# Differences in Pilot Automation Philosophies in the US and Russian Air Forces Ground Collision Avoidance Systems

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## *SUMMARY*

*G-induced loss of consciousness (G-LOC) is a pilot human factors (HF) problem that plagues all air forces that fly high performance fighter aircraft. Spatial disorientation (SD) is an even more serious HF problem that affects not only the military but also commercial aviation. By some estimates, one out of every four aircraft mishaps is due to a HF problem, and the pilot flies a perfectly operating aircraft into the terrain. Altitude warning systems and other voice or buzzer devices in the cockpit have been relatively ineffective at reducing the number of mishaps. In order to stem the tremendous loss of pilots and aircraft because of HF-related mishaps, the US Air Force and Russian Air Force have developed automated collision avoidance systems. The US Air Force has developed a Ground Collision Avoidance System (GCAS) that is automatic and requires no pilot intervention. The philosophy behind this system is reliability, pilot unobtrusiveness, and invisibility. The Russians have also developed a pilot state monitoring system that is automatic, but includes the pilot in its control loop. The Russian system even includes an onboard video camera that allows ground operators to observe the pilot during the mission. The objective of this paper is to discuss these two automated collision avoidance systems and to distinguish between the roles of the human in both systems.*

## INTRODUCTION

Two serious pilot human factors problems that plague the US and Russian tactical air forces are G-induced loss of consciousness (G-LOC) and spatial disorientation (SD). In the US Air Force, G-LOC and SD have killed 68 pilots (59 SD, 9 G-LOC) since 1991. The loss of 73 aircraft due to SD and over 20 aircraft due to G-LOC total over $2B. The US Navy reports even more serious numbers. Although the Russian Air Force does not indicate SD or G-LOC as the cause of a mishap, Russia has lost enough resources over the past twenty years to invest in an automated collision avoidance system for its fighter aircraft. G-LOC is characterized by a loss of consciousness in the pilot who is not properly protected from high-sustained acceleration (G). The average pilot can endure 4.5 Gz without straining or relying on an anti-G suit, which is typically a pair of inflatable trousers worn over the flight suit that inflate and squeeze the thighs, calves and abdomen, thus raising the eye-level blood pressure of the pilot. If the pilot does not perform a proper strain or the G-suit does not inflate properly, the pilot can G-LOC. The typical G-LOC lasts about 30 sec, during which time the pilot is not in control of the jet. Depending on the airspeed and altitude of the aircraft, the jet can hit the ground, or, if the G-LOC'd pilot is lucky, the jet will fly itself and not hit the ground.

*Paper presented at the RTO HFM Symposium on "The Role of Humans in Intelligent and Automated Systems", held in Warsaw, Poland, 7-9 October 2002, and published in RTO-MP-088.*

Spatial disorientation (SD) is characterized by an erroneous perception of the terrain. There are three types of SD that are characterized by whether it is unrecognized (Type I), recognized (Type II), or incapacitating (Type III). Unrecognized SD accounts for nearly 80% of the SD-related mishaps. Type I SD typically occurs when the pilot has channelized attention and does not perceive a change in the attitude and/or altitude of the aircraft. There are no physiological changes in the pilot that one can monitor and detect Type I SD. Type II SD is recognized and is usually the result of an in-flight illusion. The pilot cannot reconcile his seat-of-the-pants feel with the instruments and he loses altitude as he tries to dispel the illusion. Type III is incapacitating SD and it occurs when a pilot has uncontrollable nystagmus after a spin, for example.

Both the US and Russian Air Forces have attempted to train pilots about the woes of G-LOC and SD, but the statistics continue to show either no change in occurrence (G-LOC) or a rise (SD). Both Air Forces have human centrifuges that can train pilots to 9 Gz; the USAF has had SD demonstrators (Vista Vertigon) at some of its physiological training units. Both Air Forces realized that an automated system to protect the aircraft and pilot from collision with the terrain was necessary.

## THE AMERICAN APPROACH – THE GROUND COLLISION AVOIDANCE SYSTEM (GCAS)

The concept of an automated ground collision avoidance system for fighter aircraft began in the 1970s. A GCAS was developed by the General Dynamics Corp for the F-16 in the early 1980s; the GCAS was demonstrated on the AFTI (Advanced Flight Technology Integration)/ F-16 at Edwards AFB throughout the 1980s. The Air Force Research Laboratory Air Vehicles Directorate at Wright-Patterson AFB has managed the program. GCAS automatically or manually prevents penetration of a pilot-selectable minimum clearance distance using a high fidelity aircraft model and a digital terrain database. It does not require radar so it can operate without emitting a radar signature. It relies on the digital database of the mapped area it flies over. It is valid in any terrain, at night, and in all weather. The design utilizes a digital terrain system with a terrain referenced navigation algorithm to locate the aircraft spatially with respect to the terrain. The terrain database around the aircraft is scanned, and a terrain profile is created. An aircraft response model is used to continuously predict the aircraft's future recovery trajectory. A recovery is automatically performed whenever the trajectory penetrates a preset distance from the terrain profile (Swihart and Barfield, 1999). The system is designed to protect pilots in the event of unusual aircraft attitude, spatial disorientation, or G-LOC within its operational envelope. The GCAS provides protection at all altitudes, all airspeeds, in all mission phases with landing gear up, and for a large combination of store loadings (Swihart et al., 1999).

The GCAS continuously predicts the flight path of the aircraft, assuming recovery is needed, 10 to 15 seconds in the future (Figure 1). This prediction is accomplished using a high-fidelity aircraft response model. Simultaneously, the terrain database around and in front of the aircraft's position is scanned to determine all terrain features that may be dangerous to the aircraft's flight. A comparison of the future recovery flight path and the terrain profile along the flight path is made. From this comparison, a time-to-flyup is generated. At a time-to-flyup of 5 seconds, chevrons appear on the Head-up Display (HUD) as shown into Figure 2. When the time-to-flyup reaches zero, a coupler or the autopilot in the flight control system commands an automatic recovery that is wings-level and a 5 G pull-up. If inverted at the flyup initiation, the system unloads the aircraft and counters gravity during the initial roll. The pilot can always override the system and prevent an automatic recovery from occurring (Swihart et al., 1999).

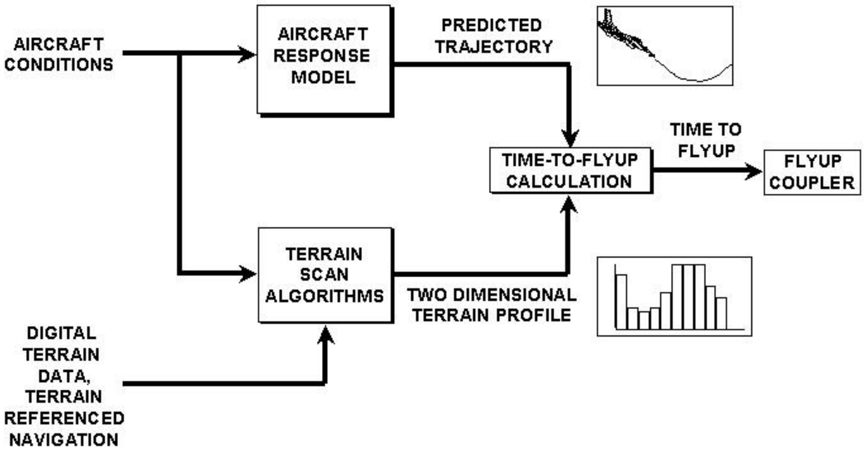

Figure 1: Automatic Ground Collision Avoidance System (GCAS) Algorithm Architecture.

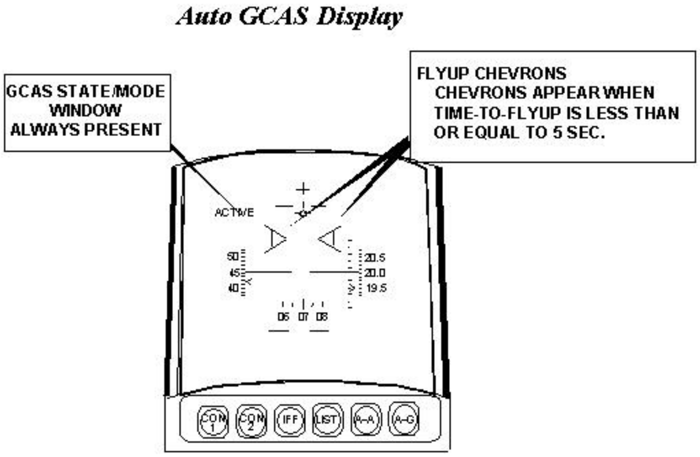

Figure 2: GCAS Symbology on the Head-Up Display.

The GCAS was designed to fit in any aircraft. Substituting new aircraft characteristics into the coupler, aircraft response model, and scanning algorithms accomplishes the transition into another aircraft. The Swedish government joined with the US Air Force in 1998 to implement the GCAS into their Gripen fighter program. In flight tests at Edwards AFB during the late 1990s, the GCAS was refined to reduce the number of false fly-ups. The current design is estimated to allow nuisance-free operation as low as 150 ft over all types of terrain. The GCAS is being integrated into the Gripen fighter fleet, but, as of 2002, the GCAS has not been selected for the USAF F-16 or other fighter aircraft.

## THE RUSSIAN APPROACH – THE PILOT STATE MONITORING SYSTEM

The Airborne Active Flight Safety System (BASBP IKSL-2) is the Russian version of a pilot state monitoring system for high performance aircraft pilot incapacitation. The Russian Systems Corporation (RSC), Moscow (Voyevodin, Kapustin, Dorofeev, Dvornikov, and Soukholitko, 1999), developed the system.

BASBP IKSL-2 provides for:

- continuous automatic control of the flight parameters, condition of the life-support equipment, the pilot's functional state and correctness of protection methods used by the pilot under extreme conditions of high-altitude, maneuvering and long-duration flight;
- trouble-shooting of the life-support equipment and pilot error, as well as prediction of a potential hazardous state;
- voice warning to the pilot on potential problems;
- evaluation of the correctness and timeliness of the pilot's actions to eliminate the problem;
- taking the decision to transfer the aircraft into an auto safe flying mode, realizing several variants of programs aimed at bringing the aircraft to a safe mode of flight in the event that the pilot's reaction to the warning information is inadequate;
- delivery of a control command to the aircraft oxygen emergency supply mechanism to supply 100% oxygen to quickly restore the pilot's functional state;
- taking the decision on recovery of the pilot's normal functional state and switching off the auto safe flight control systems;
- recording of the state of the on-board life-support systems and the pilot's functional state in the event that unstandard situations occur during the flight;
- automatic transmission of the in-flight data to the flight control group on the ground of the potentially dangerous state of the crew; or transmission to the crew on the elimination of a problem in-flight.

The system has been developed in cooperation with the PGUP RSK MiG and the State Research Institute of Military Medicine of the Russian Federation Ministry of Defense. It has successfully passed bench testing and flight trials in the MiG-29UB and ergonomic and physiological tests at GNIII VM of the RF Ministry of Defense. The IKSL can be installed in aircraft including the MiG-29, MiG-31, Su-27, Su-30, as well as other types of aircraft. RSC is currently under contract to install the IKSL in MiG-29 and Su-27 aircraft.

BASBP IKSL-2 has the following features:

- an autonomous module type system with a built-in processor permitting real-time processing of information;
- non-invasive monitoring of information about the pilot's state;
- built-in voice warning system to transfer messages to the crew and to the ground flight control center (FCC);
- a control-recording device permitting the transfer of information onto a portable computer upon landing;
- power consumed from the aircraft electrical system is not more than 20W; mass – about 4 kg.

The current IKSL is comprised of five monitoring systems, including a head position monitor, a flight control stick pressure transducer, rudder pedal force transducers, an oxygen mask transducer, and a video camera (Figure 3.) The breathing transducer monitors the breathing pattern of the pilot (5 to 60 breaths/minute) and assesses the relation of the exhalation frequency to the inhalation frequency and duration. If the ratio of inhalations and exhalations and the inhalation durations are too long or too short, the IKSL issues a verbal warning to the pilot: “check oxygen” or “tighten oxygen mask.” The IKSL also transmits this signal to the FCC on the ground that alerts air controllers that there may be a problem. If there is reduced rudder pedal pressure the IKSL signals “strain feet.” If the pilot does not respond in a few seconds with a pressure of at least 20 kg, the IKSL issues control commands to the airborne equipment (Russian Systems Corporation, 2001). Likewise, if there is not enough pressure on the flight stick the IKSL says, “hold control stick.” As mentioned above, if the head falls and is detected as an out-of-bounds condition, the IKSL says, “Raise head.” These verbal commands are delivered by the IKSL until the pilot eliminates the non-standard condition. If the pilot’s reaction is absent to the verbal warning, the IKSL delivers control commands to the airborne equipment.

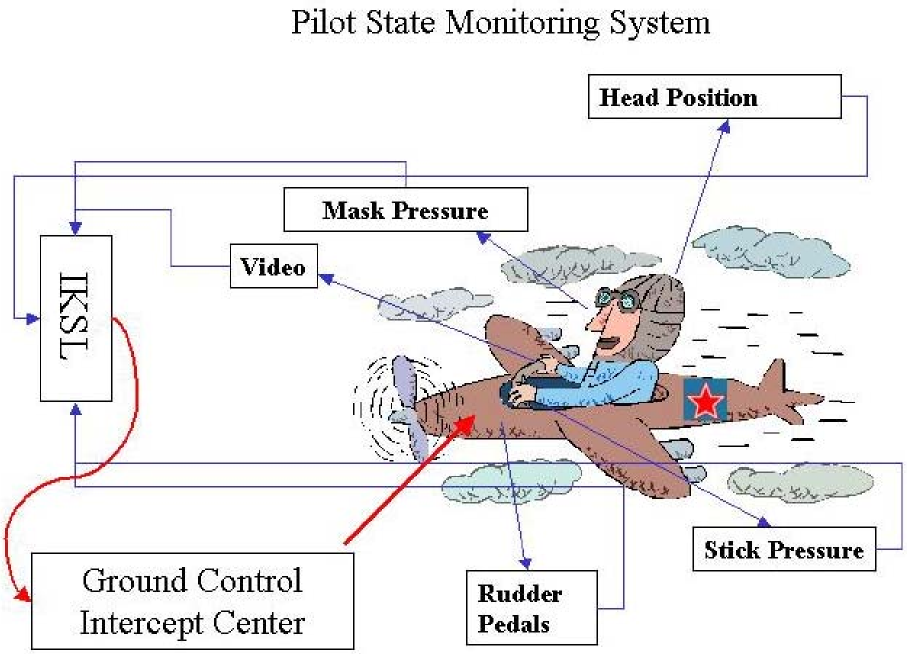

Figure 3: The IKSL Control Loop.

The IKSL monitors the altitude of the aircraft when it issues a verbal warning. A pre-selected radio altitude hold is selected by the IKSL if the pilot is incapacitated (does not respond to verbal warnings). The “level altitude” mode flies the aircraft to approximately 5 km and the “high altitude descent” mode flies the aircraft to an altitude higher than 5 km.

Equipment: The IKSL is a Line Replaceable Unit (LRU) that is aircraft compatible. It is 230 X 160 X 120 mm in dimension and weighs 2.2 kg (Figure 4). In the cockpit, the IKSL includes the display panel, an on/off switch, and an operability-monitoring button. The oxygen mask breathing transmitter is installed in the duct between the oxygen supply and the oxygen mask hose connector. The head vertical state sensor is placed on the cockpit canopy over the pilot’s head. The rudder pedal force transducers are on the surface of the pedals. The control stick pressure transducer is located on the stick’s grip surface. During the operation of the IKSL it is integrated with the following aircraft systems:

- Intercommunication system – VHF Radio
- Voice warning equipment

- Engine modes control system
- Flight and landing equipment system
- Airborne flight data recorder
- Radio altimeter
- Air data system
- Control stick
- Control pedals
- Oxygen duration indicator
- Standard airborne acceleration sensor

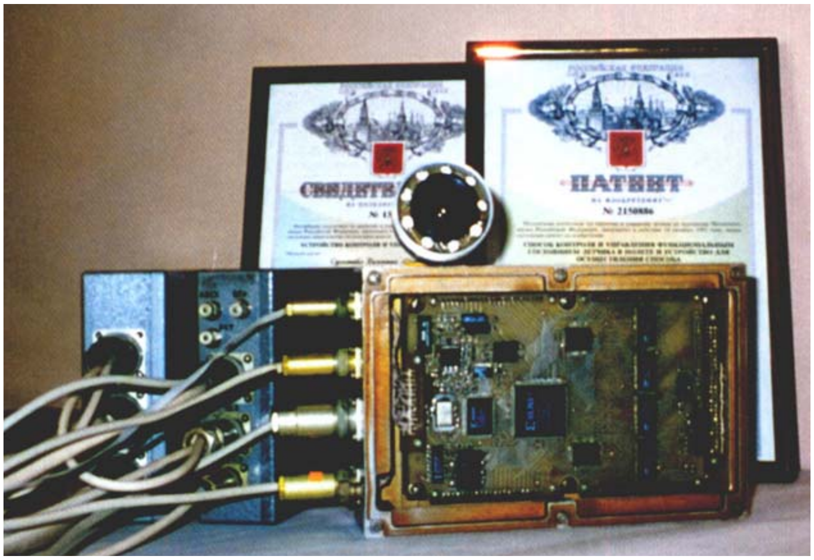

**Figure 4: The Russian Systems Corporation IKSL-2, Pilot State Monitoring System.**

The IKSL can also download its information from the flight onto a laptop computer upon landing for further analysis. Recently, RSC has developed software for the video camera that is now part of the system. The video from this camera can be transmitted by the IKSL to the FCC, and in the case of a critical situation on board the aircraft, a decision can be made by controllers observing the video of the pilot to take control of the aircraft and fly it back to the airport via the ACS. The IKSL can also be used by the FCC to alter the state of the flight, the pilot, and /or the aircraft. The IKSL has "prediction powers" that allow for warning to the pilot as the aircraft enters a high G turn, for example.

The breath-sensing element of the IKSL is a thin-film resistor with a micro-heating sensor that results in the movement of the air mixture being breathed by the pilot through the mask. The vertical head position sensor is a proximity induction detector with a sensing element that is a small coil responsive to entry into its shading ring field. The control stick deflection sensors respond to forces and are located along the perimeter of the surface surrounding the control stick. On deflection of the stick, the sensors are contacted and close, indicating the position of the stick. There are also photoelectric control stick sensors that employ opto-electronic infrared radiation for transmitting and receiving signals. They are mounted on the control stick so that the IR beam travels parallel to the envelope of the control stick's surface. The sensor registers the presence of the IR beam on the pilot's hand. Force sensors on the rudder pedals are limit switches with loading springs. They register forces up to 20 kg on each rudder pedal. In addition, there is a video camera that views the pilot's face and transmits the image to the ground station.

## DISCUSSION

The difference in philosophies between the two systems reflects the philosophies of the air forces of the two countries. First of all, the American fighter pilots would probably not turn on the GCAS during actual combat missions. The idea of an incapacitated fighter pilot bobbing and weaving in the atmosphere as he/she either recovers from a G-LOC or some other physiological event while the "bogey" lines the "sitting duck" in their sights is a pilot's worst nightmare. Furthermore, American pilots would be most intolerant of a system that gave a false positive and took control of the aircraft and flew it up while the pilot had a bogey in his/her sights! Air Force and Navy pilots are uneasy about relinquishing complete control of their aircraft to a computerized safety device (Munro and Opall, 1991a). American fighter pilots, in general, do not buy into something where a machine takes over (the aircraft) (Munro and Opall, 1991b). GCAS was never developed for the wartime sortie. US losses from SD and G-LOC have occurred over the past twenty years during peacetime training operations.

The US system is autonomous; it does not require any pilot intervention in its operation. The pilot is not in the control loop of the GCAS. After the pilot enters a minimum ceiling for the aircraft, he/she does not need to interact with the system. Even after breaking the minimum altitude and the aircraft has performed a "fly-up, fly-up, you've got it," the pilot does not need to fly the aircraft. The aircraft will continue to "fly-up" each time it breaches the ceiling and will fly, theoretically, until it runs out of fuel. US Air Force and Navy pilots would most likely not accept a GCAS that would report false positives (tell the pilot there was a problem when there wasn't). They would not like interacting with a system that was constantly reminding them that they did not have their head erect, or enough rudder pedal pressure, especially if the out-of-bounds condition was during normal flight operations. There would be little acceptance of a closed-circuit video camera system where people on the ground would be able to observe the pilot at all times.

The Russian system does include the pilot in its control loop. If the pilot does not respond to an alert from the IKSL, the aircraft control can be taken away from the pilot. When asked if a MiG fighter pilot could accept such a system, where a voice is telling the pilot "raise head" or "strain feet," Roman Taskaev (former Chief Test Pilot for MiG) said, "Yes." Taskaev felt the IKSL would be accepted by Russian Air Force fighter pilots and endorsed its inclusion in current and future MiG and Sukoi aircraft (Taskaev, 1999).

When Russian Systems Corporation visited Wright-Patterson AFB in 1999, they were told that their IKSL system would most likely be unacceptable to American pilots. A warning system that queried the pilot from time to time about stick or rudder pressure and head position would soon be turned off by American pilots, who relish their freedom in the cockpit. When the US Air Force Aerospace Medical Research Laboratory looked at a pilot monitoring system in the mid-1980s, the concept of a Loss of Consciousness Monitoring System (LOCOMS) originated (Albery and Van Patten, 1991). The novel idea behind LOCOMS was a "jury" of physiological sensors that monitored the pilot's EEG (electroencephalogram), eye blink, arterial oxygen saturation, head position, stick pressure, and several other parameters that, ironically, ended up in the Russian IKSL. LOCOMS was never built and demonstrated because 1) the state of non-invasive physiological monitoring was not advanced, and 2) if the system ever produced a false positive, it would be unacceptable to the pilot community. This latter problem was the opinion of the LOCOMS developers. Furthermore, GCAS was a proven system during the 1990s. The Swedes joined with the US Air Force and fine-tuned GCAS to virtually eliminate false fly-ups that lead to "automation surprise." GCAS is being installed in production JAS 38 Gripen fighter aircraft.

Thus, Russian approach is in the creation of "partner system" for this system can help and assure the pilot in dangerous and emergency situations. It may be achieved by a multilevel system ensuring informational support and in work capacity disorders (such as SD and GLOC) with the autopilot engaged. However it usually takes place in the strict context of the flight situation.

## CONCLUSIONS

The Auto GCAS has been developed and demonstrated and will be installed in the Swedish Gripen aircraft. The Auto GCAS has not been integrated into the F-16 or any other USAF fighter aircraft to date. Cost and other considerations have kept the system out of US fighter aircraft to date. The IKSL, on the other hand, has been selected for retrofit into the MiG-29 and Su-27 fighters in the Russian Air Force. The Auto GCAS solves the problem of a disabled or disoriented pilot by providing a "safety net" of a minimum altitude the aircraft can penetrate. The IKSL relies on the judgment of the ground controllers to interpret the signals from the on-board system and to "take over" the aircraft, if needed. The Auto GCAS does not rely on any inputs from the pilot; it is aircraft state dependent. The IKSL has the pilot in the loop and must have signals from the pilot in order to operate. Pilots in both air forces currently accept whatever intrusion each system presents in the aircraft. The end goal of both systems is to protect pilots and their aircraft from human factors related problems in-flight that, over the years, have cost both air forces billions of dollars in aircraft and lives.

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