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FLIGHT-DECK TECHNOLOGIES TO ENABLE NEXTGEN LOW VISIBILITY SURFACE OPERATIONS

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Many key capabilities are being identified to enable Next Generation Air Transportation System (NextGen), including the concept of Equivalent Visual Operations (EVO) – replicating the capacity and safety of today’s visual flight rules (VFR) in all-weather conditions. NASA is striving to develop the technologies and knowledge to enable EVO and to extend EVO towards a “Better-Than-Visual” operational concept. This operational concept envisions an ‘equivalent visual’ paradigm where an electronic means provides sufficient visual references of the external world and other required flight references on flight deck displays that enable Visual Flight Rules (VFR)-like operational tempos while maintaining and improving safety of VFR while using VFR-like procedures in all-weather conditions. The Langley Research Center (LaRC) has recently completed preliminary research on flight deck technologies for low visibility surface operations. The work assessed the potential of enhanced vision and airport moving map displays to achieve equivalent levels of safety and performance to existing low visibility operational requirements. The work has the potential to better enable NextGen by perhaps providing an “operational credit” for conducting safe low visibility surface operations by use of the flight deck technologies.

NASA is conducting research, development, test, and evaluation of flight deck display technologies that may significantly enhance the flight crew’s situation awareness, enable new operating concepts, and reduce the potential for incidents/accidents for terminal area and surface operations. The technologies that form the backbone of the BTV operational concept include: surface and airport moving maps; head-up and head-worn displays; four dimensional trajectory (4DT) guidance algorithms; digital data-link communications; synthetic and enhanced vision technologies; and traffic conflict detection and alerting systems (Bailey, Prinzel, Young, and Kramer, 2011; Prinzel et al., 2011). Preliminary research is described assessing a subset of these technologies in comparison to current-day low visibility surface operations.

The Problem

Research and experience has shown that reduced operational tempos and delays in current-day surface operations due to low visibility conditions contribute significantly, and are growing in their contribution, to airspace delays. During low visibility conditions, pilots and vehicle operators must maintain their situation awareness to ensure the continuation of safe, efficient ground operations. FAA 2010 Annual Runway Safety Report statistics showed that 951 runway incursion events with 12 serious incidents occurred during 52,928,316 surface operations. Although the total number of runway incursions is a very small percentage of total operations, a runway incursion can have catastrophic consequences. The largest category of causal factors in these events was pilot deviations (63%) suggesting that enhancement of situation awareness (ownship position and routing) could provide significant reductions in runway incursions.

Ground-Based Solutions

As a counter-measure in low visibility conditions, the FAA has established regulations, standards, and supporting advisory material in the development of Surface Movement Guidance and Control System (SMGCS) requirements where scheduled Air Carriers are authorized to conduct operations is less than 1,200 feet visibility. SMGCS involves surveillance, routing, guidance, and control for controllers, pilots, vehicle drivers, and other airfield service providers. Key enabling elements of SMGCS are enhanced visual aids – consisting of lights, markings, and signage – designed to provide visual cues for ownship position identification, navigation/route information, and status information for runways, taxiways, hold lines, maneuvering areas, etc.

Flight-Deck Solutions

The low visibility operations (LVO)/SMGCS enhanced visual aids are an established means of creating improved awareness for the crew to ensure the continuation of safe, efficient ground operations.. The present paper describes a “proof-of-concept” test to evaluate the feasibility and efficacy of a flight deck-based approach toward this same objective, specifically using: (a) enhanced vision technology displayed on a HUD and head-down display, and (b) Airport Moving Map (AMM) displays.

These technologies potentially create:

- Improved crew visibility of the airport (topography, surface, and traffic/objects) in the vicinity of the aircraft by an electronic means of enhancing a pilot’s natural vision.
- Improved surface position and airport surface status (and also possibly, traffic and object) awareness through airport maps/mapping products (e.g., electronic AMMs).

Enhanced Vision (EV) is an electronic means to provide a display of the external scene by use of an imaging sensor, such as a Forward-Looking Infra-Red (FLIR) or millimeter wave radar. In most atmospheric conditions, especially when natural visibility is reduced due to night, smoke, or haze, the EV provides a visibility improvement which may enable the flight crew (pilot) to more safely operate on the surface. Such a goal is supported by the FAA’s mid-term vision for NextGen and an operational improvement (OI) to utilize EV in lieu of SMGSC infrastructure requirements (OI 103208). Over 1000 EV systems are currently flying in the US National Air Space (NAS).

The Commercial Aviation Safety Team (CAST) recommended the use of AMM displays as a highly effective safety enhancement to reduce the risk of runway incursions. Research has supported the conclusion that situation awareness is substantially enhanced by the presence of AMM display that, as a minimum, depicts ownship position. For example, Hoey & Foyle (2007) found that 17% of low visibility and night taxi trials resulted in navigation errors that were mitigated by the use of AMMs. The NTSB has recommended the adoption of AMMs and they are standard equipment on most new commercial transport aircraft.

E-SMGCS Display Concept

The use of AMMs to enhance situation awareness has long been established. However, little research exists that investigated their use under low visibility surface operations. To date, research has been limited to visibility conditions greater than 700 RVR and without the enhanced visual aids required under LVO/SMGCS operations.



Figure 1. Airport Moving Map (Left), E-SMGCS (Center), Select E-SMGCS Symbology (Right)

In this research, the AMM design was based on NASA “best practices” for AMMs, existing published standards, and an AMM information priority survey. The survey was collected on twenty commercial pilots, experienced with SMGCS and AMMs, based on established methods (Schvencveldt, et al., 2000; Yeh & Chandra, 2003). The results

evinced that pilots desired the following SMGCS elements be depicted under low visibility surface operations: Geographic Position Markers (GPMs), clear route, stop bars, and hold lines. These additional informational elements are added to the AMM to create an E-SMGCS display concept.

The E-SMGCS concept is a display mode of the AMM that is invoked by the flight crews when known LVO/SMGCS conditions exist (i.e., under 1200 RVR). The AMM then shows specific LVO/SMGCS information elements based on information priority survey. The E-SMGCS mode retains all normal AMM functionality and also provides the pilots with specific symbology to enable the pilots to cognitively map task priority elements between the AMM, paper charts, and out-the-window visual cues.

The E-SMGCS concept is envisioned to enable the various information elements to be dynamically controlled (e.g., remove stop bar depiction when cleared onto active runway). The E-SMGCS mode may also include display of ownship route and other traffic and their *intended* route (see Prinzel et al., 2010) with 4DT depictions and conflict detection and resolution alerting and indications (e.g., see RTCA DO-323).

Research

A small-scale study was conducted to evaluate the preliminary concept of operation and display for the E-SMGCS mode that is utilized during low visibility surface conditions. Flight crews conducted approach and departure operations using a 6 degree-of-freedom full-motion large glass cockpit simulation (see Figure 2) during 300 ft runway visual range (RVR) low visibility operations at Memphis International Airport (FAA Identifier: KMEM).

The objectives of the research were:

1. Assess the use of EV on HUD (enhanced flight vision system or EFVS) during LVO/SMGCS and its potential flight deck impact when integrated with an AMM with ownship representation.
2. Assess the use of EVFS during LVO/SMGCS and its potential flight deck impact when integrated with an AMM with SMGCS-specific symbology (i.e., the E-SMGCS concept)
3. In evaluating the use of EVFS, consider the possibility of operational credit for use of EV in lieu of airport SMGCS enhanced visual aid equipage.

Four commercial flight crews (Captain, F/O), paired for same airline, served as the subjects. Pilots were HUD-qualified and had EV experience and commercial airline operational experience with SMGCS. The Captain was seated on the left-side and was "pilot-in-command" responsible for approach, landings, and taxi of aircraft. The First-Officer was seated on the right-side and functioned as "monitoring" pilot.

A two (LVO/SMGCS Level 1, LVO/SMGCS Level 2 out-the-window enhanced visual aids) by two (EV, none) by three (none, AMM with ownship, AMM with ownship and E-SMGCS) partially factorial within-subjects factor design was conducted (Figure 2):

- The simulation was carefully constructed to faithfully replicate the SMGCS enhanced visual aids (markings and lights) during Level 1 (1200-500 ft RVR) or Level 2 LVO/SMGCS (>500 ft RVR) at KMEM. For the present research, Level 1 contained taxiway centerline lighting, runway guard lights, edge lighting, and all other requirements in addition to GPMs that functioned as "surface painted location signs." Level 2 retained all of Level 1 SMGCS and additionally, provided controllable stop bars, and clearance bar lights (co-located with GPMs).
- The EV display concept used forward-looking infrared (FLIR) depicted on a wide field-of-view (42° H x 30° V) Head-Up Display (HUD) with a head-down repeater display of the FLIR (no symbology).

Scenarios were constructed using subject matter experts to create representative types of operations and flows typically experienced during low visibility surface operations. 300 ft RVR day time conditions were simulated. The EV (FLIR) provided 500 ft visibility of topology and 700 ft visibility of lights. Scenarios were balanced in presentation and included taxi-out for departure and arrivals with taxi-in to the ramp. All approaches were flown using an auto-land capability. An off-nominal trial was presented which failed the FLIR input to the HUD and head-down repeater display.

Quantitative and qualitative measures were collected during trials including Situation Awareness Rating Technique (SART) and NASA Task Load Index (NASA-TLX). SmartEye™ eye tracking measures were also recorded.

The full-motion simulator (Figure 2) modeled a large commercial transport aircraft with typical weight and balance (approximately 180,000 pounds gross weight, 25% cg using 30,000 pounds fuel) and is configured to mimic the instrument panel of current state-of-the-art aircraft, with four 10.5" Vertical (V) by 13.25" Horizontal (H), 1280x1024 pixel resolution color displays tiled across the instrument panel. A collimated out-the-window (OTW) scene provided approximately 200 degrees horizontal by 40 degrees vertical FOV at 26 pixels per degree.



Figure 2. Full Motion-Based Commercial Aircraft Simulator (Enhanced Vision HUD shown)

Briefings and simulator training was provided to ensure familiarity with KMEM and simulation set-up. Pilots were instructed to conduct operations that reflected the standard operating procedures and communications during LVO/SMGCS operations. All radio communications were pre-recorded but were backed-up with a live controller confederate. Flight crews were briefed to conduct the operation as though passengers were onboard and to emphasize aircraft safety and comfort common for line operations. A total of nine experimental trials (8 nominal, 1 off-nominal) were conducted.

Results and Discussion

Data analyses are on-going; not all results were not available at publication (e.g., eye tracking data are not reported).

Quantitative taxi performance data analyses have been conducted and no significant effects were found, $p > 0.05$. Average taxi speed was 10.69 knots and was consistent across display and SMGCS conditions and reflects typical taxi speed under visibility conditions.

Situation Awareness. A significant main effect was found for display condition for situation awareness, SA (i.e., using SART), $F(3,18) = 51.958$, $p < 0.0001$; and SMGCS condition, $F(1, 6) = 16.754$, $p < 0.01$. No significant differences were found between pilot role of Captain (SART = 3.594) and First Officer (SART = 3.250), $p > 0.05$.

Flight crews reported higher SA under the Level 2 SMGCS (3.938) compared to Level 1 SMGCS (2.906). Pilots also reported significantly higher SA using the EV+E-SMGCS AMM (7.313) compared to the other three display conditions: No EV+No AMM (0.250), EV+No AMM (2.125), EV+AMM-Ownship (4.000). The post-hoc tests also evinced that having EV was significantly better than not having EV but that the addition of the AMM display significantly enhanced SA further compared to EV+No AMM condition. No interaction was found between SMGCS x Display Type, $p > 0.05$. Post-test paired comparison SA results reflected the SART results and pilots rated the EV+E-SMGCS display to be significantly better for SA compared to the other three display conditions (in rank order): EV+AMM-Ownship, EV+No AMM, or No EV+No AMM display concepts tested. The EV+AMM-Ownship condition was also significantly rated higher in SA than EV+No AMM or No EV+No AMM conditions.

Mental Workload. The TLX ratings analysis revealed a significant main effect for display condition, $F(3, 18) = 166.8$, $p < 0.0001$ and a trend for significance in the SMGCS x Display interaction, $F(1,6) = 2.514$, $p = 0.91$ which, given the small N, is reported here for consideration. The results demonstrated that pilots reported the EV+E-

SMGCS (20.625) to be significantly lower in mental workload than EV+AMM-Ownship (35.00), EV+No AMM (73.750) or No EV+No AMM (75.625). Although not significant, the interaction for SMGCS x Display purports that pilots reported lower workload when using Level 2 LVO/SMGCS visual aids only for the display conditions that had an AMM; pilots reported slightly higher mental workload when using Level 2 LVO/SMGCS under the non-AMM display conditions.

Post-Run Questionnaire. Ten post-run questions were administered. All questionnaire items were found to be significant, $p < 0.05$. Table 1 contains the means for the questionnaire by display condition.

Table 1: Post-Run Questionnaire Means

| | Level 1 LVO/SMGCS | | | | Level 2 LVO/SMGCS | | | |
|------------|-----------------------|--------------------|-----------------|---------------------|-----------------------|--------------------|-----------------|---------------------|
| | <i>NO EV + NO AMM</i> | <i>EV + NO AMM</i> | <i>EV + AMM</i> | <i>EV + E-SMGCS</i> | <i>NO EV + NO AMM</i> | <i>EV + NO AMM</i> | <i>EV + AMM</i> | <i>EV + E-SMGCS</i> |
| Q1 | 4.88 | 4.63 | 1.75 | 1.00 | 4.25 | 4.5 | 1.38 | 1 |
| Q2 | 5.00 | 3.88 | 2.00 | 1.00 | 4.50 | 4.5 | 2 | 1 |
| Q3 | 3.38 | 3 | 1.75 | 1 | 3.38 | 3 | 1.75 | 1 |
| Q4 | 4 | 3.50 | 2.75 | 2.5 | 4 | 3 | 3 | 2.75 |
| Q5 | 4 | 3.5 | 2.25 | 2.25 | 3.75 | 3.5 | 2.5 | 2.5 |
| Q6 | N/A | 1.75 | 1.25 | 1.25 | N/A | 2.25 | 1.25 | 1.25 |
| Q7 | 3.63 | 3.5 | 2 | 1.75 | 3.38 | 3.5 | 1.75 | 1.38 |
| Q8 | 4.38 | 3.5 | 2 | 1 | 3.38 | 4.25 | 1.75 | 1.25 |
| Q9 | N/A | N/A | 1.63 | 1 | N/A | N/A | 1.75 | 1 |
| Q10 | 4.75 | 3.75 | 1.5 | 1.25 | 4 | 3 | 1.25 | 1 |

Note: 1 = Strongly Agree; 4 = Neither Agree or Disagree; 7 = Strongly Disagree

- Q1. I was able to maintain taxi accuracy during SMGCS operation.
- Q2. I was aware of ownship position on the airport surface.
- Q3. I was aware of the cleared SMGCS taxi route.
- Q4. I was aware of traffic and other vehicles during SMGCS operation.
- Q5. I was aware of SMGCS signage, markings, and visual aid.
- Q6. The FLIR presentation was effective for SMGCS taxi operation (ease of access, size, etc.).
- Q7. The display concepts and SMGCS charts contributed to communication effectiveness (ATC and Flight Crew)
- Q8. The display concepts and SMGCS charts promoted crew resource management, coordination, and cohesion.
- Q9. The airport moving map (if applicable) display was effective for situation awareness during SMGCS operation.
- Q10. The display concepts and SMGCS charts contributed to perceived safety during SMGCS taxi operation.

Off-Nominal Event. During the final trial (unbeknownst to flight crews), the EV (FLIR) failed during taxi at a critical geographical position in which the flight crews needed to first detect the failure and then decide upon the proper course of action given aircraft location and the capabilities available inside and outside the flight deck (all off-nominals were conducted during Level 1 LVO/SMGCS equipage). The failure was presented to pilots as within-subjects variable and the display conditions were EV+No AMM, EV+AMM-Ownship, or EV+E-SMGCS AMM. Pilots reported that they felt significantly safer and were willing to continue the operation (e.g., cross an inactive runway) without the EV if an AMM was available. When the AMM was not present, the flight crew terminated operation and requested to return to gate with assistance. To verify that result, a second flight crew (Crew #4) also was presented with off-nominal scenario with baseline display and, as with the other flight crew, also terminated the operation and requested follow-me vehicle assistance.

When the AMM was available, flight crews significantly reported higher SA with both the AMM-Ownship (5.65) and AMM with E-SMGCS (6.00) compared to the baseline, no AMM condition (1.50). The baseline condition received significantly higher TLX scores (82.00) compared to AMM (35.00) and E-SMGCS (42.00). The location of ownship and labels on moving map were judged to be most significant contribution toward SA followed by depiction of stop bars and runway guard lights and geographical position markers on the E-SMGCS. Pilot consistently rated “strongly agree” that a EV (FLIR on HUD) with an AMM may allow for “operational credit” to

reduce ground-based requirements for LVO/SMGCS enhanced visual aids and that the E-SMGCS was judged to be significantly better for SMGCS operations than a basic AMM. Pilots also emphasized the desire for ownship routing and display of other traffic with CD&R alerting as a bonus.

Conclusion

The results demonstrated that an enhanced flight vision system may potentially enhance situation awareness and ameliorate problems witnessed when visibility drops requiring the use of LVO/SMGCS enhanced visual aids. However, the use of EV alone was not found to substantially enhance surface operations compared to baseline (i.e., no FLIR) without the addition of an AMM. Pilots consistently rated the AMM to be of significant value for these operations and, together, the EV and AMM was rated to be of tremendous benefit in maintaining SA and workload during 300 RVR approach and departures with simulated taxi-in and -out. The results also fully support the potential direction that EV with an AMM may provide an “operational credit” for SMGCS wherein an operator, with these requisite flight deck technologies, may be able to conduct lower than 500 RVR operations at airports that may only have a Level 1 LVO/SMGCS airport visual aids in place. Another option may be to enable under 1200 RVR surface operations at airports that do not have any LVO/SMGCS airport visual aids in place.

The FAA has stated that, “taxiing on the airport surface is the most hazardous phase of flight” (Gerold, 2001). Almost a decade later, that statement still rings true, but LVO/SMGCS enhanced visual aids and other controls are significantly improving this situation. Emerging flight deck technologies offer a potential means to create an equivalent level of safety and performance. These flight deck technologies, such as the E-SMGCS -AMM display and EV, could assist in fully realizing the potential of NextGen by offering a more affordable path toward safe and efficient LVO/SMGCS operations through an “equivalent visual” paradigm.

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