PART 1.1 – COVERING NOTE

24 Mar 16

DG DSA

SERVICE INQUIRY INTO AN ACCIDENT INVOLVING A WATCHKEEPER UNMANNED AERIAL VEHICLE (UAV) WK031 AT WEST WALES AIRPORT (WWA), ABERPORTH ON 16 OCT 14

1. The Service Inquiry Panel assembled at Parc Aberporth, on the 22 Oct 14 by order of the DG DSA (ex MAA) for the purpose of investigating the accident involving Watchkeeper UAV WK031 on 16 Oct 14 and to make recommendations in order to prevent recurrence. The Panel has concluded its enquiries and submits the Provisional Report for the Convening Authority's consideration.

PRESIDENT

[redacted]
Squadron Leader
President
WK031 Service Inquiry

MEMBERS

[redacted]
Captain
Engineering Member
WK031 Service Inquiry

[redacted]
Lieutenant
Aircrew Member
WK031 Service Inquiry

2. The following inquiry papers are enclosed:

Part 1 - The Report

Part 1.1 Covering Note
Part 1.2 Convening Orders & TORs
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 1.2 – CONVENING ORDER, TERMS OF REFERENCE AND GLOSSARY

MAA SI Convening Order

24 October 14

SI President
SI Members

Hd MilAAIB
MAA-Legad 2

Copy to:
MA/CGS
CofM (Air)

Comd JHC
Comd 1 Arty Bde

MAA DG/SI/04/14 – CONVENING ORDER FOR SERVICE INQUIRY INTO AIRCRAFT OCCURRENCE INVOLVING WATCHKEEPER WK031 ON 16 OCTOBER 14 AT 1113L

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 aviation occurrence and to make recommendations in order to prevent recurrence.

3. The SI Panel is to assemble at the 14 Sig Regt Ops Block at 0900L on Friday 24 October for formal convening of the Service Inquiry which will take place via VTC at 0930L.

4. The SI Panel comprises:

President: [redacted] **RAF**
Members: **Ops Member –** [redacted] **RN**
Eng Member – [redacted] **REME**

5. The legal advisor to the SI is [redacted] **(MAA-Legad)** and technical investigation/assistance is to be provided by the Military Air Accident Investigation Branch (MilAAIB).

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:

Hd MilAAIB / DepHd MilAAIB– Unrestricted Attendance.

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

[redacted]**, RAFCAM HF Accident Investigator – Unrestricted Attendance.**

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

[redacted], RAFCAM HF Accident Investigator – Unrestricted Attendance.

8. The Panel will initially work from facilities at Aberporth and Farnborough with long term accommodation yet to be confirmed.

9. Service manning authorities have detached the panel for SI panel duties. **This is a statutory inquiry and, as such, is now the primary duty for the panel. It is to take priority over all other duties until released by the Convening Authority personally.** Any requests for release from SI duties are, in the first instance, to be discussed with the Convening Authority.

10. Reasonable costs will be borne by DG MAA under UIN D0456A.

Original Signed

R F Garwood
AM
DG MAA – Convening Authority

Annex:

A. Terms of Reference for SI into Aviation Occurrence Involving Watchkeeper WK031 on 16 October at Parc Aberporth, West Wales Airport.

ANNEX A TO
Watchkeeper Convening Order
Dated 24 October 2014

TERMS OF REFERENCE FOR SI INTO AVIATION OCCURRENCE INVOLVING WATCHKEEPER WK031 ON 16 OCTOBER 14 AT 1113L AT PARC ABERPORTH, WEST WALES AIRPORT.

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

   a. *Investigate and, if possible, determine the cause of the occurrence, together with any contributory, aggravating and other factors and observations.*

   b. *Ascertain whether any Service personnel involved were acting in the course of their duties.*

   c. *Ascertain whether any civilian personnel involved were acting in the course of their duties.*

   d. *Examine what policies, orders and instructions were applicable and whether they were complied with.*

   e. *Determine the state of serviceability of the aircraft and relevant equipment.*

   f. *Establish the level of training, relevant competencies, qualifications and currency of the individuals involved in the accident.*

   g. *Review the levels of authority and supervision covering the task during which the incident occurred.*

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

   i. *Investigate and comment on relevant fatigue implications of individuals' activities prior to the matter under investigation.*

   j. *Determine any relevant equipment deficiencies.*

   k. *Confirm that the Aircraft Post-occurrence Management procedures were carried out correctly and that they were adequate.*

   l. *Determine and comment on any broader organizational and/or resource factors.*

   m. *Assess whether the security of personnel, equipment or information was compromised and if so to what degree.*

   n. *Ascertain value of loss/damage to the Service and/or extent (and, if readily available, the value) of loss/damage to civilian property.*

   o. *Assess any Health and Safety at Work and Environmental Protection implications in line with JSP 375 and JSP 418.*

   p. *Report and make appropriate recommendations to DG MAA.*

   q. *Produce an Aircraft occurrence Summary, to be completed within 2 wks of DG MAA signing off the SI.*

2. You are to ensure that any material provided to the Inquiry by the United States, or any other 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, or amongst the documents supporting it[2] You are not to make a judgement on the origin of any classified material[3]. In addition, the relevant PDR directorate should be informed early when dealing with the US or other foreign state material, and should be engaged in the process where doubt exists.

3. 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 your MAA Legal Advisor, Hd MilAAIB and DG MAA. Following that advice it may be necessary to reconvene reporting directly to MOD PUS.

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[2] For intellectual intelligence material this should be done through DIS (DICSD-SEC).

[2] If you are unable to positively identify the origin of the material, you must contact INFO-ACCESS DPAD or, for intelligence material, DIS (DI CSD-SEC).

GLOSSARY

Acronym/ Abbreviation	**Explanation**
ABU	Airborne Beacon Unit
ACU	Antenna Control Unit
ACM	Airspace Control Measure
ADT	Air Data Terminal
agl	Above Ground Level
ALARP	As Low As Reasonably Practicable.
AM (MF)	Accountable Manager (Military Flying)
AO	Authorising Officer
AoA	Angle of Attack
AOA	Aircraft Operating Authority
AOC	Air Officer Commanding
AoR	Area of Responsibility
AoS	Angle of Side Slip
ASIMS	Air Safety Information Management System
ASMP	Air Safety Management Plan
ASIMS	Air Safety Information Management System
ATC	Air Traffic Control
ATOLS	Automatic Take-Off & Landing System
ATZ	Air Traffic Zone
AUM	All Up Mass
AV	Air Vehicle
AWC	Air Warfare Centre
BROKEN	5 to 7 Octas of cloud cover
BIT	Built In Test
CAM	Continuing Airworthiness Manager
CAS	Calibrated Air Speed
Cat	Category
CDSDO	Chief of the Defence Staff Duty Officer
CEH	Complex Electronic Hardware
CP	Connect Point
Crew in	Process of pilot arriving at aircraft including the in-cockpit pre-start checks.
CS	Client server
CtoI	Certified to Instruct
DA	Duty Authoriser
DAIB	Defence Accident Investigation Branch (formed 1 Oct 15)
DAOS	Design Approved Organization Scheme
DDH	Delivery Duty Holder
DE&S	Defence Equipment and Support
DFLM	Deputy Flight Line Manager
DGPS	Differential Global Positioning System
DL	Data Link
DO	Design Organisation
DSA	Defence Safety Authority
DSAT	Defence System Approach to Training
EMS	Exploitation Management System
Eng	Engineering
EO	Electro Optical

EO/IR	Electro Optical & Infra Red (EO/IR)
EOP	Electro Optical Payload
EP	External Pilot
ERL	Emergency Recovery Locations
ES2	Equipment Standard 2
EWO	Electronic Warfare Officer
FAP	Final Approach Point
F700	The engineering record for a specific aircraft tail number.
FCS	Flight Control Software
FEW	1-2 Octas of cloud cover
FISO	Flight Information Service Officer
FL	Flight Level (Altitude based on Standard Pressure Setting of 1013hPa
FLIR	Forward-Looking Infra-Red
FLSCU	Flight Line Support Control Unit
FRT	Flight Real-Time
FMV	Full Motion Video
FMECA	Failure Mode, Effects and Criticality Analysis
FOB	Flying Order Book
FOO	Flight Operations Organisation
FOV	Field of View
FRC	Flight Reference Cards
ft	Feet
FTC	Fly To Coordinate
FTS	Flight Test Schedule
GBU	Ground Beacon Unit
GCS	Ground Control Station
GDT	Ground Data Terminal
GFCC	Ground Flight Control Computer
GMTI	Ground Moving Target Indicator
Gp	Group.
Gp Capt	Group Captain (OF5 rank)
GPS	Global Positioning System
GRAD	Ground Radio
GMCC	Ground Mission Control Computer
GRU	Ground Radar Unit
GUI	Graphical User Interface
HF	Human Factors
HCI	Human Computer Interface
HoF	Head of Flying
hrs	Hours
IAS	Indicated Airspeed
IETP	Interactive Electronic Technical Publication
IFR	Instrument Flight Rules
INS/GPS	Inertial Navigation System/Global Positioning System
IO	On-scene Incident Officer – fire officer who takes charge initially
ITE	Independent Technical Evaluation
JARTS	Joint Aircraft Recovery and Transportation Squadron
JSP	Joint Service Publication
kg	Kilograms.
kts	Knots (Indicated Air Speed)
Km	Kilometres.

LDA	Landing Distance Available
LL	Lost Link
LMAR	Lightweight Multimode Air Radio
LoS	Line of Sight
LRU	Line Replacemnet Units
LSS	Laser Sub System
L&R	Launch & Recovery Detachment
LTDRF	Laser Target Designator/Laser Range Finder

MAA	Military Aviation Authority
MACP	Military Assurance Certification Process
MAOS	Maintenance Approved Organization Scheme
MAP	Maintenance and Airworthiness Processes
NATS	National Air Traffic Service
MET	Metrological
MFTP	Military Flight Test Permit
MIG	Materials Integrity Group
MilAAIB	Military Air Accident Investigation Branch
min	Minute
Mk	Mark
MPCM	Manual of Post Crash Management
MRP	Military Aviation Authority Regulatory Publications.
MOD	Ministry of Defence
MO	Master Override

NBDL	Narrow Band Data Link
NHP	Non-Handling Pilot
nm	Nautical Mile

OAT	Outside Air Temperature.
OC	Officer Commanding
Octas	The unit of measurement for cloud cover. 1 Octa of cloud = eighth of the sky being obscured. 8 Octas = total cloud coverage.
OCU	Operational Conversion Unit
ODH	Operational Duty Holder.
OEM	Original Equipment Manufacturer
Ops	Operations

P1	UAV Operator
P2	Payload operator
PATE	Portable Air Vehicle Test Equipment
PCDU	Power Control and Distribution Unit
PCMIO	Post Crash Management Incident Officer
PCM	Post Crash Management
PFL	Practice Forced Landing
PO	Payload Operator
PSU	Power Supply Unit
PT	Project Team
PTF	Partial Test Flight
QFE	Atmospheric pressure at aerodrome elevation (or at runway threshold).
QNH	Altimeter subscale setting to obtain elevation when on the ground.
QNI	Qualified Navigation instructor

RA	Royal Artillery
RA	Regulatory Article

RAF	Royal Air Force
RAF CAM	Royal Air Force Centre of Aviation Medicine
RFFS	Rescue Fire Fighter Service
RFI	Request for Information
RMSC	Reconnaissance Management System Computer
ROC	Rate Of Climb
RPM	Revolutions Per Minute
RR	Risk Register
RSA	Royal School of Artillery
RtL	Risk to Life.
RTS	Release To Service
SAR	Synthetic Aperture Radar
secs	Seconds
SI	Service Inquiry
SIL	Software Integrity Level
SME	Subject Matter Expert
SNOW	Serial Number Of Work
SOP	Standard Operating Procedure
SQEP	Suitably Qualified and Experienced Person
Sqn	Squadron
Sqn Ldr	Squadron Leader (OF3 rank)
SRB	Safety Review Board
STDA	Statement of Type Design Assurance
Stn	Station
SUTTO	Start Up, Taxi and Take Off
TAA	Type Airworthiness Authority
TCR	Type Certification Recommendations
TORs	Terms of Reference
U-TacS	UAV Tactical Systems Ltd
UAV	Unmanned Aerial Vehicle
UAV-p	UAV Pilot
UAV-c	UAV Commander
UR	Under Run
UTP	Unit Test Pilot.
VFR	Visual Flight Rules
VMS	Vehicle Management System
VMSC	Vehicle Management System Computer
Warned out	To notify or inform.
WBDL	Wide Band Data Link
WCA	Warning Captions and Alerts
Wg Cdr	Wing Commander (OF4 Rank)
WoW	Weight on Wheels
WPs	Waypoints
WWA	West Wales Airport

PART 1.3 – NARRATIVE OF EVENTS

All times ZULU.

Synopsis

1.3.1. At 1113hrs on 16 Oct 14, a Watchkeeper Unmanned Aerial Vehicle (UAV), WK031, operated by a civilian crew from UAV Tactical Systems Ltd (U-TacS), was involved in an accident while making an approach to land at West Wales Airport (WWA), Aberporth. Initial witness statements from the scene reported that the UAV was making a planned approach to Runway 26 (Rwy 26). At approximately 10-15ft above the runway surface the vehicle pitched rapidly nose down and impacted the ground, causing considerable damage to the fuselage structure. The vehicle undercarriage collapsed as it continued to slide along the runway before coming to rest on the runway's left hand edge (Fig 1). There was no post crash fire. The crew in the Ground Control Station (GCS) were unaware that an accident had occurred until a 'crash' call was received on the WWA Tower frequency. Subsequent Post Crash Management (PCM) procedures were rapidly initiated with both the UAV, GCS, associated equipment and documentation quarantined for investigation. The airport was then closed to all fixed wing aircraft.

Witness 2
Witness 6
Exhibit 1

Figure 1 - WK031 on Southern side of Rwy 26

Pre-Accident Events

Aircraft history

1.3.2. WK031 was allocated to the Military Aircraft Register on 26 Feb 14. The UAV was under operational control of U-TacS as the Watchkeeper Test and Evaluation Unit, with flying conducted under a Military Flight Test Permit (MFTP)[1]. WK031 had completed its post production flight test with U-TacS on 25 Jun 14 and the Off Test Certificate was signed on 28 Jul 14. WK031 had flown a total of 13:02 airframe hours.

Exhibit 2

1.3.3. The UAV was fitted with a Radar in the forward payload section and Electro Optic Payload (EOP) in the rear section. There was a current Flight Authorisation

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[1] Military Flight Test Permit ref: WKFTO/MFTP/WK060 Issue 15.

Certificate signed on 14 Oct 14, valid for 1 month authorising flights in accordance with the appropriate MFTP. The UAV had a replacement Power Control Distribution Unit (PCDU) fitted the day before the accident, which was functionally tested and assessed as serviceable prior to the flight. The last flight servicing was carried out on the morning of 16 Oct 14, prior to the accident. The recorded All Up Mass (AUM) of the UAV at the start of the sortie was 462.5kg.

Crew composition

1.3.4. **UAV Commander (UAV-c)**. The UAV-c had 13 years military UAV flying experience, with a total of 800 flying hours on Hermes 450 and Watchkeeper. On arrival with U-TacS, he had qualified as an Aircrew Instructor and completed his Watchkeeper training with Elbit in Israel before the first Watchkeeper flight within the UK. At the time of the accident he had 5 years of Watchkeeper flying experience. He had completed a single sortie within 60 days as UAV-c and one sortie within 30 days in the Vehicle Operator (UAV-p1) role, fulfilling the currency requirements. In the previous 14 days he had completed 3 sorties totalling 8:00 hours that included a sortie as the UAV-c and an Annual Competency Check. He was also acting as the UAV Pilot Instructor monitoring the UAV-p1.

Exhibit 3

1.3.5. **UAV-p1 (Vehicle Operator)**. The UAV-p1 was new to the role and had arrived at U-TacS with 10 years military experience with the RAF, which included 8 years of flying as a Chinook helicopter pilot with a total of 2000 flying hours. The UAV-p1 was not qualified in this role and was under training. He had completed simulator training throughout Aug 14 and had flown 2 training sorties at WWA in Sep 14 and a further 3 sorties in Oct 14. In the previous 90 days he had flown 6:15 hours on Watchkeeper and 7:45 hours in the simulator at U-TacS based in Leicester.

Exhibit 4

1.3.6. **UAV-p2/Payload Operator (PO)**. The UAV-p2 arrived at U-TacS with 21 years military experience, having served both in the Navy and the Army. His last Army tour was as a Predator Payload operator. Once at U-TacS, he completed his Watchkeeper training both in Israel and the UK before the first UK flight. He was a qualified Watchkeeper aircrew instructor and was deployed with the Royal Artillery (RA) to Afghanistan to assist with payload training and front-line operations. At the time of the accident he was conducting a UAV-p2 currency flight and had 4 years of flying experience on Watchkeeper, with a total of 1300 UAV flying hours on Predator and Watchkeeper. The UAV-p2 was not current in this role but had flown within 31 days as a UAV-c. He had not operated at WWA in the previous 3 months but had accumulated higher than average hours in an operational theatre. In the previous 90 days he had completed 16 sorties accruing 30:42 hours. In the previous 90 days he had flown 41:47 hours on Watchkeeper and 17:30 hours in the simulator.

Exhibit 5

1.3.7. **Authorising Officer (AO)**. The AO had 25 years military experience as an operator and instructor. His background included Canberra and Tornado flying tours, a tour as a Qualified Navigation Instructor (QNI), a unit Electronic Warfare Officer (EWO) in the Harrier force, an Aerosystems Course graduate and a tour conducting flight trials management and execution at MoD Boscombe Down. He completed his Watchkeeper training within Israel and the UK before the first UK flight. At the time of the accident he had a total of 3000 flying hours across all the platforms he has operated. The AO was monitoring the UAV-p2's currency flying and acted as the Flight Log Keeper. The AO was current in both UAV-c and UAV-p1 roles, having completed a sortie 2 days before the accident where he fulfilled both positions. In the previous 90 days he had flown 25:35 hours.

Exhibit 6
Exhibit 7

Previous 24 hours

1.3.8. A planned sortie the day before the accident was cancelled due to poor meteorological (MET) conditions. No other Watchkeeper sorties were planned or conducted.

Accident Flight details

1.3.9. The mission on 16 Oct 14 was planned as a joint Type Conversion (Exercise FLY2) for the UAV-p1 and a currency flight in Payload Management for the UAV-p2. The UAV-p1 was under instruction and supervision from the UAV-c whilst the UAV-p2 was being monitored and supervised by the Authoriser. The UAV-c signed for the aircraft as normal.

Witness 3
Exhibit 8

1.3.10. The crew received a MET forecast which indicated that there would be showers and thunderstorms (TEMPO[2] PROB 30[3]) during the period with winds of 180°/12kts TEMPO gusting 20kts. The crew decided that there would be sufficient gaps in between the showers to enable the sortie to take place safely.

Witness 1
Exhibit 9

1.3.11. Following normal pre-flight checks, WK031 was launched from Rwy 26 at WWA at 0915hrs with approximately 45kg of AVGAS fuel, equating to 4:30 hours endurance and 2 operational payloads. The weather was clear on take-off, with surface wind reported as 180°/12kts. Prior to departing to the training area, the UAV-p1 carried out two successful planned circuits to the semi-flare[4] using the normal automated systems; the landing was manually aborted each time by the UAV-p1 as planned. The UAV was climbed to 5000ft Above Mean Sea Level (AMSL) and flown into the designated Danger Area D201 (West Wales Danger Area), to conduct route flying and mission tasking. During this phase of flight the Narrow Band Data-Link dropped out on 4 occasions but this issue rectified itself without crew intervention.

Witness 1
Witness 3
Witness 4
Witness5
Exhibit 1

1.3.12. Throughout the sortie the crew were aware of the need to monitor the weather conditions, with the UAV-p2 conducting regular sweeps with the EOP to assess cloud structure. Within the operating area the weather was good, with the UAV clear of cloud and occasionally entering cloud tops at 5000ft AMSL.

Witness 4

1.3.13. The UAV-p1's training was completed coincident with a report of deteriorating weather conditions from Air Traffic Control (ATC) at WWA. The crew decided to recover the UAV at 1052hrs and commenced descent into the cloud below them to arrive at 3000ft AMSL. During the descent through cloud, Narrow Band Data Link was lost and reacquired, and one pitot-static related caption was displayed to the crew[5] which was not unexpected. The UAV descended to 2300ft WWA QNH[6] (Fig 2) when a further 2 pitot-static related captions displayed to the crew[7]. At 1106hrs the UAV entered the Air Traffic Zone (ATZ) for WWA when the crew were informed by ATC that the surface wind was 210°/10kts and thunderstorm warning 'moderate' was in force, coinciding with the report about the deteriorating weather conditions. The crew selected 'Altitude Difference Override' because of their concerns about laser altimeter performance over a wet runway, mindful that the system's safety logic would automatically abort the approach if it

Witness 1
Witness 3
Witness 4
Witness 5
Exhibit 11

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[2] TEMPO: Temporarily in the stated period.

[3] PROB 30: 30% probability that for a period of no more than 2 hours within the forecast period that thunderstorms and associated hazards of severe icing and turbulence would be present.

[4] Semi-Flare. The UAV reduces its glide angle from 3^0 to 1.5^0.

[5] 'Air Data Unit (ADU) estimated Angle of Slip (AOS) in use'.

[6] Based on pressure altitude of the centre point of the main runway above mean sea level at WWA.

[7] 'ADU velocity sensor redundancy lost' and 'ADU estimated Angle of Attack (AOA).

detected a height discrepancy. On the first leg of the high circuit, two further captions[8] illuminated but these cleared and the UAV maintained its planned descent profile. The crew discussed the deteriorating weather, and made a decision to select 'Master Override'. This was to prevent the UAV's safety logic from aborting the approach for any other performance related issues, and therefore prevent the UAV from overshooting into the deteriorating weather conditions.

1.3.14. The UAV continued its descent through the planned waypoints to the downwind leg where it broke cloud at approximately 1100-1300ft WWA QNH. Eyewitnesses saw the UAV continue along the normal ground track before it continued through the 'Connect Point' where the UAV automatically configured for the final approach. The UAV turned onto its Final Approach Point (FAP) where it met the Automatic Take-off and Landing System (ATOLS) 'sleeve'[9] and an ATOLS 'radar lock'[10] was observed by the crew. The UAV descended as expected on the glide path towards the touchdown point and overflew Rwy 26 threshold at approximately 100-120ft AGL (Fig 2). The wind was reported as 210°/9kts.

Witness 6
Exhibit 10
Exhibit 11
Exhibit 12

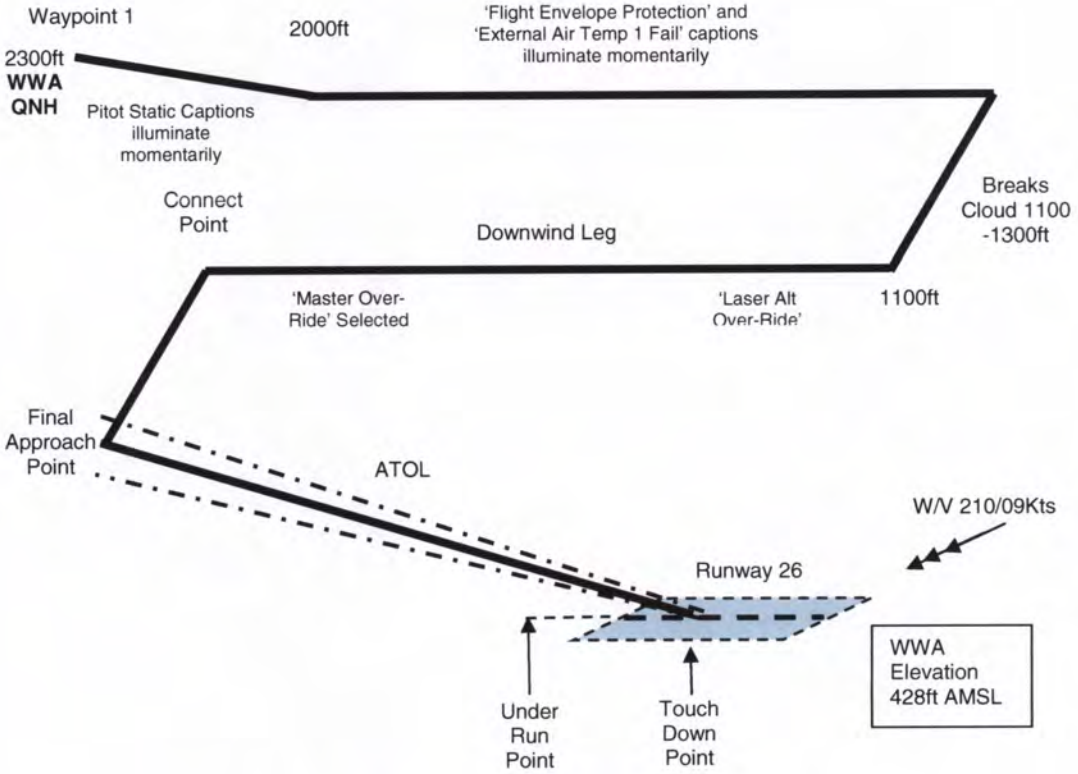

Figure 2 - Flight Path and Key Events of WK031 on 16 Oct 14

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[8] 'Flight Envelope Protection' and 'External Air Temp 1 Fail'.
[9] Describes the azimuth and glideslope funnel that the UAV needs to achieve to line up with the runway.
[10] The system has ensured that the UAV is within pre-set parameters for an ATOLS controlled approach.

Accident Event

1.3.15. During the final approach, the crew received no indications or alerts from the system and were content that the approach was stable. Post 'Semi-Flare'[11] which occurred around 7m above touchdown, the UAV-p2 stowed the EOP (as per normal procedure) to ensure that the sensor window was protected. At this point, the GCS crew had no visual picture for the final seconds of the approach and waited for the normal system cues that the UAV was on the ground. As expected the ATOLS window informed the crew that the vehicle had made 'Ground Contact' and was in 'Free Roll'. The system suddenly indicated loss of both data links. Simultaneously, a 'crash' call was received by the GCS on the WWA Tower frequency. The UAV-p2 called for 'engine cut' and the UAV-p1 pressed the Engine Cut button, which had no effect.

Witness 1
Witness 3
Witness 4
Witness 5
Exhibit 10
Exhibit 11
Exhibit 12

1.3.16. Post the UAV's 'Flare and de-crab' external eyewitnesses observed the UAV pitch rapidly nose down from a height of approximately 10-15ft AGL and impact the runway, causing considerable damage to the fuselage structure. The vehicle continued to slide along the runway with the undercarriage collapsed before coming to rest on the runway's southern side at 1113hrs.

Witness 2
Witness 6
Exhibit 10
Exhibit 11
Exhibit 12

Post Crash Management (PCM)

1.3.17. ATC conducted the immediate emergency response actions and activated the PCM Plan. The WWA Fire Service arrived on scene within 1 minute as they were already positioned close to the runway on a separate task. They identified a fuel leak but no fire; at this stage the UAV's battery power and white strobes were still on. The ATC Manager/Duty Flight Information Service Officer authorised U-TacS engineers to disconnect the emergency battery before the UAV was declared safe. The GCS, ATOLS and associated recovery equipment were quarantined.

Witness 2
Exhibit 13

Salvage operations

1.3.18. Defence AIB investigators[12] arrived at WWA just before dark on the evening of 16 Oct 14. Initial evidence gathering and preservation was carried out, constrained by the lack of remaining day light. The following day at 0730hrs, the Vehicle Management System Computer (VMSC) was removed from the UAV under supervision of the Defence AIB in order to transport it to the U-TacS facility at Leicester for download. The V-Tails were removed, followed by the main wing which was split into 3 sections. The UAV was lifted using a wheeled gantry onto a flatbed trailer and transported to U-TacS hanger for quarantined storage. The runway was cleared, a Foreign Object Debris (FOD) check carried out, and re-opened by 1400hrs on 17 Oct 14.

Annex A

1.3.19. On 21 Oct 14, U-TacS maintenance personnel, under supervision of the Defence AIB, removed the engine from the UAV to facilitate the fuselage fitting into the specialist containers for transportation to AAIB, Farnborough. Two cryptographic components were removed from the UAV and placed into a secure stowage prior to recovery to Defence AIB Crypto stowage at Aldershot Garrison. On the 22 Oct 14, the UAV fuselage, V-Tails, main wing and engine were recovered to the AAIB by the Joint Aircraft Recovery and Transportation Squadron (JARTS).

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[11] Semi-Flare - The UAV is commanded to line up (straight) with the runway centreline for landing. Decrab is a sub set of semi-flare but was not registered during this event.

[12] Orginally the Military Accident Investigation Branch; reorganised to Defence AIB on 1 Oct 15.

PART 1.4 – ANALYSIS AND FINDINGS

Methodology

Determining the Cause

Master Override (MO) Selection

Laser Altimeter Disqualification

Vertical Acceleration and Pitch Rates experienced by the UAV

Assurance

Other Factors

Summary of Findings

Introduction

1.4.1. The WK031 Service Inquiry (SI) was convened on 24 Oct 14 to investigate the circumstances surrounding the accident to a Watchkeeper (WK) Unmanned Air Vehicle (UAV) operated by Thales at West Wales Airport (WWA), Aberporth, and to make recommendations in order to enhance Defence air safety. Whilst the initial focus for the Panel centred on the technical aspects of the accident, a wide range of related organisational issues were also investigated to inform the Panel's findings.

1.4.2. The Panel had a wealth of physical evidence to examine, as well as the ability to interrogate the UAV's internal Vehicle Management System Computer (VMSC) and the mission data from within the Ground Control Station (GCS). Access to these areas was invaluable in determining the cause and it should be noted that the assistance from Industry was essential in extracting the relevant data. Overall, the Panel found the investigation challenging due to the complex technical nature of the system and the difficulty in acquiring contextual information on design and assurance decisions made years previously.

Methodology

1.4.3. **Accident Factors**. Once an accident factor had been determined it was then assigned to one the following categories:

a. **Cause**. An event which 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. **Observations**. An issue that was not relevant to the accident but worthy of consideration to promote better working practices.

1.4.4. **Available evidence**. The Panel had access to the following evidence:

a. Interviews with the crew of WK031 and other witnesses.

b. Formal written statements from witnesses.

c. Electronic data from the Unmanned Aerial Vehicle (UAV) Vehicle Management System Computer (VMSC) and GCS.

d. GCS Multi Channel Voice Recorder.

e. Photography from various sources.

f. Relevant orders.

g. Terms of Reference (TORs) and documentation including flying logbooks.

h. Aircraft documentation, sortie planning, briefing materials and engineering documentation.

i. WK031 UAV at the crash site/ hanger.

j. Technical Annex by Defence Accident Investigation Branch (Defence AIB).

k. Technical report by 1710 NAS (Naval Air Squadron).

l. HF Report provided by RAF Centre for Aviation Medicine (RAFCAM).

m. Hybrid Simulator at UAV Tactical Systems Ltd (U-TacS) Leicester.

n. All flight safety related material, including previous incidents.

o. Land Site Survey (LSS) at WWA conducted by Joint Aircraft Recovery and Transportation (JARTS).

1.4.5. **Services**. The Panel was assisted by the following personnel and agencies:

a. Defence AIB.

b. RAF Centre of Aviation Medicine (CAM).

c. 1710 NAS Handling Squadron.

d. JARTS.

e. U-TacS.

f. Thales.

g. QinetiQ.

h. Rockwell Collins (Virginia, USA).

i. Noptel (Oulu, Finland)

j. UAST

1.4.6. **Factors considered by the Panel**. Two days after the accident, the Panel and the Type Airworthiness Authority (TAA) received an initial report from Elbit that indicated that the cause was related to a wind gust that led to the UAV sensing 'Ground Touch' earlier in the approach whilst it was being flown with 'Master Override' (MO) selected. The Panel accepted the report as an initial starting point but sought to understand why the system logic had determined the UAV was on the ground when in fact it was not. Accordingly, the Panel analysed the following factors: Exhibit 14

a. The software landing logic.

b. The decision to use Master Override (MO) including available information, training, historical use and pre-conditions of the WK031 sortie.

c. Crew composition, qualifications, authorisations and currency.

d. Meteorological conditions.

e. Laser altimeter failure/height difference.

f. Vertical acceleration and pitch rates experienced by WK031.

g. VMSC Software assurance.

h. Post-Crash Management (PCM).

Determining the Cause

Introduction

1.4.7. The Panel focussed its initial investigation on the final stages of the flight and in particular the final pitch down event. Data from the Ground Control System (GCS) mission files and the UAV Vehicle Management System Computer (VMSC) were the priority areas for the investigation. The GCS had recorded Mission data, Client Server (CS) data, Ground Flight Control Computer (GFCC) data and Payload telemetry. All of this was captured and downloaded in raw format during the Post-Crash Management (PCM) phase by the Defence AIB. Subsequently, the VMSC data was downloaded by U-TacS under Defence AIB supervision and sent to the UAV manufacturer, Elbit, in Israel for initial analysis.

Watchkeeper Project Organisation

1.4.8. Thales UK are the Prime Contractor Management Organisation (PCMO) and Design Authority for Watchkeeper. They were awarded the contract for the development, manufacture and initial support phases of the Watchkeeper programme in Aug 05. The Watchkeeper Industry team led by the PCMO included: Cubic Corporation (datalinks), Elbit (air vehicles), LogicaCMG (digital battlespace integration), Marshall SV (ground station shelters and vehicles), Praxis (programme safety), UAV Engines Ltd (UAV engine) and Vega (training). In accordance with the MAA's Master Glossary, MAA02, Design Authority (DA) and Design Organisation (DO) are now referred to as 'A Designer'. The top level Designers for Watchkeeper are as follows:

a. Thales - Designer for the Unmanned Air System (UAS).

b. Elbit - Designer for the Unmanned Air Vehicle (UAV).

c. UAV Engines Ltd - Designer for the Engine Assembly.

Additionally, a joint venture company, UAV Tactical Systems Ltd (U-TacS), based in Leicester, was set up by Thales UK and Elbit to produce the Watchkeeper system in the UK. U-TacS is contracted to provide UAV crews for Watchkeeper operations at West Wales Airport (WWA). For the purposes of this document, Elbit will be referred to as 'The Designer'.

System overview

1.4.9. In order to appreciate the technical analysis it is important that the reader has a basic understanding of the whole system and how the sub-systems communicate with each other to ensure the UAV is safely operated. Furthermore, this section will highlight how the human operators interface with the system, what they can or cannot influence and how they achieve situational awareness.

1.4.10. Watchkeeper 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 UAV[1] pre-flight preparation, launch, operation and recovery whilst controlled from a Ground Control Station (GCS) (Fig 1). There are also associated ground elements to enable transportation, storage, and maintenance of the UAV.

1.4.11. The Ground Systems include the GCS and all ancillary equipment essential to maintain safe flight, take-off and landing. This includes the:

a. Ground Data Terminal (GDT).

b. Automatic Take Off and Landing System (ATOLS).

c. Portable Aircraft Test Equipment (PATE).

d. Arrestor System.

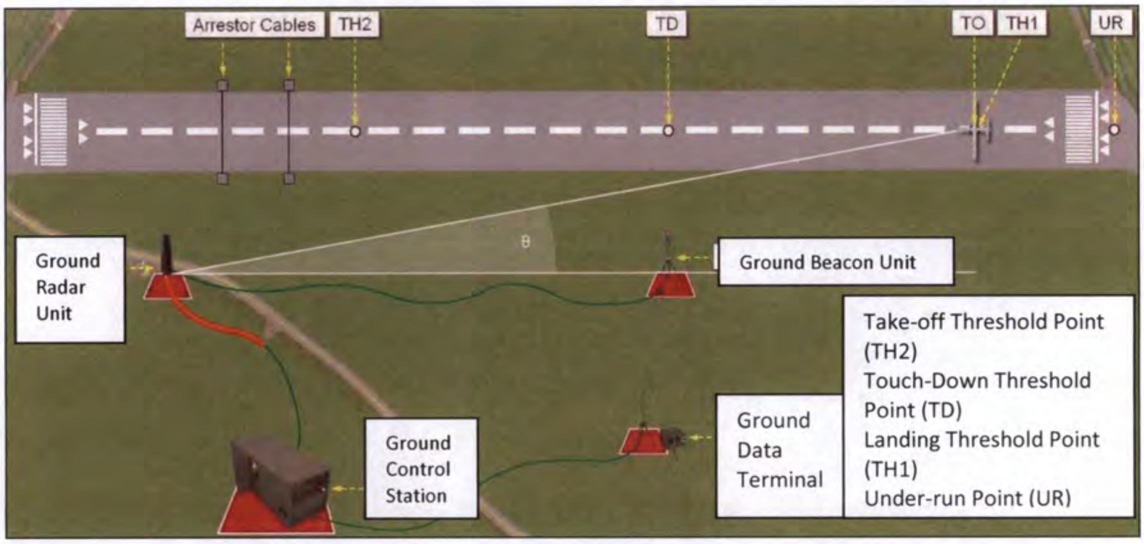

Figure 1 - Watchkeeper System – Ground Elements

1.4.12. **Unmanned Aerial Vehicle (UAV)**. The UAV comprises a cylindrical fuselage, main wing, V-Tails and a rear-mounted rotary engine with a 2-bladed pusher type propeller (Fig 2). 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. The UAV has a length of 6.50 m, a 10.95 m wingspan and an overall height of 2.18m.

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[1] It should be noted that the Unmanned Air Vehicle (UAV) is the airborne segment of the Unmanned Air System (UAS).

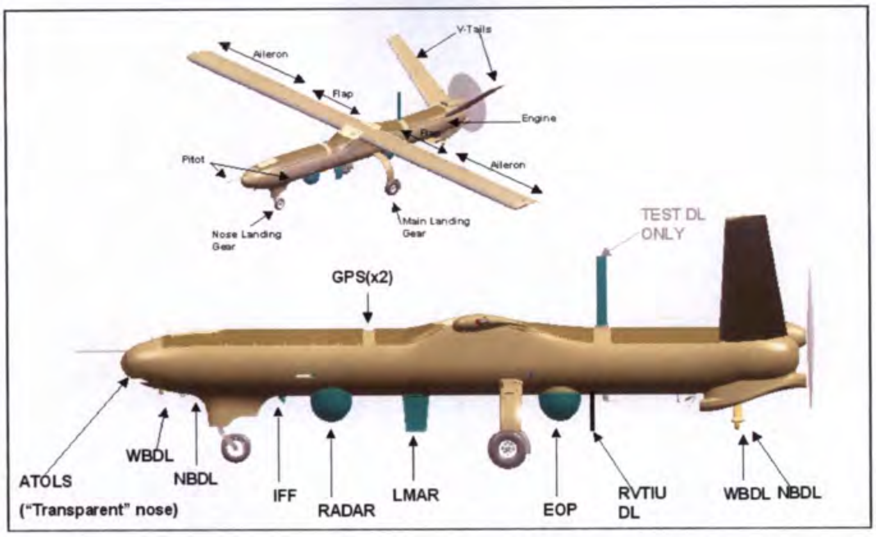

Figure 2 - General view of the Watchkeeper UAV

a. **Fuselage**. The fuselage is of a monocoque, carbon composite type design with a non-retractable tricycle undercarriage. It has a steerable nose landing gear assembly with a fixed main landing gear to enable the UAV to take-off and land on paved and semi-prepared airstrips. On landing, the UAV is halted by a fixed arrestor hook system. The majority of the avionic components are packaged inside the fuselage, with the Synthetic Aperture Radar (SAR) and Electro Optical Payload (EOP) protruding beneath the fuselage. The fuselage houses a complex suite of sensors designed to resolve the UAV aerodynamic geometry as well as its position in space.

b. **Flight Controls**. All flight control surfaces are moved by dual redundant electro-mechanical actuators located in the wings and rear fuselage under the control of the Vehicle Management System Computer (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 Flight Control Software within the VMSC maintains the UAV flight within a pre-designated operational envelope providing a significant safety margin against structural and flight limitations. In flight the VMSC Flight Control Software is programmed to protect against operation outside of the flight envelope design limitations.

1.4.13. **Ground Control Station (GCS)**. The GCS is a 20ft long, specifically designed, ISO-type container used by the crew for planning missions and for the command and control of the UAV and its sensor payloads during missions (Fig 3). Each GCS can accommodate a UAV-pilot (UAV-p), a Payload Operator (PO), a Mission Commander (UAV-c) and a Signaller.

Figure 3 – Ground Control Station (GCS)

1.4.14. **Ground Data Terminal (GDT)**. The GDT comprises external ground equipment (Fig 4) 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 UAV status data and have the facility to relay imagery back to the GCS.

Figure 4 – Ground Data Terminal (GDT)

1.4.15. **Communications**. The GCS is fitted for BOWMAN secure military tactical Comms. It also houses a V/UHF ground radio for direct Comms between the GCS and Air Traffic Control (ATC) and a Lightweight Multimode Air Radio for Comms between the UAV and other assets local to the Area of Operations. The ground crew, outside of the GCS, generally use man-portable 'walky-talky' type VHF radios to communicate directly with the ATC Tower and the GCS. The WWA Tower controller[2] also has a dedicated radio for essential communications with the GCS crew and ground crew.

1.4.16. **Automatic Take-off and Landing (ATOL)**. Watchkeeper can perform an ATOL by using either the Automatic Take-off and Landing System (ATOLS) or GPS[3] Take-off and Landing System (GTOLS). ATOLS is detailed in the Release to Service

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[2] Flight Information Safety Officer (FISO)

[3] Global Positioning System

(RTS) as a 'complementary means of landing, with the minimum requirement being the Vehicle Management System based GTOLS', within the UAV. However, notwithstanding RTS definition, the VMSC will select the more accurate ATOLS in preference to the GTOLS during the landing phase. Additionally, even though ATOLS is considered by the RTS as a landing aid it is routinely used by U -TacS and the Royal Artillery as the default method for landing.

1.4.17. **ATOLS Components**. ATOLS comprises several key components, namely the Ground Beacon Unit (GBU) (Fig 5) which acts as a terrestrial reference point, the Ground Radar Unit (GRU) (Fig 6) and the Airborne Beacon Unit (ABU). The GRU and GBU are located next to the runway at accurately surveyed points and the ABU is located in the nose of the UAV. The GRU tracks the position of the UAV and provides position 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 UAV can still perform an automatic landing by reverting to the GTOLS.

Figure 5 - Ground Beacon Unit (GBU)

Figure 6 – Ground Radar Unit (GRU)

1.4.18. **Portable Aircraft Test Equipment (PATE)**. The PATE is normally housed within the Flight Line Section Command Unit (FLSCU), a modified Pinzgauer vehicle (Fig 7) that is also used to tow the UAV during airfield /strip operations. The main functions of the PATE include:

a. UAV 'Before and After Flight' checks.

b. UAV functional system tests.

c. Pre-flight checks.

d. Engine start.

e. Data upload/ download.

f. Supporting fault diagnostics to Line Replaceable Unit (LRU) level including payloads.

Figure 7 - The Portable Air Vehicle Test Equipment (PATE)

1.4.19. **Vehicle Management System (VMS)**. The VMS is an all-encompassing term used to describe the essential electronic installations within the UAV and the associated top level tasks it carries out. It is an amalgamation of LRUs designed to fully prioritise and task the semi-autonomous UAV 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 which is mounted in the forward section of the fuselage. The VMS has full authoritative control of the UAV flying controls, utilising information derived from the UAV navigation instrument suite. The VMS monitors and controls the various systems on the UAV where real time information is relayed via the data links to the GCS for display on the client server Human Computer Interface.

1.4.20. **Vehicle Management System Computer (VMSC)**. The VMSC forms the 'brain' of the UAV and is a single physical LRU; it houses dual redundant computers primarily responsible for controlling the VMS (Fig 8). An in-built VMS monitor compares the health status of the two computers (Side A and B) and will decide which computer to utilise. The VMSC is a software based computer system which houses a multitude of hardware interfaces designed to interact in real time with sensors, monitors and controls incorporated within the UAV. It responds to the pre-programmed flight mission plan and reacts dynamically to near real time commands received from the GCS via the data links. It is designed to automate routine tasks normally carried out by the pilot of a conventional aircraft through all phases of flight from Engine Start to Engine cut, including Automated Take Off and Landing.

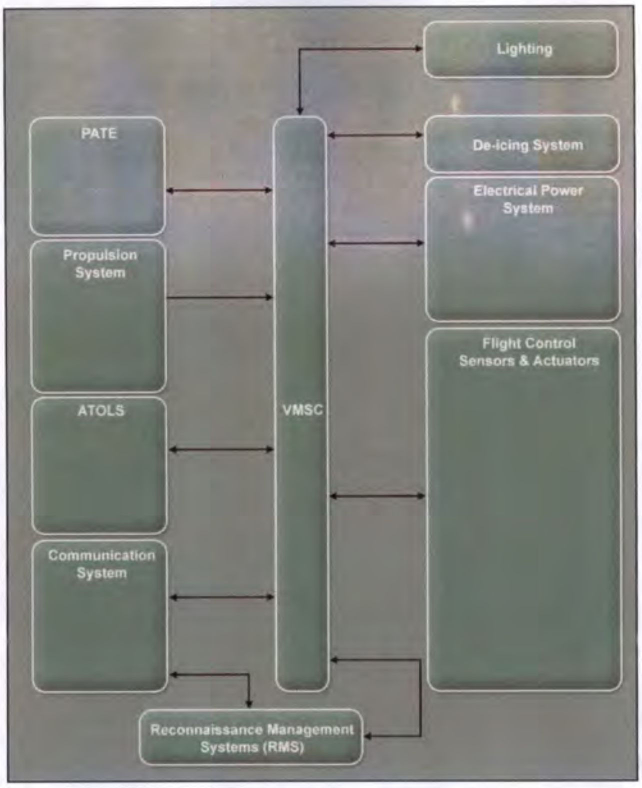

Figure 8 - Vehicle Management System Computer (VMSC)

1.4.21. **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 UAV 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.

1.4.22. **Inertial Navigation and Global Positioning System**. There are 2 Athena GS-411 units located side by side and mounted on the centre of the fuselage. They are integrated Inertial Navigation and Global Positioning System (INS/GPS) units, which work in conjunction with a dual redundant pitot system and are augmented by dual redundant Magnetometers. In the event of dual INS/GPS failure (or GPS denial) the UAV's position can be calculated by range, azimuth and elevation data from the data link. In the event of both GPS and data link failure the UAV 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. Worthy of note, the GS-411 units are used to sense changes in vertical acceleration and pitch rate, used in a software based pseudo ‘Weight on Wheels’ (WoW1) ground-touch sensing system within the VMSC, which will be discussed in Para 1.4.24.

1.4.23. **Pitot Systems**. There are 2 dual redundant pitot systems fitted to the Watchkeeper. Both the Kollsman (Fig 9) and Space Age pitot probes (Fig 10) supply static and total pressure, which feeds dual redundant Air Data Units (ADU) within the Athena units. 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.

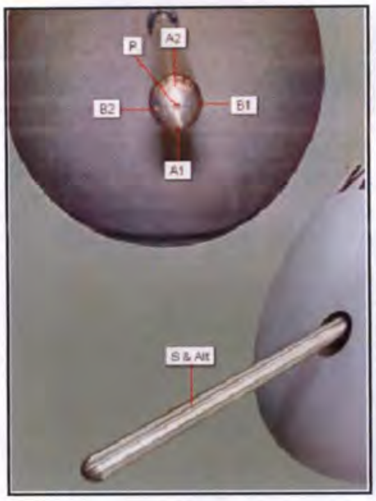

Figure 9 – Kollsman Pitot Probe

Figure 10 – Space Age Pitot

1.4.24. **Weight on Wheels (WoW) systems**. There are 2 separate WoW systems in the UAV. There is the WoW1 system which is a mathematical algorithm using accelerometer inputs sensed by the INS/GPS units and fed to the VMSC for resolution. There is also a mechanical 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 UAV is on the ground. Of note, the WoW2 switch is not used by the VMSC to determine whether the UAV is on the ground or not. The Panel found that during the development of Watchkeeper, a prototype UAV 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. The Designer indicated that there had been some failures of the mechanical WoW system when fitted to the Hermes 450 UAV, most likely through heavy landings, which had resulted in the main landing gear suffering damage. The Designer also highlighted that one of the operational requirements for the Watchkeeper design specification was that the UAV needed to be able to operate from semi-prepared take-off and landing strips, which made this particular design of mechanical WoW system susceptible to damage. It was this over-arching requirement which led the Designer to favour the software based pseudo WoW algorithm embedded within the VMSC and remove the mechanical WoW system.

Annex A

1.4.25. **Laser Altimeters**. The UAV contains 2 Noptel CMP3 laser altimeters situated just forward of the fuel tank under the fuselage. They supply accurate height measurements to the VMSC which is then used by the ATOLS/GTOLS in the landing process. This additional accuracy ensures the UAV lands smoothly and helps it to account for imperfections in landing strip elevation that the system would otherwise be unaware of. The VMSC evaluates the laser altimeter readings from the Underrun point. They are switched on and off automatically by the Power Control Distribution Unit (PCDU), commanded by the VMSC at the Connect Point and do not operate during any other part of normal flight.

Annex A

Normal ATOL approach and landing

1.4.26. **Normal ATOL approach**. The Watchkeeper VMSC Flight Control Software system is programmed automatically to prioritise aircraft attitude, speed, height and bearing dependant 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. For the purposes of this investigation only the landing phase from Downwind, through the Connect Point (CP) to Touch Down will be discussed. These key phases, points and heights are detailed below and should be read with reference to Fig 11. Of note, these points remain the same whether the UAV is carrying out an ATOLS or a GTOLS landing with the only difference being which sensor is providing UAV height and position information to the VMSC.

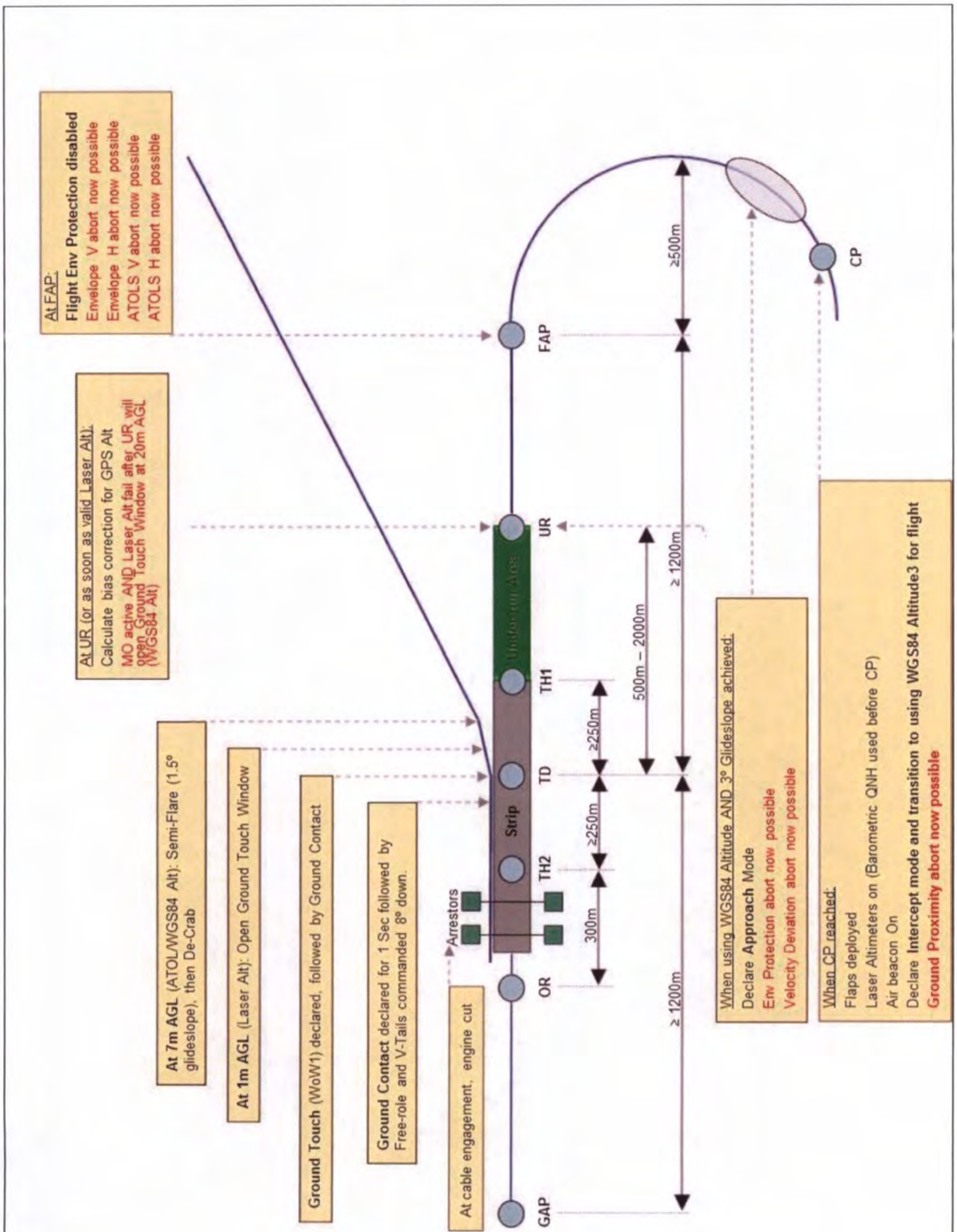

Figure 11 – Watchkeeper Normal Approach Circuit Diagram

a. **The Downwind Leg**. During this phase, the VMSC Flight Control Software will attempt to maintain a stable TAS by controlling engine throttle commands. The UAV 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.

b. **The Connect Point (CP)**. At this point, the flaps are commanded down to allow the TAS to reduce to approximately 55kts. The GPS (World Geodetic System WGS84 Reference) is now used for height reference after being transferred from the barometric channels. Both laser altimeters are energised and tested. Concurrently, the UAV declares 'Intercept' mode and prepares for landing through a banked semi-circular turn. The ATOLS Ground Radar Unit (GRU) will attempt to acquire the UAV as the Airborne Beacon Unit (ABU) becomes visible to the GRU. Once ATOLS has acquired and 'locked', it will provide azimuth, elevation and range data to align the UAV on to the correct approach.

c. **The Final Approach Point (FAP)**. At the FAP, the approach is prioritised and the UAV continues to maintain a 3 degree glide slope angle through a combination of engine speed and control surface adjustments. At this time Flight Envelope Protection is disabled: envelope and ATOL vertical and horizontal aborts are now possible.

d. **The Underrun (UR) Point**. At the UR point the laser altimeters are referenced to apply an offset bias to fine tune any GPS height error, for GTOLS landing, and to account for real life differences between the calculated and the runway physical surface height. The VMSC continues to prioritise a 3° glide slope and calculates a landing point to confirm the UAV will land in the vicinity of its actual runway touch down point.

e. **At 7m Height**. At 7m (ATOLS / GTOLS height), 'Semi-Flare' is commanded by the VMSC to reduce the glide slope to 1.5° which is followed by a De-Crab manoeuvre to align the UAV with the runway.

f. **At 1m Height Above Ground Level (AGL) – Ground Touch Window**. At 1m AGL (laser altimeter reference) the VMSC software will open the 'Ground Touch' window and respond to any 'Ground Touch' sensing as part of the WoW1 algorithm. These vertical accelerations and changes in pitch rate are sensed by the accelerometers within the independent INS/GPS units.

g. **Post Ground Touch Declaration**. The VMSC Flight Control Software looks for any 'bounce' of the UAV post landing (designated as an 'Air Jump'), before declaring 'Ground Contact'. The VMSC pauses before declaring 'Free Roll' and commanding maximum negative V-Tail deflection to provide a positive downward force onto the undercarriage and nose wheel for increased traction. Also the WoW2 nose wheel sensor is now mechanically activated which isolates the EOP Laser/ Radar to prevent injury to ground crews. This will be expanded on later in the report.

h. **Cable Engagement.** Finally, the UAV approaches the two arrestor cables at the end of the runway which are engaged by the use of a hook bringing the UAV to a stop before the engine is cut.

UAV Height Reference

1.4.27. UAV height can be referenced from 4 different sources, these are:

a. Barometric altitude from the Kollsman and Space age pitot probes.

b. GPS altitude provided from the Athena GS-411 INS/GPS units.

c. Altitude provided by the ATOLS Ground Radar Unit (GRU) during landing and take-off.

d. Height reference provided by the laser altimeters during landing.

1.4.28. During route flight conditions the UAV uses barometric altitude for its primary height reference within the INS. GPS is then used to calibrate the INS positional solution due to its tendency to drift over time. The GPS provides redundancy should there be a failure of the pitot static system. During the landing phase, which commences once the UAV has passed through the CP, the VMSC will select its height reference from ATOLS if available, or GPS. If no ATOLS is initially available, GPS will continue to be referenced until the UAV has been captured within an ATOLS Radar 'lock'. From that point on ATOLS height is used to guide the UAV to the Touch Down point. If an ATOLS 'lock' is not achieved during the final approach the UAV will continue to use INS/GPS and conduct a GTOLS landing. In the event of landing during a GPS denied situation, and no ATOLS 'lock' has been achieved, post the CP, the VMSC will utilise the INS solution to determine its height. Laser height reference is only used during a normal landing situation and when the UAV has passed the UR point. In these conditions the VMSC will use the laser altimeter height to apply an offset to the GPS height at the UR to account for any error. Height reference from the Laser Altimeters is then used to measure when the UAV is 1m above the runway at which point the 'Ground Touch' window is opened.

Annex A

ATOL Aborts

1.4.29. During a normal automatic approach the VMS will monitor a variety of flight parameters to ensure that the UAV maintains a safe and accurate approach to the touchdown point. However, if the VMS detects 1 or more of the pre-determined flight parameters as out of limits or a failure of an ATOL component, the UAV will automatically abort the approach. There are 2 types of ATOL abort:

a. Automatic – Occurs during take-off or landing if the ATOL detects a fault or inaccuracy in one or more of the ATOL components.

b. Manual – Initiated by the operator by pressing the 'ABORT ATOL' button within the GCS. It is used during the take-off or landing phase if an abort condition exists e.g. during a ground emergency.

1.4.30. If the ATOL abort command is received when the UAV 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 UAV to Go Around Point (GAP). Subsequently, the operator within the GCS will be informed of the system abort so he can then decide whether to command the UAV to re-fly the approach, if the fault or flight deviation was transitory, or to apply a specific ATOL override before attempting the next approach in order to prevent the UAV aborting for the same issue.

ATOL Overrides

1.4.31. ATOL overrides only affect UAV behaviour during the landing phase of flight and have no effect in any other phase of flight. They are only set prior to recovery and are designed to assist when:

a. Conditions are sub-optimal and/or the first attempt to recover was aborted.

b. An emergency/failure condition exists.

1.4.32. Using an ATOL override removes an element of safety defence within the system. Therefore, the operator would need to consider the implications of selecting an override based on the environmental and operational context at the time and the imperative to land the UAV.

1.4.33. There are a total of 11 ATOL automated abort parameters that can be individually selected for override by the operator. There are an additional 7 abort parameters that do not have individual overrides where only a Master Override (MO) function is provided (Table 1). If MO is selected by the operator, it will override all 18 automatic abort parameters. Therefore selection of MO will override every inherent safety abort mechanism designed into the UAV and it will therefore proceed to 'Land' even if the system would normally deem it unsafe to do so. There is an additional abort facility in the form of a 'hard key' within the GCS which allows the operator to command a manual ATOL abort.

	ATOL Abort Cause	Individual Override	ATOL Override to Select
1.	INS/GPS HOR inaccuracy	Yes	INS/GPS Horizontal
2.	INS/GPS VER inaccuracy	Yes	INS/GPS Vertical
3.	Envelope vertical	Yes	**Ground Proximity**[4]
4.	Envelope horizontal	Yes	Lateral Deviation
5.	Envelope ground proximity	Yes	**Altitude Deviation**[5]
6.	No comm	Yes	No Comm
7.	Altimeter fail	Yes	Altitude Difference
8.	ATOLS horizontal inaccuracy	Yes	Radar Horizontal
9.	ATOLS vertical inaccuracy	Yes	Radar Vertical
10.	ATOLS comm rate /validation	Yes	Radar Data
11.	Faulty Air Beacon	Yes	Air Beacon
12.	INS/GPS fail	No	MASTER OVERRIDE
13.	VMSC CPU transition	No	MASTER OVERRIDE
14.	Envelope Protection during approach	No	MASTER OVERRIDE
15.	Velocity Deviation during approach	No	MASTER OVERRIDE
16.	Contradiction in altimeter ALT and WGS84 ALT when semi-flare conditions apply	No	MASTER OVERRIDE
17.	Ground Touch identification timeout	No	MASTER OVERRIDE
18.	Difference between altimeters fault or	No	MASTER OVERRIDE

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[4] ATOL override incorrectly designated in system. Known official workaround in place for operators.

[5] As footnote 4.

	both altimeters are faulty		🟥
19.	Operator abort	No	ATOL ABORT – Hard key

Table 1 - Automatic Abort Parameters and Overrides

Ground Touch Sub-Logic

1.4.34. In normal landing conditions the VMSC will start looking for 'Ground Touch' as the UAV descends below 1m AGL. This 1m AGL parameter is measured by the 2 laser altimeters allowing the VMSC to open the window for 'Ground Touch'. At the same time, vertical accelerations and changes in pitch rate are sensed by the 2 independent INS/GPS Units, which also feeds into the VMSC. This information is fed into the pseudo Weight-on-Wheels (WoW1) software algorithm to sense when the main undercarriage has contacted the runway and for the VMSC to register 'Ground Touch'. The VMSC requires the following for a valid first 'Ground Touch':

a. Combination of change in vertical acceleration + pitch rate is above a set value for >100ms.

1.4.35. The VMSC then looks to measure any vertical 'Air Jump' (takes account of the UAV bounce back into the air). If an 'Air Jump' is sensed then the system will wait for a further 'Ground Touch' before latching 'Ground Contact'.

1.4.36. Once the 'Ground Contact' has latched, the VMSC will wait for 1 sec before declaring 'Free Roll,' at which time the VMSC commands the engine RPM to idle and the V-Tails to a constant 8° deflection causing the nose to pitch down. A 'Landing End' state is declared once the UAV takes the arrestor cable and/or velocity is below a given value.

Exhibit 15

1.4.37. **Effect of Master Override on Ground Touch window**. When the UAV is landed with Master Override (MO) selected there is no change to the 1m AGL 'Ground Touch' window. However, after the Underrun (UR) point, if the VMSC detects a laser altimeter fault, failure or height difference, the VMSC software increases the 'Ground Touch' window to 20m AGL and disqualifies both laser altimeters. The UAV height is now measured by the best of ATOLS or GPS. In the event of an ATOLS failure, the height reference would then purely be from GPS which is significantly less accurate than the height measured by the laser altimeters or the ATOLS Radar. Thales and U-TacS confirmed that the 20m 'Ground Touch' window was developed to take account of a possible GPS height error in the expected order of 15m. Therefore, the 20m AGL 'Ground Contact' window had been designed to maximise the chance of a successful landing (with MO selected and a laser altimeter failure / height difference) even with an inaccurate GPS height channel. The Designer regarded this approach scenario as a back-up option that would only be used after several system failures and/or emergency use.

Degraded modes

Annex A

1.4.38. Taking a normal approach without MO selected as the baseline, the Panel examined how the landing logic changes with a laser altimeter failure and/or MO selected. The following four scenarios (Table 2) were deemed appropriate by the Panel for comparison with the accident event to identify differences in the landing logic:

a. Scenario 1: Normal approach with no MO selected.

b. Scenario 2: Normal approach with no MO selected but with single laser altimeter failure / altimeter difference. ALT DIFF override selected to prevent abort.

c. Scenario 3: MO approach. No faults.

d. Scenario 4: MO approach but with single laser altimeter failure / altimeter height difference post Underrun (UR)

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Accident Sortie**
	Normal approach no MO	Normal approach no MO + single laser altimeter failure/difference below 15m ATOLS/22m GTOLS (ALT DIFF override selected)	MO approach no faults	MO approach + single laser altimeter failure/ height difference post Underrun (UR)	MO approach + single laser altimeter failure/difference post UR + early ground touch sensed
Approach mode	Yes	Yes (will not abort as Alt Diff override selected)	Yes		Yes
Glideslope	3°		3°		3°
Underrun (UR)	Bias correction to GPS height channel		Bias correction to GPS height channel		Bias correction to GPS height channel
20m ATOLS/ GTOLS Ground Touch Window	Closed		Closed	**Open**	**Open**
17m ATOLS/ GTOLS	N/A		N/A		1st Ground Touch sensed before touchdown, +Air Jump, +2nd Ground Touch
7m ATOLS/ GTOLS	Semi Flare command followed by De-crab (sub-set of semi flare)		Semi Flare command followed by De-crab		Semi Flare command, no de-crab indication
1m AGL Ground Touch Window	Open		Open	**No – Open at 20m**	**No – Open at 20m**
0m	Ground Touch		Ground Touch		**Already sensed**
Ground Contact	Post Ground touch latched		Post Ground touch latched		Post semi-Flare/ de-crab at 7m ATOLS/GTOLS
Wait 1 Sec	Yes		Yes		Yes
Free Roll (V-Tail command)	Yes		Yes		Yes at 3.95m AGL

Table 2 – Approach Logic - Normal and Master Override (MO) Options

The Accident flight.

1.4.39. **Approach up to Underrun (UR) Point**. The Panel initially assessed WK031's approach path from the Connect Point (CP), through the Final Approach Point (FAP) towards the UR Point (Fig 11). Documentation provided by the Designer states that the radius of the arc of flight between the CP and FAP must be no less than 500m and the angle between the FAP and Touch Down (TD) point limited to ± 90°. A review of WK031's programmed flight path for Rwy 26 confirmed that it was on both of these minimum limits. In addition, it was reported that U-TacS had set the altitude for the downwind leg, prior to the CP at WWA, artificially high. The Panel believes that this was designed to cater for the envelope protection manoeuvre[6] and downdrafts. As was the case with WK031, this additional height can cause the UAV, once it has crossed the CP, to make a moderately aggressive dive down manoeuvre to intercept and establish a 3° glide path before it reaches the FAP. This nose down manoeuvre can result in the UAV arriving at the FAP faster than desired. The Panel noted that if this occurs the UAV will abort the approach[7] unless MO is selected and, on occasion, Watchkeeper crews at WWA have selected MO to prevent this eventuality. The Panel concluded that the programmed flight path for WK031 had a compressed landing approach from CP to FAP. This compressed approach can prevent the UAV from losing the excess speed gained as a result of the additional height on the downwind leg. A revised downwind height to the CP, and track from the CP to the FAP would allow future UAV landing approaches to be flatter and smoother. Although this was not considered a factor in the accident, it is considered an **Other Factor**.

Annex A
Witness 4
Witness 7

1.4.40. **Recommendation**. The Panel recommends that the Thales Head of Flying should review the Watchkeeper UAV approach routes and height into West Wales Airport (WWA) and amend if appropriate to minimise the possibility of a Velocity Deviation During Approach ATOL abort.

1.4.41. **UR Point to Impact**. Immediately prior to the UR point, the UAV achieved an ATOLS Radar 'lock', confirming the UAV was in an ATOLS landing mode. Post the UR point, at a height of 35.14m, the VMSC detected a height difference between the two laser altimeters with laser altimeter 1 reading normally and laser altimeter 2 reading zero for 3.5 secs. As expected, the VMSC disqualified both laser altimeters and the 20m 'Ground Touch' window opened. 1.3 secs later, the VMSC, through the accelerometers, sensed a change in vertical acceleration and pitch rate, which resulted in the first 'Ground Touch' being registered at a laser altimeter height of 16.89m AGL. 250ms later, an Air Jump was declared followed by a second 'Ground Touch' at a laser altimeter height of 15.05m AGL. The 'Ground Touch' then latched. At this point, the UAV continued on its approach without the VMSC immediately switching to 'Ground Contact' and commanding 'Free Roll'. The UAV passed 5.83m AGL (equivalent to 6.89m above the VMSC's computed datum[8] between the runway start point and touchdown) where it completed a 'Semi-Flare'/'De-Crab', and the status changed to 'Ground Contact'. 1 sec later the VMSC commanded 'Free Roll' and the V-Tails to a constant full 8° deflection causing the nose to pitch down.

Annex A

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[6] Envelope protection – Automatic protection and recovery from UAV stall condition with possible associated height loss.

[7] Velocity Deviation During Approach ATOL abort (Table 1).

[8] The distance between the known point of Semi-Flare along the actual runway profile and the VMSC generated runway line was measured at 0.924m. When this distance was added to the VMSC recorded 5.97m laser altimeter height which proved that the UAV was at a height of 6.89m, which was the first VMSC recorded cycle below 7m.