army re-commenced WK flying operations from BDN on 18 Mar 15 and WK flying continued from BDN until 2 Nov 15, with only one brief pause Aug to Sep 15. Exhibit 4

WK Army Organisational Structure

1.3.7. **WK Programme Delivery, including training**. Programme delivery and the provision of WK Instructors, was the responsibility of the Capability Combat Support (Cap CS). The WK Senior Responsible Owner (SRO) was the Head of Cap CS[2]. At the time of the accident, Cap CS maintained ownership of the 'Development Course' personnel, a small group of individuals who were on an accelerated path to become qualified WK operators, Captains and Instructors. They would form the instructional cadre for the delivery of WK Pilots Course One, due to commence in Jan 16. With the introduction of Course One, responsibility for initial WK Pilot training would migrate from Cap CS to the Royal School of Artillery (RSA). Witness 12

1.3.8. **WK Operations Organisation and Aviation Duty Holder Chain**. Army flying at BDN was conducted by the Royal Artillery (RA). 43 Bty, sitting within 47 Regt, RA, provided the physical environment and support structure for flying to be undertaken. Engineering and other support functions and personnel were provided by 74 Bty, sitting within 1 ISR Bde. 1 ISR Bde provided the support for 43 Bty and also provided the Delivery Duty Holder (DDH) and his Safety team. The Operating Duty Holder (ODH) was the Commander of Joint Helicopter Command (JHC). Figure 2 shows an overview of the Army WK flying organisation.

[2] The WK programme was a Government Major Project, and as such a SRO was appointed. He was personally responsible to the Army Top Level Budget Holder and Parliamentary Select Committees for the delivery of the WK programme.

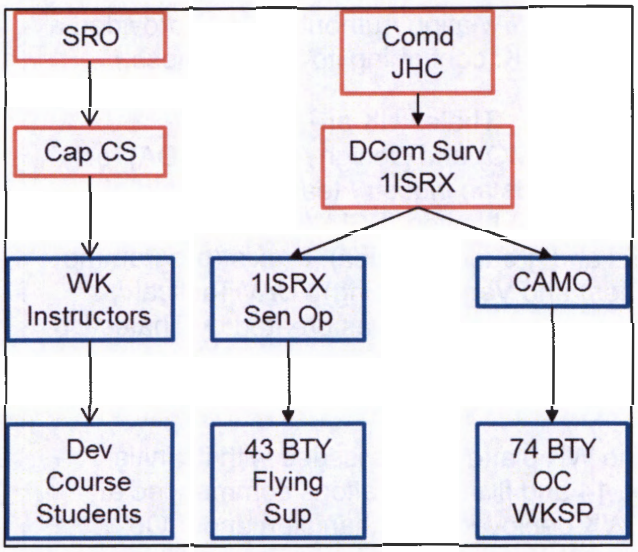

Figure 2 - Overview of Army WK Flying Organisation

1.3.9. **Hierarchy of WK Rules and Regulations**. The 1ISR Bde Flying Order Book (FOB) defined the hierarchy of orders pertaining to Army WK operations. The 1SR Bde FOB and associated orders and policies, were released by the DDH and were subordinate to the MAA's Military Aviation Regulatory Publications and Comd JHC's Flying Orders and Command Instructions, released by the ODH. Exhibit 5

Captain

1.3.10. **Background and previous UA experience**. The UA Captain joined the Army in 1998, and had served within the Royal Artillery in non-aviation related roles for approximately 7 years. The Captain had been involved in the Army Unmanned aviation environment for 10 years, and had been qualified on numerous types. Exhibit 8 Exhibit 9

1.3.11. **WK experience**. The Captain had converted onto WK during 2011 and 2012 and was part of the initial Army cohort of WK operators who converted onto WK at WWA. Operating WK for 4 years, the Captain was also a WK Instructor and had a total of 92 hrs live flying on WK, split over 39 sorties and a further 141 hrs of simulated flying split between the Hybrid Facility in Leicester and the Emergency Procedural Trainer at Larkhill camp. He had operated WK on its inaugural operational deployment to Afghanistan. Witness 1 Exhibit 9

1.3.12. **Monthly Flying Hrs**. The Captain flew a total of 17 hrs live flying in the month prior to the accident. Exhibit 8

Pilot

1.3.13. **Background and previous UA experience**. The Pilot had spent the first 10 years of his Army career within the RA in non-aviation roles. He was selected for Army aircrew training and had approximately 178 hours of manned aviation experience before transferring to Unmanned Air Systems. The Pilot was qualified to operate the Desert Hawk 3 prior to transferring to the WK programme in 2014. Witness 4 Exhibit 10

1.3.14. **WK experience**. The Pilot was selected to be a participant of the WK Development Course (Dev Cse), which began in Jun 14. He completed the course on 13 Oct 15. He had completed a total of 48 hrs live flying over 17 sorties on type, between 22 Jan 15 and the accident. He had a further 78 hrs of simulated flying over 24 sorties, split between the Hybrid facility and the Full Task trainer at Larkhill. The sortie on 2 Nov 15 was his first sortie post completion of the Dev Cse.	Exhibit 11
1.3.15. **Monthly Flying Hrs**. The Pilot flew a total of 21 hrs live flying in the month prior to the accident.	Exhibit 10
Payload Operator	
1.3.16. **Background and previous UA experience**. The Payload Operator (PO) joined the Army in 1995, and had served within the RA in non-aviation related roles for approximately 9 years. He operated a number of unmanned aircraft over an 11 year period, prior to converting to WK.	Witness 3 Exhibit 12 Exhibit 6
1.3.17. **WK experience**. The PO was also a participant of the Dev Course, which he completed on 14 Oct 15. He had completed a total of 47 hrs live flying over 16 sorties on type, between 21 Jan 15 and the accident. He logged a further 85 hrs of simulated flying over 27 sorties, split between the Hybrid facility and the Full Task trainer at Larkhill. The sortie on 2 Nov 15 was his first sortie post completion of the Dev Cse.	Exhibit 12
1.3.18. **Monthly Flying Hrs**. The PO had flown a total of 18 hrs live flying in the month prior to the accident.	Exhibit 12
Authorising Officer	
1.3.19. **Background and previous UA experience**. The Authorising Officer (AO) was a civilian contractor, who had previously served in the Army. The AO operated the Phoenix system in 2007, before converting onto the Hermes 450 platform (Aug 2007). He had accrued 461 hrs as a Hermes 450 operator. Since leaving the Army in 2008, the AO had been working for UTacS.	Exhibit 13 Exhibit 14
1.3.20. **WK experience**. The AO has been involved in the WK programme since 2009. He had completed a total of 435 hrs live flying on WK, of which 200 hrs were acting as the Aircraft Captain.	Exhibit 14
Other information	
1.3.21. **WK006 Crew Configuration/Seating Positions.** WK is operated by a Pilot and a PO as shown in Figure 3. The Pilot is principally concerned with the safe operation of the UA, whilst the PO is employed manipulating the sensors, in addition to assisting the Pilot as required. Qualification on type is a single qualification; therefore a qualified WK Pilot can either operate the Pilot or PO position. On 2 Nov 15, the Pilot was in the left hand seat and the PO was in the right. The Captain was the third crew member, who was positioned behind the operating crew in the Ground Control Station (GCS).	Witness 4

Figure 3 - Photograph of WK GCS operating position.

1.3.22. **History of WK006**. WK006 was awarded its Military Airworthiness Review Certificate (MARC) on 26 Mar 15. The UA had flown 81hrs 57 minutes prior to the flight on 2 Nov 15. Exhibit 15

1.3.23. **Pre-Flight Maintenance**. Flight Servicing was commenced at 0700hrs on 2 Nov 15 and WK006 was recorded as having a fuel load of approximately 79.1kg, equating to approximately 14hrs endurance[3]. It had 2 operational payloads fitted; an I Master fitted in the forward payload section and an Electro-Optical Payload (EOP) in the rear payload section. Exhibit 16 Exhibit 18

Pre-sortie

Sortie preparation – 2 Nov 15

1.3.24. **Previous 24 Hours**. Following weekend leave, the Crew, AO and Flying Supervisor arrived at work and attended the Bty Morning Brief at 0800 hrs. The crew were within prescribed crew rest periods and none of them reported any reason why fatigue may have been an issue leading up to the accident sortie. Witness 1 Witness 2 Witness 3 Witness 4

1.3.25. **Aim of the Sortie**. The aim of the sortie was to conduct a currency training sortie for 2 recent graduates of the WK Pilot Conversion to Type Training (CTT). This sortie was the Pilot and PO's first flight since completing WK CTT in mid Oct 15, and marked the beginning of their accelerated programme to become WK Captain and Instructors. The training and development of the Pilot and PO was an essential requirement to provide trained personnel to deliver WK Pilot Course One, which was scheduled to commence early in 2016. Witness 1 Witness 2 Witness 3 Witness 4 Witness 5 Witness 12

1.3.26. **Sortie Plan**. The plan was to take-off from BDN between 1100 and 1130 hrs and operate in segregated airspace, principally in the confines of the Salisbury Plain Training Area (SPTA), the centre of which is approximately 12km North West from BDN. Due to the forecast overcast fog/cloud layer at the surface for the majority of the sortie, the Captain viewed it as an excellent Exhibit 18 Exhibit 19 Exhibit 7 Exhibit 9 Witness 1

[3] 6kg Minimum Landing Allowance, 6kg average burn rate per hour.

opportunity to further demonstrate to the crew the capabilities of the SAR[4]. Additionally, the Captain and the AO believed that the weather conditions afforded them the opportunity to show the recent graduates, system functionality in poor weather, whilst also allowing them to develop as Aircraft Captains and gain confidence in the system. A recovery slot between 1530 and 1600 hrs had been agreed with BDN Ops and Air Traffic Control (ATC) and the crew planned to recover during this period.	Witness 4 Witness 5
1.3.27. **Timeline**. The timeline prior to take off was:	
a. **0800 hrs**. The Morning Brief was held in the Bty Ops building and was attended by the Crew, AO, Flying Supervisor and other Bty personnel. The brief consisted of a Meteorological brief, prepared and delivered by a BDN Met Forecaster, and Ops brief, covering airspace allocation for the sortie, crew constitution, sortie objectives and equipment. The forecast Met (described further from paragraph 1.3.28), was low cloud and fog at BDN, with a chance of a slight improvement later in the day.	Witness 2 Witness 3 Witness 4
b. **0820 hrs**. The Pilot and PO carried out the majority of the pre-flight mission preparation. The Pilot concentrated on preparing the WK Sortie Brief Form, an annex to the WK BDN SOPs. This was used as a briefing aide to capture important information, such as airspace, UA details, and other 'domestic' information. The Pilot also reviewed the F700s, the maintenance documentation for the component parts of the UA and associated systems. The Pilot and PO stated that the process took a little longer than normal due to a new form they were using and the Met conditions of the day. The Pilot, PO, Captain, AO and the Flying Supervisor all stated that they reviewed the weather, and Release to Service (RtS), to ensure that there were no applicable weather restrictions which could have prevented them from flying. The Captain liaised with BDN ATC and Main Ops to ensure they were content with WK launching in the forecast met conditions. When planning was complete, the Pilot delivered the Sortie Brief to the Captain and PO. The Flying Supervisor also attended this brief.	Witness 1 Witness 2 Witness 3 Witness 4 Witness 7
c. **0930 hrs**. The Pilot gave a brief to the AO, who subsequently authorized the sortie.	Witness 5
d. **0950 hrs**. The aircrew left the Ops building for the GCS, which was located near to Rwy 17 West.	Witness 3
e. **1000 hrs**. WK006 was towed out to the start position.	Witness 9
f. **1038 hrs**. Engine Start was recorded.	Exhibit 16
g. **1105 hrs.** WK006 took off from Rwy 17 West.	Exhibit 1
Weather	
1.3.28. **Forecast**. The Terminal Aerodrome Forecast (TAF), issued at 0730	Exhibit 20

[4] The WK Synthetic Aperture Radar (SAR) is a capability of the I Master radar on the forward payload and is used to create images of objects on the surface and can function through a cloud layer, unlike the EO/IR payload.

hrs is shown below at Figure 4. Exhibit 21

TAF	Decoded TAF
EGDM	Boscombe Down Airfield.
020730Z	Issued 0730Z on 2nd.
0209/18	On 2nd day, between 0900 and 1800hrs.
10004KT	Wind 100 degrees at 4 kts.
0300 FG	300 metres in Fog.
VV///	Sky obscured.
BECMG 0211/0213 2000 BR BKN002	Becoming between 1100 hrs and 1300 hrs, 2000 metres visibility in mist, cloud base BKN 200 feet.
BECMG 0213/15 4000 BKN004	Becoming between 1300 hrs and 1500 hrs 4000 metres visibility, cloud base broken at 400 feet.
BECMG 0215/0217 2000 BKN002	Becoming between 1500 hrs and 1700 hrs 2000 metres, cloud base broken at 200ft.
PROB40 0217/0218 0500 FG OVC001	40% probability that between 1700 hrs and 1800 hrs, 500 metres in Fog, cloud base overcast 100 feet.

Figure 4 – 0730hrs BDN TAF

1.3.29. **Actual Weather Conditions**. At the time of take-off, surface visibility was 150 metres, with the sky obscured (RED[5] conditions). The forecast improvement to the cloud base and visibility did not materialise during the course of the flying day. At 1550 hrs, during the approach to land, the actual conditions were recorded as overcast cloud below 100ft, with surface visibility 200 metres (RED conditions). Exhibit 22 Exhibit 23

Sortie Execution

1.3.30. **Sortie Overview**. The UA was launched at 1106 hrs and flew within its designated segregated airspace until it crashed at 1550 hrs. Figure 5 shows the route flown by the UA during its sortie, as recorded by the Vehicle Management System Computer (VMSC). The majority of the sortie was focussed on operating the SAR, as the ground was obscured by low cloud, rendering the EOP ineffective. Exhibit 17 Witness 1 Witness 5

[5] RED conditions are defined as the lowest cloud base (SCT or more cloud) below 200 ft, with surface visibility less than 800 metres

Exhibit 1

Figure 5 - Route of WK006 on 2 Nov 15

1.3.31. **External Air Temperature (EAT) Sensor 1 and 2 fail**. The initial departure was uneventful, with the UA breaking out of the low cloud at 700ft into a clear sky. During the climb out to Salisbury Plain Training Area (SPTA), an *External Air Temp 1 and 2 sensors fail* message was displayed to the crew, warning that external air temperature readings from both met sensors had failed. The crew referred to FRC guidance and elected to continue the sortie. The warning was displayed to the crew until recovery commenced at approximately 1445 hrs.

Witness 3
Witness 1
Exhibit 17

Accident Event Sequence

1.3.32. **Recovery from SPTA to BDN**. After completion of the main part of the sortie, the crew recovered the UA to BDN and configured the aircraft for landing, in order to meet the pre-planned recovery window of 1530 – 1600 hrs. At 1445 hrs, the crew informed the Launch and Recovery Detachment (L & R Det) that they had commenced their recovery. The L&R Det then prepared the Take-off and Landing (TOL) site for recovery; during this process, it became evident that the ATOLS equipment was unserviceable, and despite attempts to try and resolve this during the recovery, it remained so. As ATOLS was unavailable, the crew were aware that the UA would conduct its landing sequence using its GPS/INS Take Off and Landing System (GTOLS).

Exhibit 17
Witness 1
Witness 3
Witness 4
Witness 9

1.3.33. **First Approach**. Figure 6 provides an overview of the first approach. At 15:33:40, with the aircraft in the circuit at BDN and approaching

Witness 1
Exhibit 24

the *Connect Point* (CP), the crew selected the ATOL override for Altitude Deviation[6] (*Alt Dev*) due to the prevailing weather conditions (fog/cloud), in accordance with the Flight Reference Cards (FRCs). The override *Alt Dev* remained selected for the remainder of the flight. The UA registered the CP at 1538:05 hrs and transitioned from *Flight* to *Approach* mode. Shortly after, the UA automatically aborted the approach and displayed the caution *LAND STATUS TIMEOUT* on the operator's display screens. The crew then re-commanded *LAND*, in an attempt to ensure that the original command had been received by the UA and recommence the recovery profile. As illustrated in Figure 6, the UA did not re-join the landing profile, instead navigating towards the beginning of the recovery route. The crew then manually aborted the landing; the UA then turned back towards the runway and flew to the Go-Around Point. Exhibit 17

Exhibit 17

Figure 6 - First Approach to Rwy 17(W)

1.3.34. **Second Approach**. At 15:42hrs, the UA crossed the CP for the second landing attempt and transitioned to Approach mode. Shortly after, as depicted in Figure 7 below, the UA aborted the approach with a *LAND STATUS TIMEOUT* caution displayed on the operator's screens. The UA climbed and flew to the Go Around Point. Exhibit 17

[6] The purpose of Alt-Dev was to provide an individual override which overrode spurious ground proximity warning alerts, principally caused due to the presence of cloud beneath the UA at the Connect Point.

Figure 7 - Second Approach to Rwy 17(W)

Exhibit 17

1.3.35. **Final Approach**. The crew discussed the situation with AO in the GCS. At 1545hrs, the crew selected *MASTER OVERRIDE*[7] (MO) to ensure that the UA would not abort the landing. At 1549:46hrs (approximately 62 seconds from impact), the UA passed through the CP and transitioned to *Approach* mode, turning and descending to intercept a 3 deg glideslope and positioning for runway centreline, as shown in Figure 8. The UA continued on the approach, until over the runway at a height of 23 ft, a deflection to the V-tails was applied, resulting in a 35 deg nose down attitude, which led to the nose of the UA impacting the runway. The UA travelled along the runway for approximately 120 metres, before coming to rest on the Western side of the runway, as shown in Figure 8.

Exhibit 17

[7] Master Override is an ATOL override designed to ensure that the UA lands following its selection. By selecting MO, all ATOL automatic aborts are overridden and the UA will attempt to continue to land in all circumstances. The function of MO is described in detail in section 1.2.

Exhibit 17

Figure 8 - Final Approach to Rwy 17 (W)

Post-accident events

Post-Crash Management (PCM)

1.3.36. 'CRASH, CRASH, CRASH' was called over the WK ground radio channel, by a member of the Launch and Recovery Detachment. A PAN was declared by the crew to ATC, who initiated BDN Aircraft Post Crash Management (APCM) procedures. Due to the poor visibility, the L&R Det were not able to inform ATC and the Fire Services of the exact location of the UA; after a short delay, the Fire Services confirmed that it had been located.

Witness 2
Witness 9
Exhibit 16
Exhibit 25

1.3.37. 43 Bty initiated their APCM procedure. The GCS, ATOLS and associated recovery equipment were quarantined, along with aircrew and engineering documentation.

Exhibit 17

Accident investigation

1.3.38. **Initial Investigation.** Defence Accident Investigation Branch (Defence AIB) personnel arrived at BDN at approximately 1900 hrs on 2 Nov 15. Initial evidence gathering, including the taking of written witness statements and the preservation of evidence was conducted, constrained by the lack of remaining light. The following day at 0730 hrs, Defence AIB investigators returned to the crash site in order to complete the evidence collection. During this process the Vehicle Management System Computer (VMSC) was removed by REME Technicians under supervision of the Defence AIB. The VMSC was prepared for transport to UTacS, for download on 4 Nov 15. The wreckage of WK006 was then recorded and moved to a secure facility at BDN by the Joint Aircraft Recovery and Transportation Squadron (JARTS).

1.3.39. **Damage assessment**. The UA sustained significant damage as shown in Figure 9. Following an assessment and recommendation by 1710 NAS on 10 Feb 16 the damage to the UA was formally categorised as CAT 5 (beyond economical repair) by the DE&S Unmanned Air Systems Team (UAST). Exhibit 27

Figure 9 - Damage to UA (wing assembly removed).

PART 1.4 – ANALYSIS AND FINDINGS

SECTION 1.4.1 – CAUSE, CONTRIBUTARY, AGGRAVATING AND OTHER FACTORS AND OBSERVATIONS

TOR1: Investigate and determine the cause of the occurrence, together with any contributory, aggravating and other factors and observations.

a. *Specifically to establish whether there are any significant similarities to the causes identified in the loss of WK031 at West Wales Airport on 16 Oct 14, but not to further investigate known issues.*

b. *To identify and investigate any key differences between the two accidents that may have contributed to the loss of Watchkeeper WK006.*

Introduction

1.4.1.1. At 1550 hrs on 2 Nov 15, a Watchkeeper (WK) Mk1 Unmanned Aircraft (UA), registered as WK006 and operated by the Army, crashed on final approach to Runway 17 West at MoD Boscombe Down (BDN). Following 2 aborted landing attempts, on the third attempt at 23ft Above Ground Level[1](AGL), the UA pitched nose down, resulting in it impacting the ground at approximately 35-deg nose down, on the centreline, just over 100 metres short of the planned touchdown point. The UA nose and main undercarriage collapsed and the UA slid along the runway for approximately 120m before coming to rest just off the western side of the runway. Exhibit 1 Exhibit 2

1.4.1.2. A comprehensive description of the events and circumstances surrounding this accident is given in Part 1.3 and a description of the WK system is given in Part 1.2. This Section reports the Panel's analysis and findings on the cause of the accident, together with contributory, aggravating and other factors and observations. To avoid repetition throughout the report, factors identified in later Sections are not repeated, however reference is made to them, where appropriate. A list of the Panel's findings is given in Section 1.4.6. At the time of writing, the Service Inquiry (SI) into the loss of WK031 at West Wales Airport (WWA) on 16 Oct 14 had recently reported. An analysis of significant similarities and key differences between the two accidents are also discussed at the end of this Section.

Methodology

Definitions

1.4.1.3. **Air Safety**. Air Safety is defined in Military Aviation Authority (MAA) Master Glossary as *'the state of freedom from unacceptable risk of injury to persons, or damage, throughout the life cycle of military air systems. Its purview extends across all Defence Lines of Development and includes Airworthiness, Flight Safety, Policy, Regulation and apportionment of Resources. It does not address survivability in a hostile environment'.* Therefore, in their deliberations, the Panel considered the risk to both the safety of personnel and to equipment.

1.4.1.4. **Accident factors**. The Panel examined the accident factors and assigned them to a category according to the following definitions.

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[1] During this report, for ease of reference, the Impact Point has been assumed as zero ft AGL.

a. **Causal Factor**. A factor which, in isolation or in combination with other factors and contextual details, led directly to the accident.

b. **Contributory Factor**. A factor which made the accident more likely.

c. **Aggravating Factor**. A factor which made the outcome worse.

d. **Other Factor**. A factor which was none of the above but was noteworthy in that it may cause or contribute to future accidents.

e. **Observation**. An issue that was not relevant to the accident but worthy of consideration to promote better working practices.

Available evidence

1.4.1.5. The following paragraphs list the evidence made available to the Panel. Specific limitations on the evidence made available are also described.

1.4.1.6. **Witness Statements**. The Panel had access to written witness statements and recorded witness interviews. Witnesses included:

a. The Crew of WK006.

b. The Authorising Officer (AO).

c. The Flying Supervisor.

d. Launch and Recovery Detachment (L&R Det) pers.

e. A Thales UK Pilot.

f. Visitors from RNAS Culdrose.

g. ATC.

h. 1ISR Bde HQ.

i. Unmanned Air Systems Team (UAST).

j. Thales UK Senior WK Flying Instructor.

k. Army Aviation Standards (AAvn Stds).

l. Independent Safety Adviser (ISA) to the UAST.

1.4.1.7. **Cockpit Voice Recorder (CVR)**. The Panel had access to the CVR recordings from the Ground Control Station (GCS) and were able to listen to audio recordings from the GCS for the following periods of activity:

a. Initial GCS power-up.

b. Crew pre-flight activity.

c. The take-off and approximately 30mins of the initial part of the sortie.

d. The recovery and the accident.

e. The period of time following the accident until shut down.

1.4.1.8. **Ground Flight Control Computer (GFCC) logs**. With assistance from UAV Tactical Systems (UTacS), the Defence Accident Investigation Branch (AIB) and the Panel were able to review data captured by the GFCC at the time of the accident.

1.4.1.9. **Vehicle Management System Computer (VMSC) Data**. With the assistance of UTacS, the Panel and the Defence AIB were able to analyse flight data recorded by the VMSC.

1.4.1.10. **Wreckage and land survey**. The location of all pieces of wreckage and scuff marks on the runway was recorded accurately by the Joint Aircraft Recovery and Transportation Squadron (JARTS) prior to recovery of the UA. The wreckage was stored under the custody of the Defence AIB at MOD Boscombe Down (BDN) for further examination by 1710 Naval Air Squadron (NAS).

1.4.1.11. **Photographic imagery of the crash scene**. The panel had access to the Post Crash Management, Defence AIB and JARTS photographs taken at the crash site.

1.4.1.12. **Orders, procedures and guidance**. Relevant orders, procedures and guidance included:

a. MAA Regulatory Articles (RA).

b. JHC Flying Order Book (FOB) Edition 5.

c. 1 ISR Bde FOB Edition 10.

d. 1 ISR Bde Trg Directive Edition 2, 15 Oct 14.

e. 1 ISR Bde Pers Directive Edition 2, 15 Oct 14.

f. 1 ISR Bde Boscombe Down SOP.

g. MOD Boscombe Down FOB Edition 7.

1.4.1.13. **Flying related documents**. Flying related documents included:

a. Flying Authorisation sheets.

b. AO and crew Flying Logbooks.

c. Flying and Training Record Folders (F/TRFs).

d. Sortie planning and briefing material.

e. Flight Reference Cards (FRCs) Issue 2.

f. Watchkeeper Known Problems and Workarounds Issue 2.

g. WK Release to Service (RtS), Issue 1, AL4, dated Jun 15.

1.4.1.14. **Engineering records and technical documentation**. Engineering records and technical documentation included:

a. UAS F700s.

b. GOLDesp.

c. Eng Auths records.

d. Physical Aircraft Audit (PAA) records and Military Airworthiness Review Certificates (MARCs).

e. Record of F760 and F756s.

f. Record of technical queries raised.

g. The WK Interactive Electronic Technical Publication (IETP) Issue 7.1

1.4.1.15. **Air Safety material**. This included previous Defence Air Safety Occurrence Reports (DASORs) and SI Reports including material from the on-going WK031 SI.

1.4.1.16. **Specialist reports**.

a. Defence AIB Technical Report, drawing from a number of SQEP organisations and industry experts.

b. 1710 NAS reports.

c. Noptel (the laser altimeter manufacturer) report on laser altimeter testing.

d. Rockwell Collins, the Inertial Navigation System/ Global Positioning System (INS/GPS) manufacturer, reports on tests carried out on Athena GS-411 units.

e. RAF Centre of Aviation Medicine (RAFCAM) HF report.

1.4.1.17. **Manufacturers' documentation**. A detailed description of the landing logic was requested by the Panel. The Panel were permitted to review, under the supervision of UTacS and Thales UK, the VMSC Functional Requirements Specification (FRS), owned by Elbit Systems Ltd (ESL). This document contained a functional description of the landing logic used by the UA. This together with the subset of the VMSC FRS published in the ESL reports into Flight 395 (the loss of WK031) and WK006 provided the Panel with all the information required to understand the UA's behaviour leading up to the crash and specifically to independently analyse the recorded VMSC data.

Assessing Accident Factors

1.4.1.18. **Human factors**. The Panel was assisted in considering human factors relating to the accident by a RAFCAM Aviation Psychologist who was present during the initial Panel interviews with the crew, Authoriser and Flying Supervisor.

1.4.1.19. **Technical factors**. The Panel was assisted in investigating technical aspects of the accident by the Defence AIB. In addition, the Panel was provided with technical services and support from a number of military and civilian organisations.

1.4.1.20. **Determining the accident sequence**[2]. The Panel took ESL's initial analysis of the VMSC data as a starting point for determining the accident sequence and corroborated it through independent analysis of recorded events. The Panel sought to understand the technical sequence of events, alongside the human decisions made prior to the accident, in order to build up a complete picture of the accident sequence. Exhibit 28

Services

1.4.1.21. Personnel and agencies which provided assistance to the Panel included:

a. Defence AIB.

b. JHC Safety Assurance.

c. Army Aviation Standards (AAvn Stds).

d. 1 ISR Bde HQ.

e. 47 Regt RA.

f. Royal School of Artillery (RSA).

g. DE&S and the UAST.

h. QinetiQ.

i. Thales UK.

j. ESL.

k. Unmanned Air Vehicle Tactical Systems Ltd (UTacS).

l. 1710 NAS.

m. Rockwell Collins (Ohio, USA).

n. Noptel (Oulu, Finland).

o. UAS Test and Evaluation Squadron (TES).

p. MAA.

q. Independent Safety Adviser (ISA) to UAST.

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[2] Accident Sequence' is defined in the MAA02 Military Aviation Authority Master Glossary Issue 6.1 as "Accident Sequences, which generally have a CAUSE (eg equipment failure, human error, external event), a HAZARD (an intermediate state where potential for harm exists) and an ACCIDENT (the realization of a Hazard becoming a harmful outcome). The Panel have chosen to use the term accident chain as multiple events led to a hazardous situation that caused the accident.

Determining the cause

Events

1.4.1.22. **Sortie overview**. The VMSC data showed that the UA got airborne at 1106:12 hrs and flew within its designated segregated airspace until it crashed at 1550:48 hrs. Further analysis of the VMSC data and GFCC logs showed that there were no significant events or faults recorded during the flight, other than the External Air Temperature sensors failing, and the un-serviceability of ATOLS. Exhibit 16 Exhibit 29 Exhibit 30

1.4.1.23. **Recovery**. GFCC log data showed that the ATOL *Alt Dev* override was selected as part of the pre-landing checks before the Connect Point (CP) was reached on the first landing attempt at 1533:40 hrs. It remained selected for the remainder of the flight. Exhibit 16

1.4.1.24. **First landing attempt**. Figure 1 and Table 1 show the UA's track, height and key events recorded by the VMSC and GFCC during the first aborted approach and go-around. Following the auto abort, *Land* was re-commanded by the crew with the intent of getting the UA to reacquire the landing profile. Instead the UA turned to the right and headed towards the first waypoint in the landing sequence. Manual abort was subsequently commanded and the UA turned back to the left to re-acquire the aborted landing route above Taxiway Hotel to the Go-Around Point. This unintentional manoeuvre is discussed from Paragraph 1.4.1.66. Exhibit 16 Exhibit 1 Exhibit 17

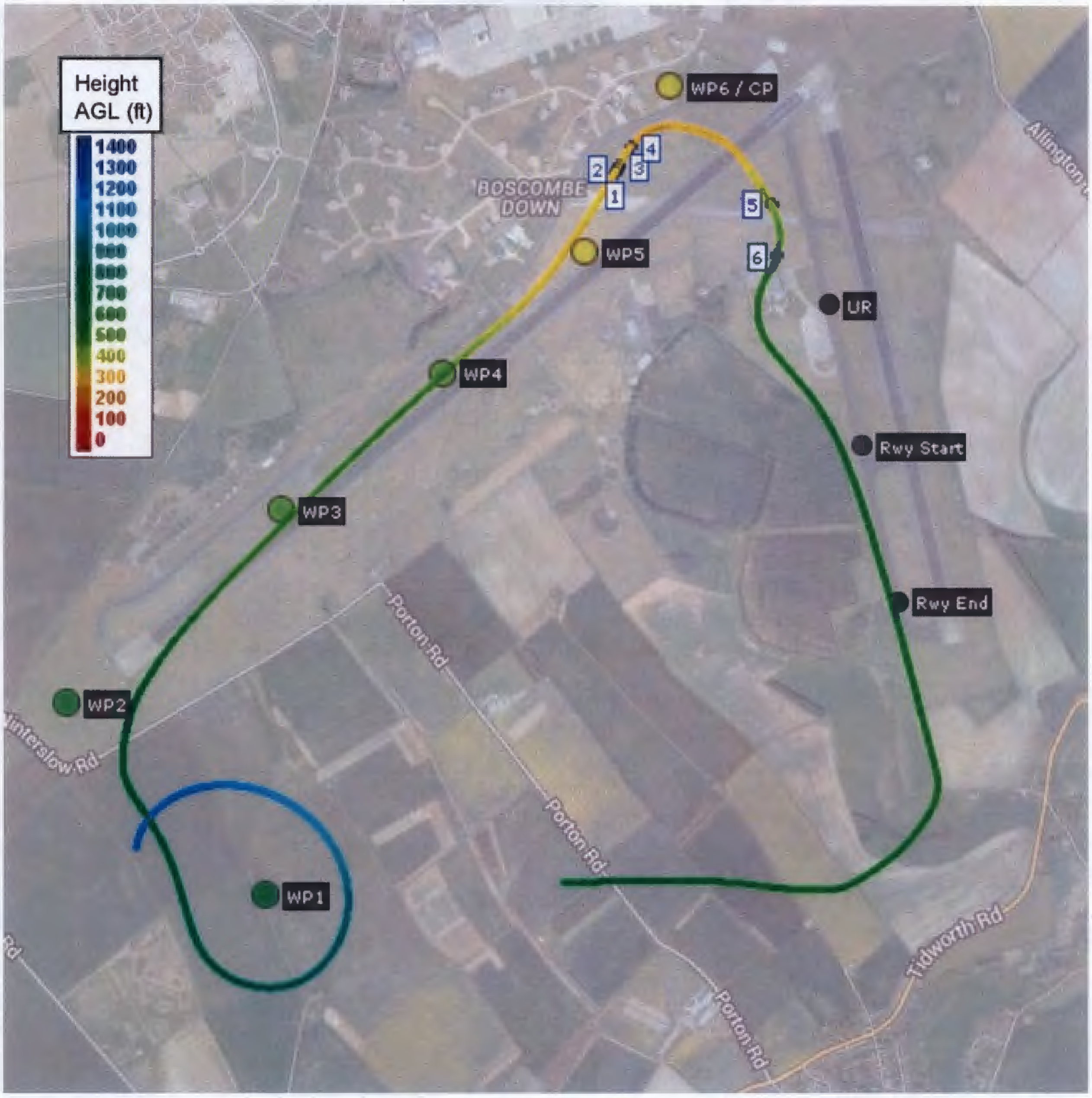

Figure 1 – First aborted approach and go-around.

Event Label	UTC	Description
1	1538:04.00	The ATOL mode recorded in the VMSC data changed from *Standby* (ATOL_STATE 11) to *Intercept* (ATOL_STATE 5), signifying that the UA had reached the CP.
	1538:04.05	The UA intercepted the glide slope. The ATOL mode changed from *Intercept* to *Approach* (ATOL_STATE 6)
2	1538:04.55	In the Master Fault List (MFL) *ATOL_MSG_67* was recorded, which means that no ATOLS data had

Exhibit 16
Exhibit 1

		been received by the UA. ATOLS was unserviceable, so this was as expected.
3	1538:04.95	Laser altimeters 1 read 0.53m.
	1538:05.00	The laser altimeters read 0.53m and 0.85m. This opened a *Ground Touch identification window.*
	1538:05.10	*MFL ATOL_LANDING_ALT_DEV* message was recorded indicating that a ground proximity had been detected.
4	1538:07.80	*MFL ATOL_LANDING_TIME_OUT* was recorded indicating that the *Ground Touch identification window* had 'timed-out' (as the UA had not progressed to *Free roll* within 2.8 seconds of opening). This was displayed to the crew as *Land Status Timeout.*
	1538:07.85	The ATOL mode changed from *Approach* (ATOL_STATE 6) to *Standby* (ATOL_STATE 11) signifying that the landing had been aborted due to the *Ground Touch identification window* timing out.
5	1538:29	*Land* was commanded. The UA initiated a turn to the right towards WP 1.
6	1538:35	*Manual abort* was commanded and the UA initiated a turn to the left towards the *Go Around Point.*

Table 1 – Sequence of events shown in Figure 1

1.4.1.25. **Second landing attempt**. Figure 2 and Table 2 show the UA's track and height and the key events recorded by the VMSC and GFCC during the second aborted approach and go-around.

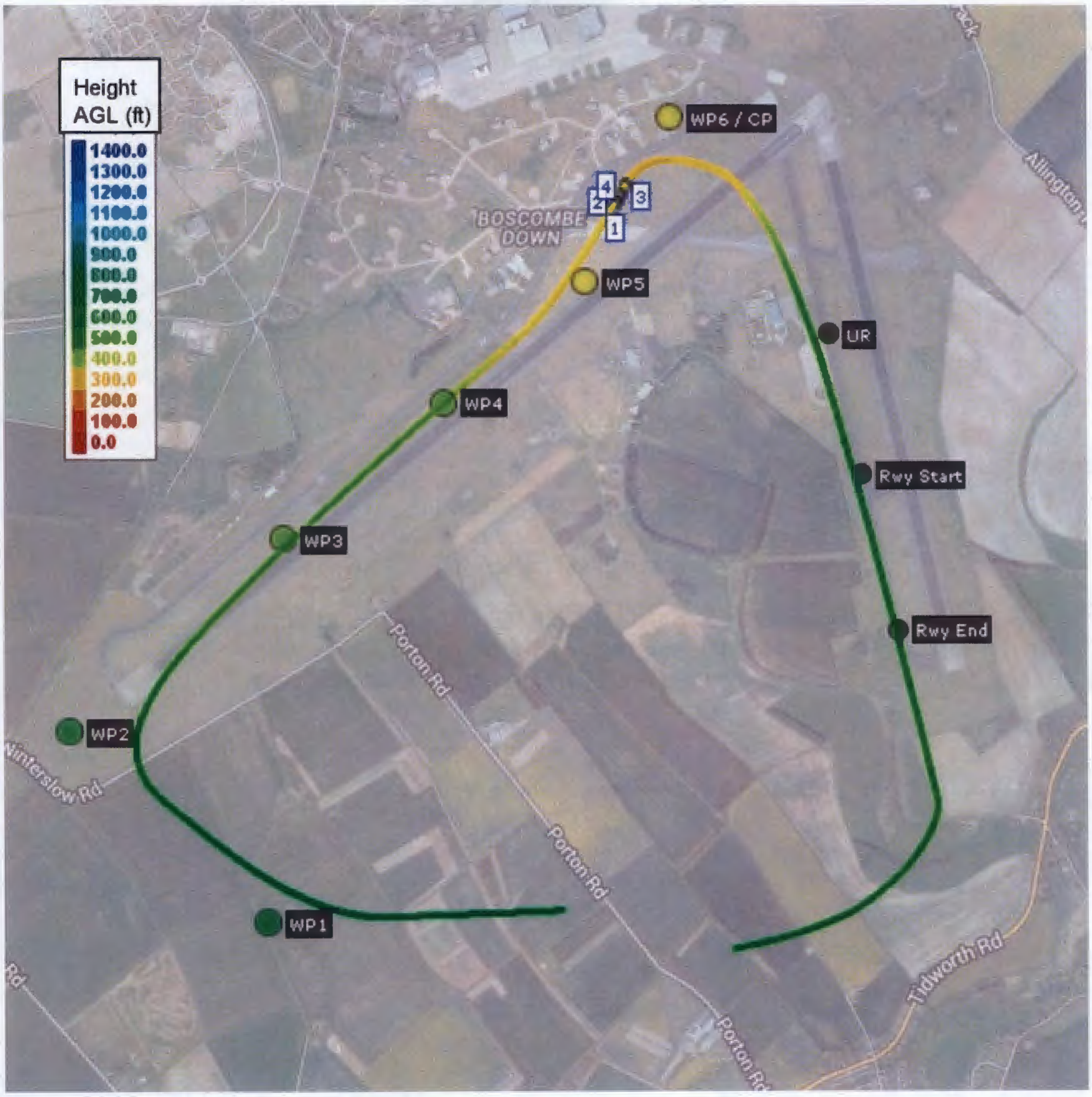

Figure 2 – Second aborted approach and go-around.

Event Label	UTC	Description
1	1542:54.00	The ATOL mode recorded in the VMSC data changed from *Standby* to *Approach*[3] showing that the UA had reached the CP and was within glide path limits. The laser altimeter readings were 0.25m and 0.78m, which opened a *Ground Touch identification window.*
2	1542:54.50	*MFL – ATOL_MSG_67* was recorded indicating that the UA was not receiving ATOLS data.
3	1542:55.30	The Weight on Wheels (WOW)1 code changed from *In-air* (WOW1 code 0) to *Air-to-ground* (WOW1 code 4) showing that the UA had sensed a *Ground Touch.*
	1542:55.35	The WOW1 code changed to *Ground-to-air* (WOW1 code 64) showing that the VMSC had sensed that the UA had 'bounced'. The ATOL mode changed from *Approach* to *Air Jump* (ATOL_STATE 15) as a result.
4	1542:56.80	MFL – ATOL_LANDING_TIMEOUT was recorded indicating that the *Ground Touch identification window* had again timed-out. The landing was automatically aborted.

Table 2 – Sequence of events shown in Figure 2

1.4.1.26. **Final approach**. The GFCC logs showed that Master Override (MO)[4] was selected at 1545:40 hrs. Figure 3 shows the programmed waypoints, system set-up, UA track and approximate height and the sequence of key events

[3] Intercept mode was not recorded by the VMSC on Side A, but as this mode is transitory of the UA is within glideslope limits, it is likely that it occurred between clock cycles and hence was not recorded on the VMSC.

[4] Information on Master Override is provided in Part 1.2, under Systems Description.

recorded in the VMSC data and GFCC logs for the final approach from 1549 hrs and Table 3 describes the events 1-8 shown in the Figure.

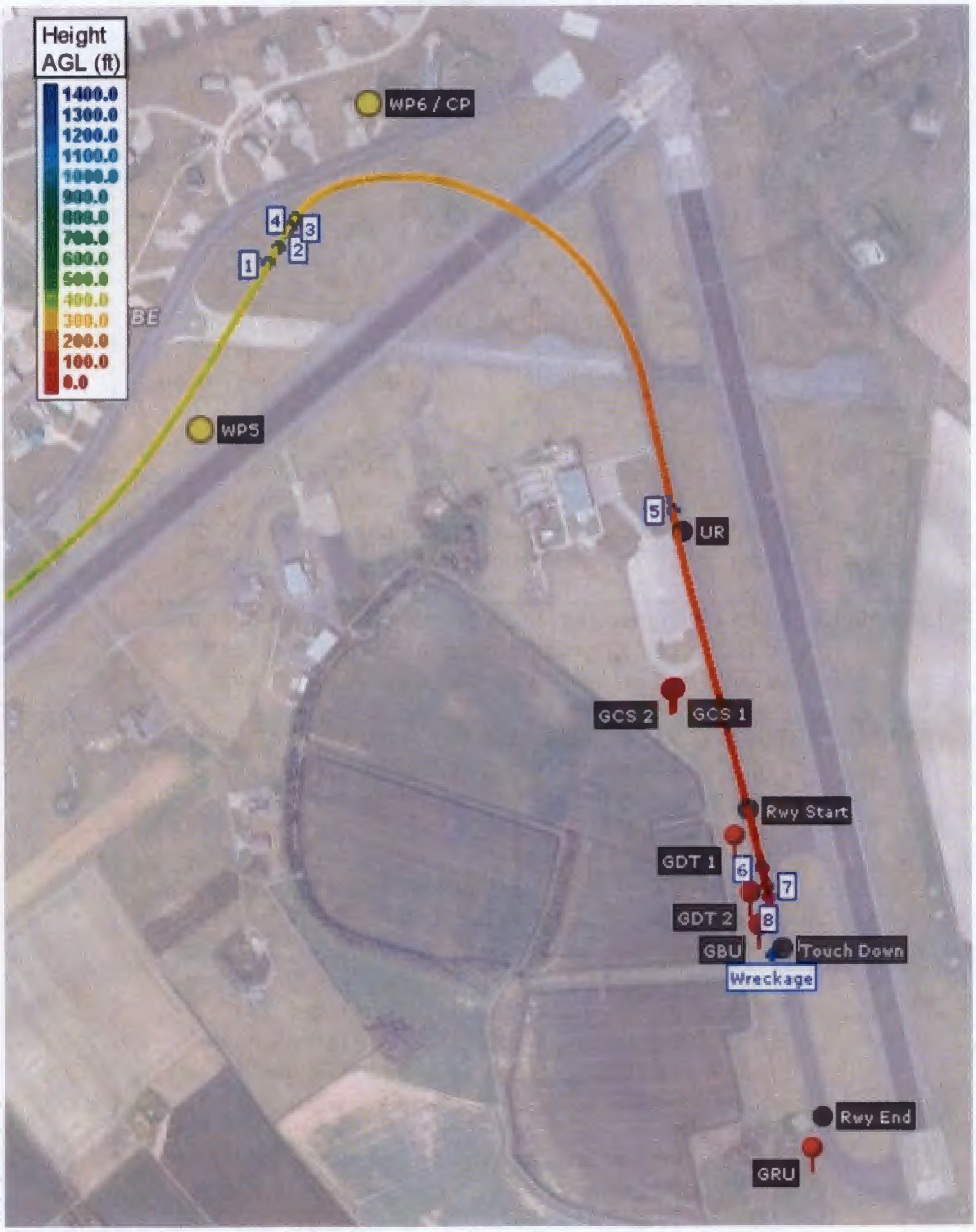

Figure 3 – Final approach and crash landing on the runway

Event Label	UTC	Description
1	1549:46.00	The ATOL mode changed from *Standby* to *Intercept* denoting that the UA declared that it had reached the CP. The laser altimeters gave readings of 0.34m and

Exhibit 28
Exhibit 31
Exhibit 32
Exhibit 1
Exhibit 33

		0.94m. The UA was 362ft[5] AGL. These laser altimeter readings were assessed by ESL to be due to laser reflection from cloud at the CP. A *Ground Touch identification window* was opened.
	1549:46.05	The ATOL mode changed to *Approach*, denoting that the UA was within glideslope limits.
	1549:46.55	*MFL – ATOL_MSG_67* was recorded signifying that no ATOLS data had been received by the UA.
2	1549:47.20	The WOW1 code changed from *In-air* to *Air-to-ground*, showing that the UA had sensed a *Ground Touch*.
	1549:47.25	The WOW1 code changed to *Ground-to-air* showing that the UA had sensed that it had 'bounced'. The ATOL state accordingly changed from *Approach* to *Air Jump*.
3	1549:48.80	MFL – ATOL_LANDING_TIME_OUT was received indicating that the *Ground Touch identification window* had timed out. As a result of MO being selected, no automatic abort was initiated.
4	1549:49.45	Vertical acceleration reduced sufficiently to trigger the ATOL mode to return from *Air Jump* to *Approach*. The WOW1 code changed from *In-air* to *Air-to-ground*.
	1549:49.50	The WOW1 state changed to *On-ground* (WOW1 code 68). The UA was at 325 ft AGL. The WOW1 system continued to indicate *On-ground* from this point onwards.
5	1550:25.50	*MFL – ATOL_LALT_DIFF* was recorded indicating that the UA had reached the Under Run (UR) point and that there was a difference between the two laser altimeters of greater than 0.2m and/or a difference between the laser altimeter height and the GPS/ATOLS height of over 5%[6]. The laser altimeter heights were 0.58 and 1.61m and the UA was 136ft above the ground, hence both criteria were met. No automatic abort was initiated due to the selection of MO and both laser altimeters were disqualified (*MFL – ATOL_LALT1_VMSC_DISQUALIFY* and *MFL – ATOL_LALT2_VMSC_DISQUALIFY*).
6	1550:46.30	The ATOL mode changed to *Semi-flare* (ATOL_STATE 7) indicating that the *Semi-flare* and *Decrab*

[5] Based on VMSC recorded PP_ALT parameter (in metres AMSL,) which is based on barometric altitude at this stage in the flight. Ground level is taken as the impact point.

[6] The IETP Document Code WATCHKEEP0MK1-AAA-C00-00-00-0000-442A states that the meaning of the caution 'ATOLS Laser Altimeters Diff' means "A difference of over 20cm between the Laser Altimeters measurements or there is a measurement difference of over 5% between the Laser Altimeter measurements and the aircraft's actual altitude".

		manoeuvre was initiated.
	1550:46.35	The ATOL mode changed immediately to *Ground Contact* (ATOL_STATE 8), as the WOW1 state was already *On-ground*.
	1550:46.55	Post landing actions were commanded; the V-tails moved, pitching the UA nose down.
7	1550:47.35	The ATOL mode changed to *Free Roll* (ATOL_STATE 9), 1 second after declaring ground contact. The UA pitch was 31.39° nose down and continued to pitch down at a rate of 13.31°s^{-1}.
8	1550:48.00	There was a sudden reduction in negative acceleration on the UA, coupled with a sudden reduction in nose-down pitch which shows that an impact had occurred. The recorded coordinates in the VMSC data at this point tallied with the coordinates of the initial mark on the taxiway as recorded by the JARTS survey on 3 Nov 15. Immediately prior to impact the UA was at -35.29° pitch.

Table 3 – Sequence of events shown in Figure 3

Determining Weight-on-Wheels

1.4.1.27. **Analysis of events**. From the events described above, the Panel noted that:

a. The VMSC had opened a *Ground Touch identification window* at the CP on all 3 approaches due to erroneous laser altimeter readings caused by cloud at the CP.

b. Protection measures, which may have resulted in a ground proximity abort due to the erroneous laser altimeter readings, were overridden, initially by the selection of the *Altitude Deviation* (*Alt Dev*) override and then by the selection of MO.

c. On the 2nd and 3rd attempts to land, the VMSC detected a *Ground Touch*.

d. On the 3rd attempt the protection measure designed to abort the landing of the UA if it did not progress to free-roll within 2.8 seconds from opening a *Ground Touch identification window* was overridden by the selection of MO.

e. On the 3rd attempt the VMSC declared WOW1 *on ground*, whilst at 325ft AGL and within 4 seconds of declaring that the CP had been reached. Because the VMSC was already reporting the UA to be on the ground, once it passed the semi-flare point, it immediately carried out post landing actions to put traction on the nose wheel. This caused the UA, whilst still airborne, to pitch nose down and impact the ground before the touchdown point.

The following paragraphs analyse the VMSC logic which allowed these events to unfold.

1.4.1.28. **Opening the Ground Touch Identification Window**. A *Ground Touch identification window* is a period of time during which the VMSC is able to sense *Ground Touch* through its weight on wheels logic. During a normal landing, a *Ground Touch identification window* will only open when the UA is 1m above the runway surface. The normal landing sequence and the weight on wheels system is described in further detail in the System Description in Part 1.2. To understand why the VMSC opened a *Ground Touch identification window,* it was necessary for the Panel to understand the logic detailed in the Functional Requirements Specification (FRS) for the VMSC. This document describes how the VMSC should react to any given set of inputs. The following extract of the FRS, which describes the altitude requirements for opening a *Ground Touch identification window* was provided to the Panel:

> 'Altitude Window for Ground Touch Identification' shall be defined as open when:
>
> - If (master override is not activated) or (master override is activated and both altimeters are valid (see FRS_VMSC_3231 for conditions) and BIT_933 'diff between altimeters' is not declared): altitude is within a range of "Altitude for starting to sample the vertical acceleration" (FRS 3204 parameter no.1) during the required time (FRS_VMSC_3204 parameter no. 2).
> - Else
>   When the AV is below 'alt_window_altitude_for_master_override' altitude above ground (see FRS_VMSC_3204)
>
> Note: UAV altitude shall be the WGS84 altitude. Ground altitude shall come from the FCS.
>
> FRS_VMSC_3204: Parameter 1 has a default value of 1 m. Parameter 2 has a default value of 2 VMSC cycles (100 msec).

Exhibit 34

ESL confirmed that the altitude reference used to detect when a *Ground Touch identification window* should be opened is taken from the laser altimeters. In each instance when a *Ground Touch identification window* was opened (given in Tables 1 - 3), valid[7] laser altimeter readings of less than 1m were recorded by the VMSC (despite the UA being over 300ft above ground level), hence the logic conditions described in the FRS were met. The reason for the erroneous laser altimeter readings was assessed[8] as being due to laser energy reflection from cloud immediately beneath the UA. Finally the Panel noted that a *Ground Proximity* abort would have occurred had it not been overridden by the selection of *Alt Dev* override on the first 2 approaches and MO (and *Alt Dev* as it remained selected) on the final approach.

Exhibit 28
Exhibit 35
Exhibit 36

1.4.1.29. **Sensing Ground Touch**. An extract of the FRS for the VMSC provided to the Panel stated:

Exhibit 34

> The VMSC shall identify "<u>first</u> ground touch" after starting to sample the vertical acceleration as following:

[7] FRS_VMSC_3523 describes the laser altimeter value taken based on a set of conditions. This is incorrectly referenced as FRS_VMSC_3231 in the extract provided.

[8] ESL assessed in their technical report that the low cloud and fog that was known to be present was the cause of the erroneous laser altimeter readings. Significant optical reflection at the operation wavelength of the lasers would be expected from dense cloud.

[dACCZ[m/s^2] – Pitch Rate [deg/s]] is greater than required (FRS_VMSC_3204 parameter no. 5) during required time (FRS_VMSC_3204 parameter no.6).

FRS_VMSC_3204 parameter 5 has a value of 7 (no units) and parameter number 6 has a value of 2 VMSC cycles which is equal to 0.1 seconds.

```
If ACC Z > -9.8 then
  dACCZ = -9.8 – ACC Z
ELSE (ACC Z<-9.8) then
 dACCZ = SQRT((ACC Z+9.8)^2 + ACC Y^2 + ACC X^2)
End if
```

Pitch, Pitch Rate and Acceleration (given as *ACC X, ACC Y* and *ACC Z* in the FRS extract above) are measured by the INS/GPS units and recorded by the VMSC. The parameter *dACCZ,* defined in the FRS as a function of acceleration, is then used to determine a *Ground Touch value* by subtracting *pitch rate* from it. *Ground Touch* is declared when this value goes greater than 7. The recorded VMSC data showed that the *Ground Touch value* went greater than 7 and the WOW1 code changed from *In-air* to *Air-to-ground* indicating a *Ground Touch* had been sensed on the second and third landing attempt shortly after the CP had been declared. Figure 4 shows this on the final landing attempt, where it can be seen that as soon as the difference between *dACCZ* and *pitch rate* reached 7, the WOW1 state changed indicating *Ground Touch*. The panel concluded that it was the difference between the *pitch rate* and vertical acceleration that caused Ground Touch to be sensed.

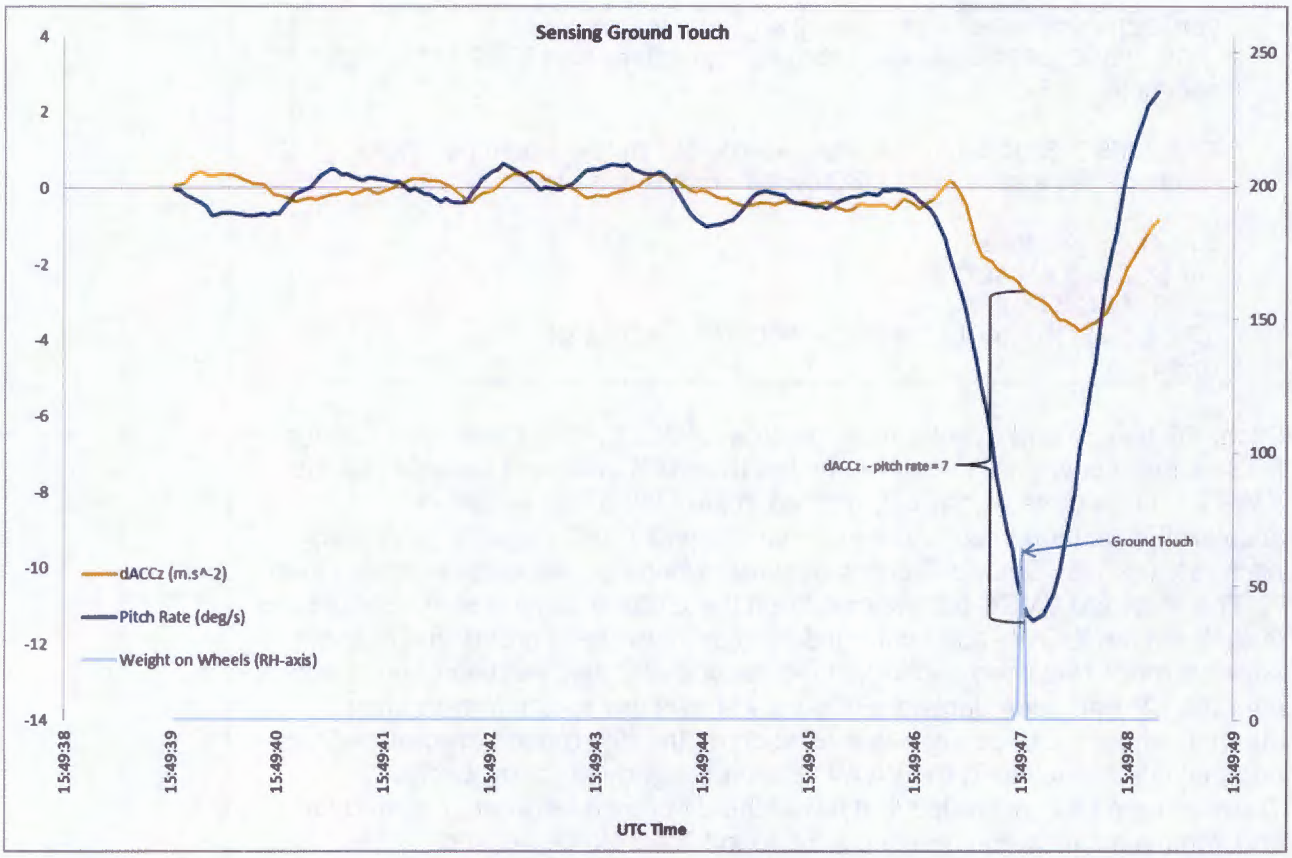

Figure 4 – Sensing Ground Touch whilst airborne on the final circuit

1.4.1.30. **Sensing Air Jump**. The VMSC data showed that on the 2nd and 3rd attempt to land the ATOL state went to *Air Jump* and the WOW1 state went from Ground-to-Air immediately after the VMSC sensed a *Ground Touch*. *Air Jump* was also briefly displayed to the Pilot and PO on the air vehicle display computer. The VMSC FRS explained this behaviour as follows:

Exhibit 34
Witness 3
Witness 4

> After first time of "*Ground Touch*" identification during landing:
>
> The VMSC shall identify "air jump" if vertical acceleration is greater than required (FRS_VMSC_3204 parameter no. 7).
>
> After the second *Ground Touch*, no further "air jump" shall be defined (while in landing mode).
>
> FRS_VMSC_3204 parameter 7 has a value of -9 ms^{-2}.

Analysis of the VMSC data showed that the vertical acceleration was greater than -9ms^{-2} on both occasions that *Air Jump* was noted. The Panel concluded that the *Air Jump* message seen by the crew was an indication that a *Ground Touch* had occurred[9].

1.4.1.31. **Returning from Air Jump and latching WOW1 to On-ground.** On

Exhibit 34

[9] It should be noted that the Panel does not believe that the absence of *Air Jump* can be used to categorically say that a Ground Touch identification window has NOT been opened.

the 2nd recovery attempt the VMSC data showed that the ATOL state *Air Jump* ended when *Ground Touch identification window* closed, which caused the automatic abort and the ATOL state to revert to *Standby*. Due to the selection of MO, on the final approach the UA did not abort at the end of the *Ground Touch identification window* and the ATOL state *Air Jump*, therefore, continued past this point. The FRS for the VMSC defined when the ATOL state *Air Jump* shall end in this situation as follows: Witness 3 Witness 4

> After an "air jump", the VMSC shall define "Ground Touch = Ground" when dACCZ is greater than 0.3*(FRS_VMSC_3204 parameter no. 3), during required time (FRS_VMSC_3204 parameter no. 6).
>
> Parameter no.3 has a value of 3ms^{-2} and parameter number 6 has a value of 2 VMSC cycles or 0.1 seconds.

Therefore, it can be seen that *Air Jump* should end when dACCz has a value of greater than 1ms^{-2} for more than 0.1 seconds. Analysis of the VMSC data showed that on the final approach *Air Jump* ended when these parameters were met, with a corresponding change in the WOW1 state to *On-ground*. Figure 5 shows that vertical acceleration (labelled as ACC Z) was greater than -9ms^{-2} at the first *Ground Touch* and that the ATOL State changed to *Air Jump*, only returning to *Approach* when dACCz reached a value of 1ms^{-2}, at which point WOW1 latched to *On-ground*.

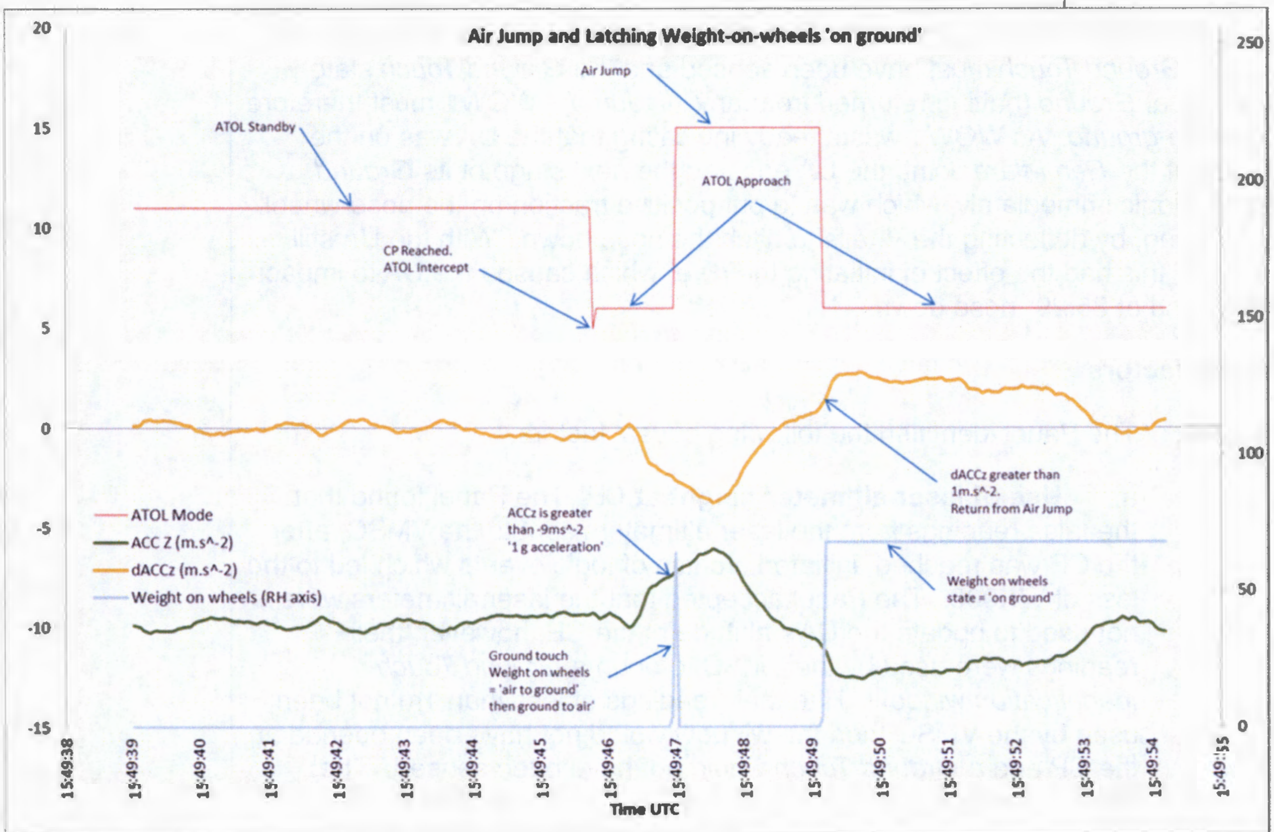

Figure 5 – Air Jump and Latching Weight-on-Wheels

1.4.1.32. **Land Status Timeout**. *LAND_STATUS_TIMEOUT* was seen by the crew in the GCS on each recovery attempt. On the first two attempts, *LAND_STATUS_TIMEOUT* indicated that a *Ground Touch Identification Timeout* Exhibit 34 Witness 3 Witness 4 auto abort had occurred as the UA had not progressed to *Free Roll* within a pre-defined time period. On the final approach *LAND_STATUS_TIMEOUT* was seen, but the corresponding abort was overridden by MO. The FRS logic that describes the time period from the opening of the *Ground Touch identification window* to the *Timeout* is as follows:

The VMSC shall define "Landing Abort" if "Free Roll" stage has not been defined during required time after starting to sample the vertical acceleration. The required time calculation (sec.): 0.3 + 0.9 + parameter no. 10 The VMSC shall report a failure according to BIT doc. The VMSC shall report it in A/G ICD message no. 0-205, atol_fault_status. Parameter 10 is 1.5 seconds.

As it takes 100 msec to open the *Ground Touch identification window* from the first valid laser altimeter readings, this explains why the *ATOL_LANDING_TIME_OUT* was recorded 2.8 seconds (ie 0.1 + 0.3 + 0.9 + 1.5 = 2.8) after the valid laser altimeter readings at the CP on each recovery attempt.

1.4.1.33. **Pitch down at the Semi-flare point**. At the *Semi-flare* point (defined in the VMSC FRS as 7m above the runway), the UA is programmed to enact a *semi-flare* and then a *decrab* manoeuvre. The ATOL state changes from *Approach* to *Semi-flare* at 7m above the runway[10]. The next ATOL state is *Ground Contact.* To progress from *Semi-flare* through the *Ground Contact* state, a *Ground Touch* must have been sensed and the *Ground Touch* state must equal *Ground* (having returned from any *Air Jump*). WOW1 must therefore equal *On-ground.* As WOW1 was already indicating that the UA was on the ground at the *Semi-flare* point, the UA enacted the next stage of its *Ground Contact* logic immediately, which was to put positive traction on the nose-wheel for steering, by deflecting the V-tails to pitch the nose down. With the UA still airborne, this had the effect of initiating the dive, which caused the UA to impact the ground at 35.29° nose down. Exhibit 17

Causal factors

1.4.1.34. The Panel identified the following causal factors:

a. **Use of laser altimeter height at CP.** The Panel found that the false readings from the laser altimeters sent to the VMSC, after the CP was reached, initiated a chain of logic events which led to the loss of WK006. The Panel accepted that the laser altimeters were not used to update the UA's altitude at the CP; however, their readings were used by the VMSC to open a *Ground Touch identification window.* Had their readings of less than 1m not been used by the VMSC then the window would not have been opened at the CP and a *Ground Touch* would not have been sensed. The Panel concluded that the use of the laser altimeter height at the CP

[10] The VMSC recorded its present position altitude (PP_Alt) to be 127.4m at the point where semi-flare was also recorded and 120.2m at the impact point. The Panel noted that the altitude would not have been corrected due to the laser altimeter's disqualification, but that it was accurate to well within a metre nevertheless.

was a **Causal Factor**.

b. **Cloud at the CP.** The Panel found that it was the laser energy reflection from cloud at the CP, which caused the laser altimeters to erroneously read less than 1m. The Panel concluded that cloud at the CP was a **Causal Factor**. The weather limitations associated with the operation of WK are discussed further in 1.4.2, and a recommendation to address this causal factor is at Paragraph 1.4.2.93.

c. **VMSC software logic**. The Panel found that the VMSC used the readings from the laser altimeters to open a *Ground Touch identification* window. The VMSC's WOW1 logic then sensed a *Ground Touch*, followed by an *Air Jump* and then declared that the UA was on the ground, all whilst the UA was still above 300ft AGL. Automatic protection measures were overridden by the selection of MO (the effects of which are discussed further in Paragraph 1.4.1.54) and once the UA reached the *semi-flare* point, post landing actions were commanded resulting in the pitch down manoeuvre and impact with the ground. The VMSC software had, therefore, declared the UA was on the ground and ultimately commanded post landing actions whilst the UA was still airborne. The Panel concluded that flawed VMSC software logic was a **Causal Factor**.

1.4.1.35. **Recommendation. The Panel recommend that Head Unmanned Air Systems Team ensures that the Vehicle Management Systems Computer landing mode software logic is modified to prevent a *Ground Touch* declaration and post landing actions being commanded whilst the aircraft is still airborne.**

Further Analysis

Ground Touch

1.4.1.36. **Cause of Ground Touch at the CP**. The Panel investigated what caused the difference between the pitch rate and vertical acceleration, which triggered *Ground Touch* shortly after the CP was declared on the final 2 approaches. The VMSC data plotted in Figure 6 shows that on declaring the CP, the UA pitched nose-down to a maximum of -8°. The rate of change in pitch (pitch rate) associated with this reached a maximum rate of $-12^{\circ}s^{-1}$. This manoeuvre also induced an upwards vertical acceleration (negative g-force), shown by the negative dACCZ values at the start of the manoeuvre. Despite dACCZ and pitch rate both moving in the same direction (becoming increasingly negative), the pitch rate changed more rapidly and a sufficient difference between the two parameters developed resulting in a *Ground Touch* being declared (as previously shown in Figure 4). The Panel, therefore, concluded that it was the rapid pitch down manoeuvre immediately after the CP was declared that caused *Ground Touch* to be sensed on the second and third approach.

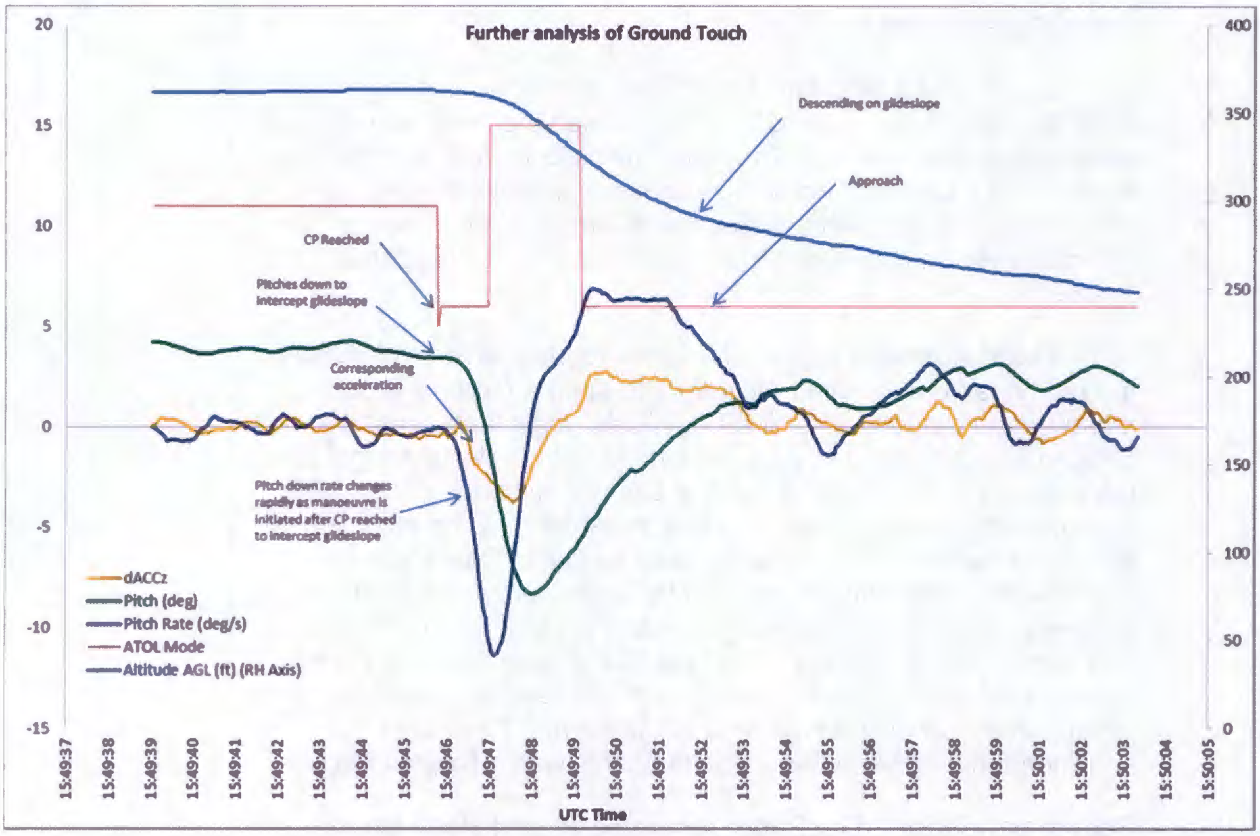

Figure 6 – Further analysis of Ground Touch

1.4.1.37. **Cause of manoeuvre after passing the CP**. Thales UK explained to the Panel that the UA was designed to select the final waypoint on the recovery route to use as the CP. The CP was, therefore, Waypoint 6, as previously shown in Figure 3. On each approach, the CP was declared approximately 300m before Waypoint 6. As the UA initiated a turn after declaring the CP, Waypoint 6 was never actually flown through. Thales UK explained that this was because the UA declared WPs within a lateral tolerance[11], which was a function of Ground Speed, where the faster the UA was moving the greater the tolerance. Analysis of the VMSC data showed that the UA was above the 3 deg glideslope when it declared the CP, which caused it to pitch nose down to attain the glideslope, which in turn, for the reasons explained above, triggered the *Ground Touch*. The Panel, therefore, concluded that the pitch down manoeuvre to intercept the glideslope, following declaration of the CP, was a **contributory factor**. In discussions with UAS TES, Thales UK and UTacS, the Panel noted that it may be possible to reduce the chances of a false *Ground Touch* being sensed by eliminating the need for the manoeuvre to intercept the glideslope through careful positioning of the CP and preceding WPs in the recovery route. Exhibit 37

1.4.1.38. **Recommendation. The Panel recommends that Head of the Unmanned Air Systems Team investigates and provides advice to operators on how to set up a recovery route to minimise the possibility of sensing a false *Ground Touch* as a result of a pitch down manoeuvre to**

[11] For 'non-critical' WPs there is no vertical tolerance, hence the UA will declare a WP as soon as it is within the lateral tolerance of it. For critical waypoints, if the UA is not at the right height when it reaches the lateral tolerance boundary, it will climb or descend in a spiral until it is within 200ft of the WP, before it declares it.

intercept the glideslope after the Connect Point.

Free Roll

1.4.1.39. Figure 7 shows a subset of the VMSC data recorded during the 8 seconds leading up to the impact. It can be seen that:

a. The UA was descending on a constant glide path up to the Semi-flare point.

b. On reaching the Semi-flare point, the ATOL state immediately changed to Ground Contact.

c. Both V-tails deflected down (note a positive value denotes a downward deflection) inducing a pitch down manoeuvre.

d. Free-roll was declared one second after *Ground Contact* was declared, by which time the UA was already pitching down.

The Panel concluded that the UA commanded post landing actions after *Ground Contact* was declared and that Free-Roll had no effect on the pitch of the aircraft, which continued to increase until it hit the ground. *Free-Roll* was therefore **not a factor**.

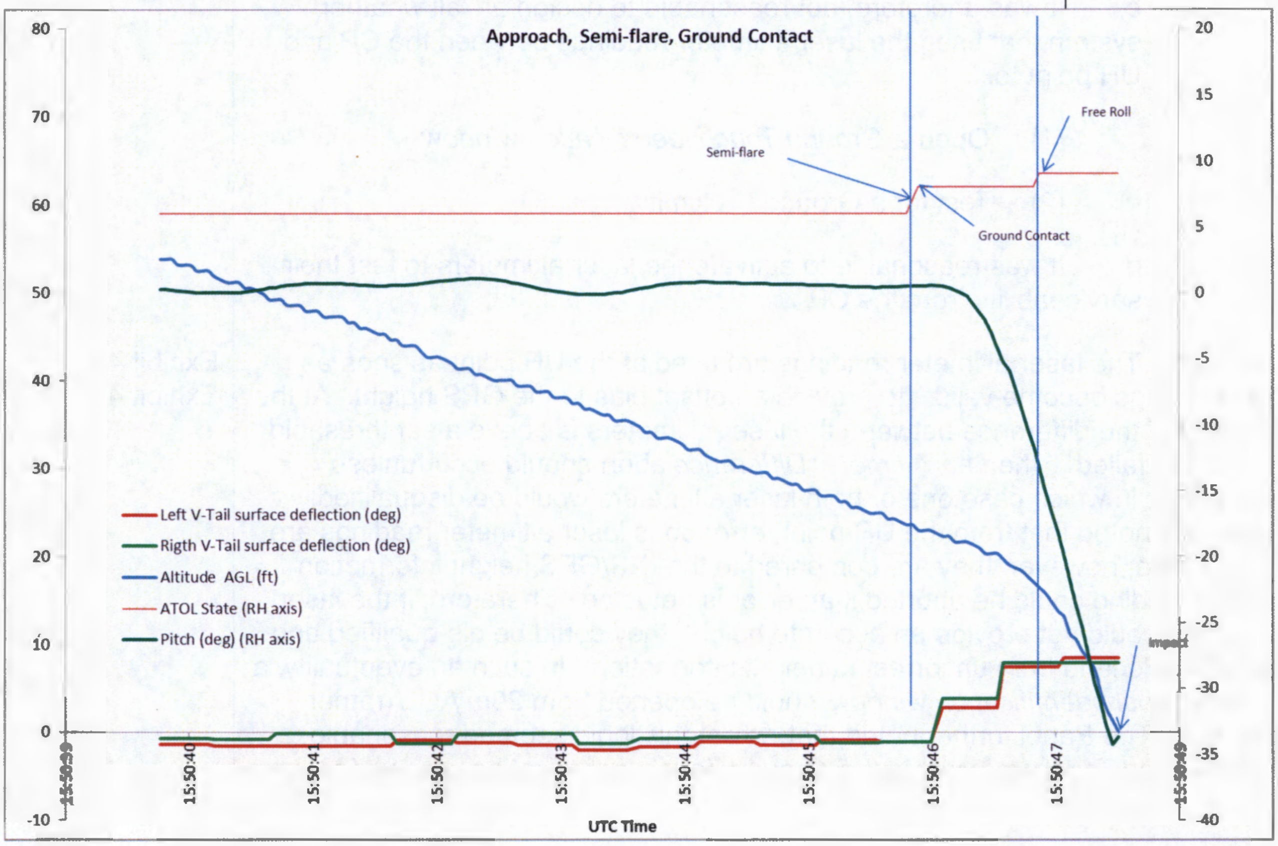

Figure 7 – Approach, Semi-flare, Ground Contact, Free-roll

Use of laser altimeters

1.4.1.40. The Panel determined that the use of laser altimeter height (to open a *Ground Touch identification window*) at the CP was a causal factor in the accident (Paragraph 1.4.1.34.a), but that the laser altimeters themselves were serviceable at the time of the accident (Section 1.4.3). The following paragraphs consider the use of the laser altimeters and whether they are fit for purpose as used in the UA.

1.4.1.41. The laser altimeters are switched on during take-off and landing and are not operated during any other phase of flight. During landing they are turned on and used from the CP to test their serviceability and test for discrepancies between the two laser altimeter readings. Whilst any laser altimeter readings accepted by the system can be used to initiate a ground proximity abort or to open a *Ground Touch identification window*, their readings are not used to update the UA's altitude information at the CP. The IETP suggests that the effective range of the laser altimeters is 1 to 30m. Noptel, the manufacturer, suggests that their effective range[12] is between 1 and 50m and maximum range[13] is up to 80m. The CP was declared at approximately 110m AGL. The Panel, therefore, concluded that: Exhibit 38 Exhibit 39

a. At the CP a laser altimeter reading giving true height above ground level would have been unlikely as the CP is expected to be above the effective range of the laser altimeters.

b. A laser altimeter reading from a reflection off cloud was a possibility if there is cloud below the UA.

c. It was, therefore, not reasonable to design an 'all weather' system that used the laser altimeter readings between the CP and UR point to:

(1) Open a *Ground Touch identification window*.

(2) Test for a Ground Proximity.

d. It was reasonable to activate the laser altimeters to test their serviceability from the CP.

1.4.1.42. The laser altimeter readings are used at the UR point as soon as their readings become valid[14] to provide an offset bias to the GPS height. At the UR point, if the difference between the laser altimeters is above a set threshold or one has failed[15], then an *Altimeter Difference* abort should occur unless overridden; in which case one or both laser altimeters would be disqualified. The Panel noted that from the UR point, erroneous laser altimeter readings are still possible; however, they are compared to the INS/GPS height information and the landing could be aborted if an error is detected. Therefore, if the laser altimeters could not provide an accurate height, they could be dis-qualified and the UA could land from uncorrected height information. In such an eventuality, a *Ground Touch identification window* would be opened from 20m AGL (rather than 1m). The Panel further noted that, whilst this logic seemed reasonable, a false *Ground Touch* from within the *Ground Touch identification window* (opened Exhibit 40 Exhibit 41

[12] Based on a surface with 28% reflectivity (a natural surface).

[13] Based on a surface with 90% reflectivity (ie a white surface).

[14] The Panel understood 'valid' to mean with reference to each other and the UA's GPS height.

[15] As described in the IETP Document Code WATCHKEEPER0MK1-ABA-DTF-22-50-1000-043A-A_001. IETP Document Code WATCHKEEP0MK1-AAA-C00-00-00-0000-442A states that the caution 'ATOLS Laser Altimeters Diff' means "A difference of over 20cm between the Laser Altimeters measurements or there is a measurement difference of over 5% between the Laser Altimeter measurements and the aircraft's actual altitude".

at 20m AGL), had led to the loss of WK031 when a false *Ground Touch* was also sensed.

1.4.1.43. The Panel concluded that, whilst the laser altimeter readings could not be relied upon in cloud, the UA should be able to land from GPS information alone. Therefore, the use of laser altimeters was not necessarily unreasonable if their readings were used in conjunction with other positional information and mitigation was provided through suitable system logic protection measures. In the opinion of the Panel, the VMSC system logic did not adequately mitigate the risks of incorrect laser altimeter readings because it did not compare the laser altimeter readings when it first started using them at the CP with either barometric or GPS height information, which allowed a *Ground Touch identification window* to open.

1.4.1.44. **Recommendation. The Panel recommend that Head Unmanned Air Systems Team should review the risks associated with incorrect laser altimeter readings and ensure they are adequately mitigated.**

Decision to fly

1.4.1.45. As previously described, the Panel concluded that cloud at the CP was a causal factor. Moreover the Panel considered that the operation of Watchkeeper when low cloud was forecast during the planned recovery period made the accident more likely and therefore, the decision to operate in the forecast conditions was a **contributory factor**. The environmental limitations for the operation of the system are discussed in Section 1.4.2. The levels of planning and preparation prior to the sortie and the factors which influenced the decision to fly are discussed in Section 1.4.5.

Decision to land with cloud at the CP

1.4.1.46. The Panel wanted to understand the rationale for making 3 consecutive attempts to land in the prevailing weather conditions and explore whether other options existed. The Panel considered:

a. **Prospect of a break in the weather**. The crew launched the UA knowing that there was likely to be significant amounts of low cloud and fog during the recovery with only a slight chance of an improvement later in the day. During interview the crew reported seeing clear patches on the ground prior to recovery, but not over BDN. The low cloud recovery procedure was used, which had been briefed prior to the sortie and on the first recovery attempt. Analysis of the CVR audio showed that there was no discussion on waiting for a gap in the weather. The Met Office, who may have been able to provide further information about the weather conditions, was not contacted.

Witness 1
Witness 3
Witness 4
Witness 5

Exhibit 42
Exhibit 43

b. **Low cloud recovery procedure**. The crew had briefed the use of the Low Cloud Recovery Procedure[16] as an option for the recovery prior to the sortie. In the same way that the existence of the low cloud recovery procedure had influenced the decision to fly in the forecast conditions, it was considered by the Panel that it led

Witness 1
Exhibit 44

[16] A procedure to recover the UA in low cloud was listed in the FRCs and the IETP and is covered in section 1.4.2.

the crew to believe that it was safe and normal to attempt a recovery in cloud by selecting *Alt Dev* Override on the first attempt. As discussed further in Section 1.4.2 the Panel noted a discrepancy in the Aircraft Document Set (ADS) about when to apply overrides and a difference in the low cloud recovery procedure between the IETP and FRCs.

c. **Perceived pressure to land in the allocated timeslot**. The Captain, during interview, reported feeling under pressure to land to stay within the crew duty period, but was aware that they still had plenty of crew duty time remaining. The Captain also reported considering the fact that it was going to be dark within 90 minutes of the first recovery attempt. The Panel considered that: Witness 1

(1) The WK recovery window was 1530 to 1600 hrs, with the runway embargo due to end 1600 hrs. Due to the weather, WK006 was the only planned movement at BDN from the recovery period onwards. The crew were aware that an extension, had it been requested for technical issues, would therefore, most likely have been granted. Witness 4

(2) Sunset and evening civil twilight were at 1643 hrs and 1718 hrs respectively. The L&R Det and the crew were not familiar with recovering the aircraft in darkness. The L&R Det had not completed their night flying cycle currency requirement of one night launch in a 3 month period, listed in the 1ISR FOB. Witness 1 Exhibit 5 Exhibit 45

(3) The crew duty period (normally 12 hrs with a maximum of 8 hrs flying in a 24 hr window without extension), as directed in the 1ISR Bde FOB (U2345), ended at approximately 1900 hrs. Exhibit 5

(4) The crew had discussed the possibility of an abort during the first approach, however there was some initial confusion when the Pilot attempted to advise ATC of this. He requested a 'low approach' and was advised that the visual circuit was closed. Although the Pilot clarified that the approach may terminate for a technical reason, the crew then thought that ATC were becoming agitated, believing them to be deliberately conducting circuits. Analysis of the ATC recordings showed that nothing that could be construed as articulating this was heard during any of the subsequent radio communications. Exhibit 46 Witness 6 Witness 3 Exhibit 42 Exhibit 43

1.4.1.47. **Summary**. The Panel found:

a. The availability and the normalisation of the low cloud recovery procedure lead the crew to believe that they had a good chance of landing the UA safely on the first attempt. As the crew had pre-briefed a low cloud recovery and were expecting to find the UA in cloud at the CP, the timing of the first landing attempt was driven by the start of their allocated landing time rather than by the weather conditions.

b. The crew did not consider an immediate improvement in the weather conditions was likely.