INERTIAL REFERENCE UNITS
WITH INTEGRATED AIR SPEED DETERMINATION
FOR HELICOPTERS

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Abstract

As the ever increasing demand for more and more avionic functions is faced with the well known cost, weight and size constraints of Helicopters a fusion of functions is the way to satisfy the needs. To match this requirement LITEF has developed a family of Strap Down Inertial Reference Units (SDIRU's) with selfmonitoring of system integrity and true airspeed determination.

The fusion of true airspeed determination with the SDIRU makes a separate air data computer obsolete, saves weight and installation space and reduces cost of ownership. LITEF's LAASH (LITEF Analytical Air Data System for Helicopters) adds another dimension to the SDIRU's. It is not based on standard air mass sensors and the LAASH algorithms are processed in the SDIRU's CPU using motion parameters to provide accurate true airspeed throughout the entire flight envelope.

The application of two of the well proven highly reliable K-273 dry tuned gyroscopes assures effective timely failure detection thus providing selfmonitoring of system integrity and a very low probability of the occurence of undetected failures.

Together with a doppler velocity sensor one gets a very accurate navigation system being able to provide enhanced attitude and heading angle accuracy in conjunction with even more accurate true airspeed and wind information.

Helicopter performance monitoring could be included using already existing information on airspeed, collective pitch control lever position, static pressure, outside air temperature and sensor inputs from e.g. engines, torque and rotor systems.

Strapdown Inertial Reference Unit Family

The Strapdown Inertial Reference Unit (SDIRU) familiy comprises a Strapdown Attitude and Heading Reference System (AHRS) and a doppler velocity sensor and magnetic sensor augmented SDIRU which provides navigation capability.

The strapdown AHRS and the strapdown navigator are based on identical hardware but different software. The hardware and the major portion of the AHRS software are taken from the well proven ARINC 705 LTR-81 Strapdown AHRS which has demonstrated a MTBF exceeding 10,000 hrs within more than 2,000 000 flight hours. As of today more than 1,200 of these LTR-81 AHRU's (Attitude and Heading Reference Unit) have been manufactured.

The additional software needed to determine TAS (True Air Speed) using LAASH and to provide present position in the doppler velocity sensor and magnetic sensor augmented configuration is flight proven as well.

As the LTR-81 commercial airline ARINC 705 AHRU has an ARINC 600 8 MCU housing the effort was made to reduce weight and volume by repackaging the LTR-81 AHRU into an ½ ATR short housing. In doing this the 5 boards containing the gyro and accelerometer elecronics, the CPU and the ARINC 429 I/O are left identical to the ones of the LTR-81 AHRU. K-273 gyroscopes and B-280 accelerometers are identical to the LTR-81 AHRU inertial instruments but the sensor block has been redesigned. To meet the requirements of commuter and general aviation aircraft the power supply accepts 28VDC power input.

The fixed wing version AHRU is called LCR-88 and is manufactured under the Technical Standard Order (TSO) sytem to C4c, C5e, and C6d.

Strapdown Attitude and Heading Reference System

In order to meet the ARINC 705 functional requirements the AHRS needs to be augmented by TAS.

In contrast to fixed wing aircraft helicopters are not normally equipped with TAS determination covering the entire speed regime of the rotorcraft.

As LAASH is able to provide TAS throughout the entire flight envelope independent of the standard airmass sensor related equipment required to obtain airworthiness certifcation a helicopter AHRS with ARINC 705 attitude angle accuracies is possible. Due to the independence from standard airmass sensors no recertification of the existing airspeed indicating system is required when installing a helicopter AHRS with attitude accuracies of .5° in 95% of all cases.

With an interface to the control lever position sensors of collective, cyclic forward and cyclic lateral pitch of the main rotor computation of TAS is performed within the SDIRU's CPU. If required, TAS and side slip angle can be made available for indication.

With the LAASH derived TAS the airmass sensor derived TAS can be monitored thus increasing the reliability of the existing airspeed indicating system.

The LHR AHRU complies to the following specification:

Size	½ ATR short; 388x124x194 (mm)
Mass	14 lbs; 6.3 kg
Cooling	Integrated Fan
Power	28 VDC, 85 W
MTBF	> 7,000 hrs

Outputs *	(Accuracies 95%)
Magnetic Heading	1.0 degree ** (45 sec align)
Pitch & Roll Angle	0.5 degree
Ground Speed	12 knots (with VOR/DME)
True Air Speed	6 kTAS
Body Angular Rates	0.1 degree/sec or 1%
Body Acceleration	0.03 g

* ARINC 429 & Synchro or ARINC 429 & MIL-BUS

** Without calibration of tailcone bending effect

The magnetic heading sensor could either be a standard flux valve or a 3 axis magnetometer whereby the magnetometer requires an inflight compass swing.

Doppler Velocity Sensor and Magnetic Sensor Augmented SDIRU

With the LHR AHRU hardware and the AHRU software amended by the navigation loops, the Doppler editor and the control port to the Control and Display Unit (CDU) the SDIRU becomes the heart of an accurate navigation system with integrated TAS determination.

A unique LITEF flight calibration provides automatic magnetic variation determination and calibration of doppler velocity sensor and magnetic sensor boresight errors, Doppler lateral bias and tail cone bending (assuming the tail cone being the best place to install the magnetic sensor). No restriction is made to the type of magnetic sensor (flux valve or magnetometer).

With this inflight calibration there is no need anymore to use a theodolite for boresight error reduction on Doppler and magnetic sensors.

In order to propagate the automatically determined local magnetic variation to the actual present position a flight proven MAG VAR algorithm is used.

The LHN complies to the following specification:

Size	½ ATR short; 388x124x194 (mm)
Mass	14 lbs; 6.3 kg
Cooling	Integrated Fan
Power	28 VDC, 85 W
MTBF	> 7,000 hrs

Outputs * (Accuracies 95%)

Magnetic Heading	0.5 degree ** (120 sec align)
True Heading	0.5 degree
Pitch & Roll Angle	0.5 degree
Ground Speed	0.5% plus 0.1 kts
True Air Speed	4 kTAS
Wind	5 kts, 1 degree
Body Angular Rates	0.1 degree/sec or 1%
Body Acceleration	0.03 g
Present Position	Better than 1.5% of distance travelled

* ARINC 429 & Synchro or ARINC 429 & MIL-BUS

** With calibration of tailcone bending effect

The Doppler editor implemented makes it possible to accept a large variety of Doppler sampling frequencies. Three and four beam Dopplers can be used. The false lock on detection capability could be enhanced using a unique LITEF detection algorithm.

False lock on to an uncalibrated side lobe may occur when the main lobe return is too weak which could happen whilst flying over calm water or similar surface structures. Lock on to an uncalibrated side lobe in general produces the indication of a higher speed than the helicopter flies in reality.

For auto-hover application this could be flight safety critical.

Selfmonitoring of System Integrity

Integrity monitoring of aircraft motion parameters requires redundant measurements. This can be accomplished in many ways depending on system architecture and safety requirements.

A simple and very cost effective selfmonitoring method is to install a redundant angular rate measuring axis since angular rate measurement is the basic input to all strapdown algorithms inclusive the attitude angle computation.

As the application of two degree of freedom DTG's (Dry Tuned Gyroscopes) already provides the redundant rate measuring axis it only requires the proper orientation of the four axes and the implementation of the failure detection and isolation algorithm.

The rate sensing axes orientation already certified in the LTR-81 flight safety critical application (AIRBUS, MD 80 etc.) is to have the two spin axes perpendicular to each other and the rate sensing axes rotated by 45° around the respective spin axis.

In the LTR-81 configuration with the gyro spin axes parallel to the aircraft's roll and pitch axis one gyro measures the rotation around the yaw and pitch axis and the other gyro measures the rotation around the yaw and the roll axis. Thus the four angular rate sensing axes form a pentahedron.

This axes configuration has been maintained in the LCR-88 and hence in the LHR and LHN SDIRU's.
The skewed axes configuration with four measurement axes allows immediate detection and isolation within the SDIRU. High speed, BITE independent detection and isolation is hence assured.

The ability to isolate the faulty rate measurement to the SDIRU is the result of the said skewed axis configuration and allows Fail Op - Fail Safe operation using only two identical SDIRU's.

The following failure rates of the gyros and associated electronics apply:

1 Gyro with associated Electronics:
47 failures/10^6 hrs,

1 Set of Processor, Power Supply and I/O Electronics:
89 failures/10^6 hrs.

The probability of loss of any angular rate signal then is $1.83 \cdot 10^{-4}$ for the single SDIRU. In case, two SDIRU's are installed the probability of loss of rate signals then becomes $0.33 \cdot 10^{-7}$ since the failure can be isolated to the individual SDIRU.

It should be noted however that a SDIRU with only the minimum of angular rate sensing axes (three) does not have the selfmonitoring capability and two of these SDIRU's will exhibit a probability of loss of rate signals of $3.66 \cdot 10^{-4}$ using the same failure rates as above. If however a Fail Op - Fail Safe operation is required three SDIRU's are needed. The probability of loss of function then is $3 \cdot Q^2$ with e.g. $Q = 1.83 \cdot 10^{-4}$. This is three times the value one gets employing only two SDIRU's featuring one redundant angular rate sensing axis each.

Figure 1 depicts a Fault Tree representation of the probability of loss of function for the one SDIRU with four skewed angular rate sensing axes. To combine the different functional blocks locical "OR" and locical "AND" symbols are used. The locical "OR" is used when the probabilities of failure are added since there is a detection but no isolation capability and the logical "AND" is used when a detection and isolation capability is available.

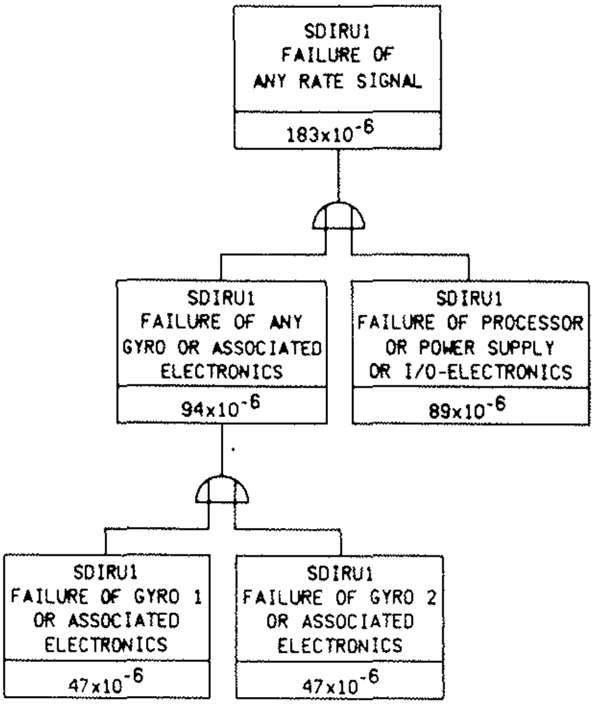

Figure 1: Fault Tree "Loss of Validity of any Rate Signal"

Figure 2 depicts the Fault Tree representation for two SDIRU's with individual selfmonitoring capability.

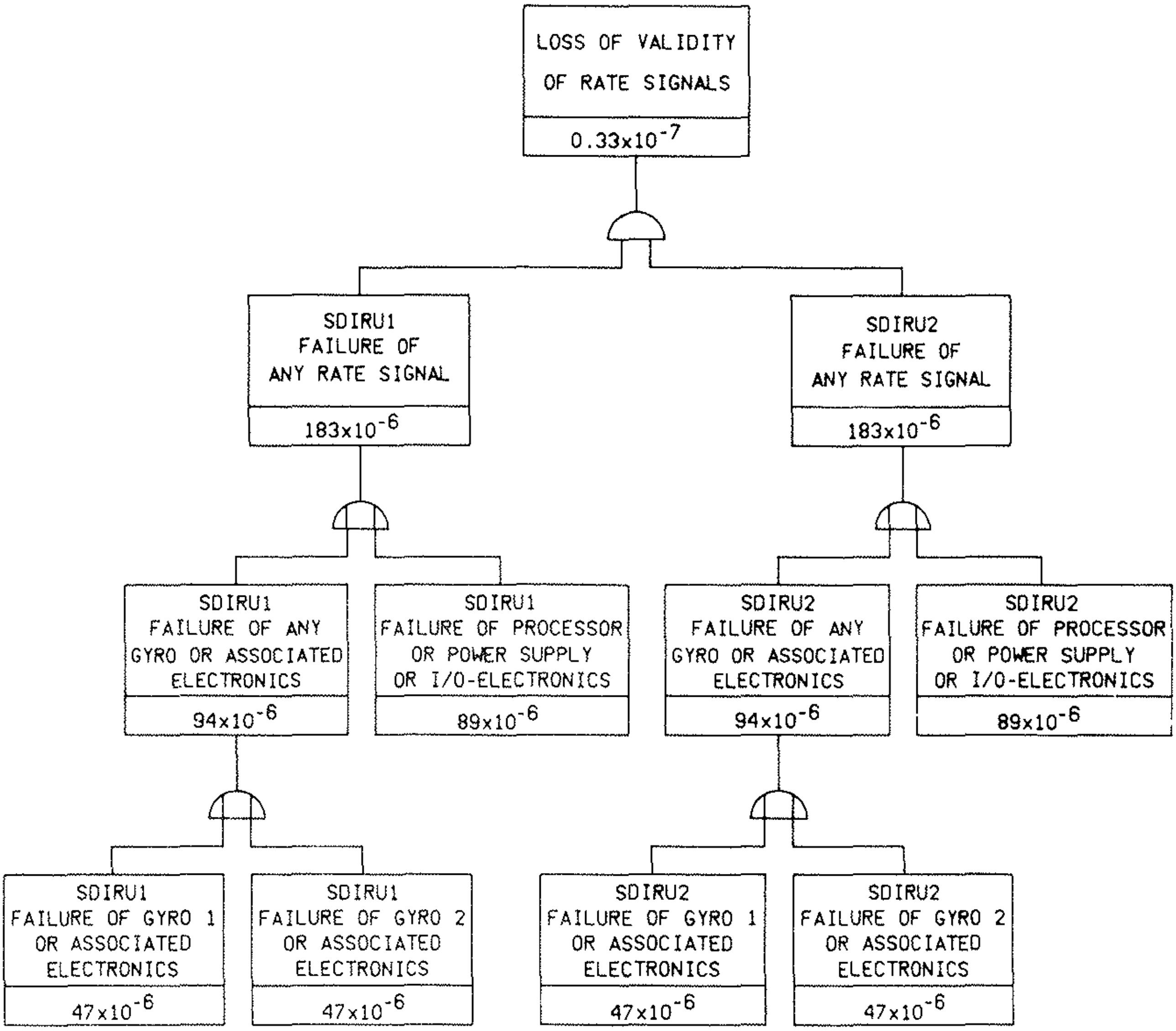

Figure 2: Fault Tree "Loss of Validity of any Rate Signal in both SDIRU's"

From the above it is quite obvious that the selfmonitoring feature implemented through the redundant angular rate sensing axis has its merits not only in the case of a single SDIRU but even more if a Fail OP - Fail Safe operation is required since one would need three SDIRU's with only three rate sensing axis versus two of the configuration with four rate sensing axes and the probability of loss of function would still be less with two times four rate sensing axes.

Analytical True Air Speed Determination

Introduction

True Air Speed (TAS) determination based on fixed air mass sensors is limited to speeds exceeding 40 kTAS, forward flight and stabilized flight conditions. Methods like LORAS, LASSIE and air mass sensors at the tips of opposite rotor blades require specific external sensors not needed by LITEF's Analytical Air Data System for Helicopters (LAASH) which provides TAS with an accuracy of 4 kTAS 95% probability within the entire flight regime of helicopters. In the speed regime below ± 40 kTAS LAASH is based on collective and cyclic pitch control lever positions. As speeds exceeding 40 kTAS a combination of cyclic pitch forward control lever position and pitch attitude angle is used. By using aircraft motion parameters derived from a SDIRU, accurate TAS is provided under stabilized and non stabilized flight conditions e.g. acceleration, deceleration and flight path changes. With height above ground information proper and accurate operation within the ground effect regime is assured.

The Low Speed Regime

At constant rotor speed the collective pitch angle is a measure of the power which must overcome induced, profile and parasitic drag. Up to 40 kTAS the parasitic drag could be neglected without noteworthy loss of accuracy. This implies that the air speed/power relationship could be used at all side slip angles. The profile drag is almost constant, the power required and the induced drag decrease with increasing horizontal speed and the slope of the two functions is almost identical. The reason for this is associated with direct incident airflow that reduces the proportion of the air which is induced by the main rotors own power. Furthermore the power versus speed function is unequivocal in this range.

At constant barometric height the collective pitch angle decreases with increasing speed since the additional air flow caused by the translatory motion provides additional lift at the rotor blades. In order not to climb and not to descend collective pitch needs to be adjusted to compensate for the additional lift and thus collective pitch represents the absolute value of horizontal TAS. Collective pitch and power required are interrelated.

The High Speed Regime

In this domain at speeds from 40 kTAS onwards the cyclic pitch angle forward versus along heading TAS has sufficient slope to be used to determine TAS with an accuracy of 4 kTAS 95% probability.

Due to the very low aerodynamic damping of helicopters about the pitch axis even at high speed the pilot/autopilot is required to augment the damping by correcting these pitch attitude deviations. This happens with the unavoidable time delay and would significantly reduce the accuracy of the measurement. Since the time delay between the resultant pitch attitude and the cyclic pitch forward is almost 180° and the slope of pitch attitude versus forward TAS is sufficient the appropriate combination of both parameters would yield a TAS determination almost undisturbed by the indifferent pitch attitude of the helicopter.

LAASH at Transient Flight Phase

During non stabilized or transient flight phases main rotor control signals and pitch attitude information are transient as well. A TAS calculation using these inputs would not be accurate enough. Transient flight phases occur:

- during climb and descent
- during acceleration and deceleration
- during heading changes
- during roll- and pitch manoeuvres

The transient phase is recognized by means of the body angular rates, the vertical velocity and the main rotor pitch rates. During these non stabilized flight conditions TAS is calculated using ground speed and last remembered wind.

Entire Flight Envelope

The entire flight envelope comprises the low and high speed regime, the stabilized and non stabilized flight phases and the entire altitude range including the ground effect regime.

In order to provide the necessary TAS filtering in the low and high speed regime, to smoothly combine the low and high speed algorithms and to propagate TAS during transient flight phases an appropriate Kalman filter has been employed. It estimates the wind vector and uses unfiltered TAS as observations.

Robustness of LAASH

As LAASH uses collective pitch, cyclic pitch forward and lateral in the low speed regime and the combination of cyclic pitch forward and pitch attitude angle in the high speed regime the impact of measurement accuracy of control lever positions, pitch attitude angle, outside temperature, static pressure and helicopter's actual mass in relation to the masse at calibration needs to be considered. Furthermore, center of gravity shifts are compensated for by appropriate adjustments of cyclic pitch forward and/or cyclic pitch lateral thus affecting the accuracy of the TAS determination.

If the control lever positions are measured to an accuracy of 2.5% of full deflection, the outside temperature is accurate to 5°C and the static pressure is accurate to 6 hPa then Figure 3 depicts the impact of changes to mass and center of gravity to the LAASH derived TAS. The influence of pitch attitude accuracy on TAS is 4.74 kTAS/degree. A properly mechanized SDIRU is always capable to fournish the required accuracy.

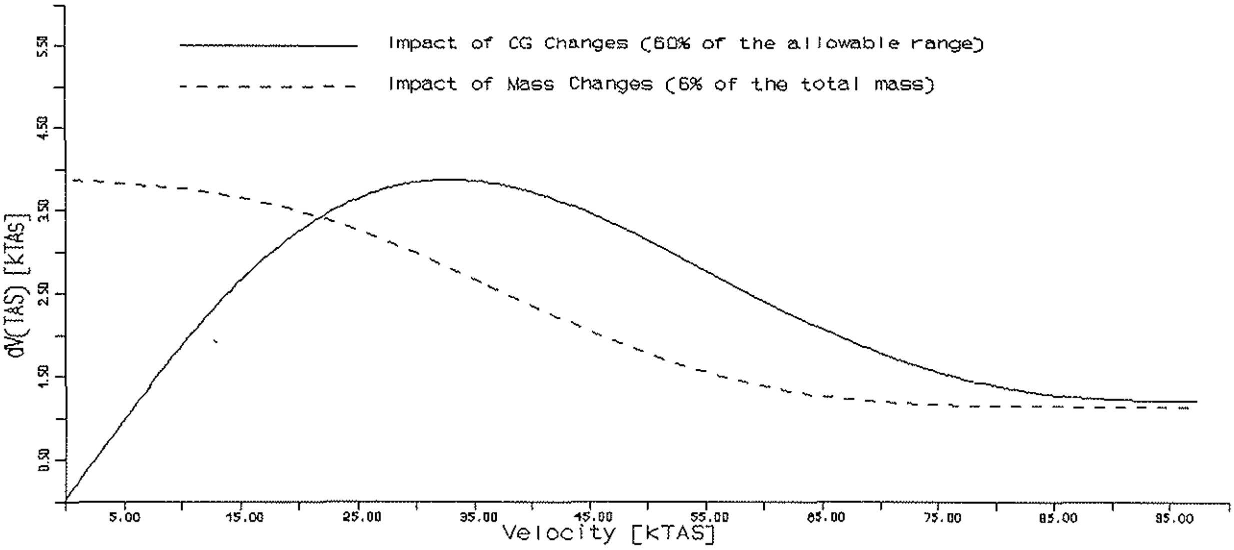

Figure 3: Impact of Helicopter's Mass and Center of Gravity Shift

It should be noted that there is no center of gravity shift impact on TAS accuracy whilst hovering.

LAASH Integration into a SDIRU

Integrating LAASH into a SDIRU is to fuse the TAS computation with the strapdown processing. It is to our believe the most effective way to save mass, installation space and last but not least cost, since the necessary computing power is anyway available as well as the aircraft motion parameters needed to enhance TAS computation during non stabilized flight phases.

It simply requires the interface to accept the signals delivered from the main rotor control lever position sensors, memory space comprising 784 Byte RAM and 4382 Byte EEPROM and the software to process the algorithms and to handle the interface.

Calibration

As quite usual for air data system LAASH needs to be calibrated to the type of helicopter. The calibration comprises the data required to generate the collective/horizontal TAS relation, the control characteristics, the cyclic pitch forward and the pitch attitude/along heading TAS relation at speeds exceeding 30 kTAS. To our experience, 10 flight hours including time for take off and landing are sufficient to calibrate for the entire flight domain. This includes tactical flights and flights within the ground effect.

It is very important to maintain calibration over the life of the helicopter and to be able to check the validity of the calibration if so desired.

This can easily be done in a calibration mode with the helicopter on ground using distinct positions of the control lever positions.

The algorithm behind this calibration mode is designed to detect deviations to the original calibration and in case these exceed predetermined limits a correction to the original calibration is calculated and stored.

Performance Monitoring

Having integrated LAASH into the SDIRU the following information is available:

- Collective Pitch as a Measure of Power used
- Air Density from Static Pressure and Outside Temperature
- TAS and Side Slip Angle
- Mass to be lifted

Adding torque indication with respect to the limits (engine or transmission) and data on specific design limits the following information could be fournished:

- Power available
- Side Slip not exceeding Design Limits
- Lift Margin

The above information would enable the pilot to make optimal use of the helicopter without exceeding design limits.

It should be noted that LAASH implementation would eliminate unknown rearward motion with respect to the local air mass which could create a safety hazard.

As one can see very little effort is required to fournish the pilot with very useful performance data.

Concluding Remarks

The fusion of a Strapdown Inertial Reference Unit family with

- Selfmonitoring of System Integrity
- Analytical True Air Speed Determination
- Performance Monitoring

supports the customers' need for more and more avionic functions without paying the penalty of increasing cost, weight and installation space. Selfmonitoring of system integrity adds to the safety of flying as well as the TAS determination throughout the entire flight envelope.

Well proven technology assures unmatched hard- and software reliability.