A preliminary assessment is presented of the required lower landing minima (LLM) capabilities needed to support the Small Aircraft Transportation System (SATS) Program. The goal of this analysis is to understand the number of potentially challenged SATS airports and to identify methods to remove obstacles by using technology solutions. Four obstacle removal methods are considered to assess the challenges faced by the SATS Program in providing LLM capabilities to 3,416 U.S. airports. Two views of runway obstacle analysis are presented: a critical object analysis and a detailed multiobject analysis that includes terrain information. A comparison is made between decision altitudes (DAs) derived by approach lighting infrastructure and glide path angle thresholds and DA values considering other airport characteristics such as terrain. A detailed case study is presented to compare the single critical object analysis with the more detailed multiobject analysis, which was performed for Blacksburg Airport, in Virginia.

The Small Aircraft Transportation System (SATS) is composed of a series of technologies being developed by the National Aeronautics and Space Administration (NASA) at Langley Research Center and the National Consortium for Aerospace Mobility (NCAM) to provide point-to-point air transportation service between thousands of underutilized airports. The analysis presented here centers around 3,416 public airports in the United States identified as candidate SATS airports, which are public landing facilities with a minimum runway length of 915 m (3,000 ft). If priced correctly, the SATS Program could improve the mobility of that segment of the population who use these services. NASA is developing four SATS technical capacities as part of the SATS Program: (a) improvements to lower landing minima (LLM) at airports without precision instrument approaches (PIR), (b) high-volume operations at nontowered airports, (c) single-pilot performance and safety operations, and (d) seamless integration of SATS vehicles in the en route airspace system. LLM capability is the subject of further investigation in this paper.

The Air Transportation Systems Laboratory at Virginia Polytechnic Institute and State University (Virginia Tech) has developed an air transportation system decision support model to assess the impacts of SATS and other aerospace technologies on the National Airspace System (NAS) (1). At the core of the model is the use of a mode choice model in which the number of SATS airports and the reliability of the airports play an important role in the outcome of mode choice behavior. Higher airport reliability can be achieved by utilizing SATS LLM capabilities, thus providing higher accessibility to airports that do not have PIR. The purpose of this study is to understand, from a systems engineering viewpoint, the technical constraints of providing LLM capabilities in support of the SATS Program to 3,416 public airports currently without PIR. The analysis reflects the status of all 3,416 NAS airports and considers the implementation of the Global Positioning System (GPS) and the Wide Area Augmentation System (WAAS).

LITERATURE REVIEW

WAAS is expected to provide a near-precision approach to achievement of LLM capabilities at minimally equipped airports. Theoretically, WAAS is able to provide a decision height (DH) of 76.2 m (250 ft). Three types of WAAS-aided approach procedures have been published, namely, lateral navigation (LNAV), lateral and vertical navigation (LNAV/VNAV), and lateral precision with vertical guidance (LPV). LNAV is a form of nonprecision approach with an optimal minimum of 121.9 m (400 ft). This approach provides lateral guidance to pilots flying WAAS-certified approaches. LNAV/VNAV provides a precision approach down to 106.7 m (350 ft) by offering both lateral and vertical guidance. LPV combines LNAV/VNAV lateral and vertical accuracy to utilize full WAAS satellite signal protection limits. LPV approaches can achieve near instrument landing system precision down to 76.2 m (250 ft). The first commercial flight equipped with a Technical Standard Order—certified GPS/WAAS receiver was conducted in Juneau, Alaska, on March 31, 2003. The best-known receivers today provide localizer-equivalent precision. According to the FAA, there are 2,057 LNAV-, 719 VNAV-, and 39 LPV-certified procedures (2).

WAAS approach certification procedures involve geospatial analysis of terrain and navigation facility information to determine the obstacle clearance surface (OCS). The approach analysis also includes the determination of DH minima. These procedures are developed by specialists considering potential obstacles in the approach path on a case-by-case basis for each runway. For the SATS Program, a systems-wide study is required to derive the optimal airport set that maximizes the potential SATS demand subject to airport cost–benefit constraints. There are few active nationwide LLM research programs. The GPS Approach Minima Estimator (GAME), developed by the MITRE Corporation, is a computer-based tool to estimate GPS landing minima considering terrain and controlling objects (3). Height above touchdown (HAT) and runway visual range (RVR) are derived without

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consideration of airport infrastructure effects. However, the benefit of introducing WAAS approaches cannot be assessed without knowing aviation demand and without consideration of obstacle removal costs. The approach proposed in this paper addresses some of the shortcomings of GAME by using a logit model to consider potential SATS demand.

SATS CANDIDATE AIRPORTS

According to the FAA, there are more than 20,000 landing facilities in the United States (4). This analysis of LLM capabilities for the SATS Program considers all public-use airports with a paved runway longer than 915 m (3,000 ft). The selection of 915 m of runway takes into account the performance of the set of aircraft expected to make up SATS. The analysis considers proposed very light jets, weighing less than 4,546 kg (10,000 lb), such as the Eclipse 500, Adam 700, Safire Jet, and Cessna Mustang. The SATS aircraft population involved includes proposed and existing turboprop aircraft (Raytheon B300, Pilatus PC-12, Ibis Ae 270, and Cessna Caravan) and the new generation of high-performance single-engine piston-powered aircraft (e.g., Cirrus SR-22 and Lancair 400). A 915-m runway is an absolute minimum for operating a very light jet with a modest payload at sea level conditions. Turboprop and single-engine piston aircraft can operate from a 915-m runway with good payloads.

The total number of airports meeting the runway length and ownership criteria is 3,416. This number excludes the top 31 hub airports, to avoid further congestion at these airports. The airport locations are shown in Figure 1. Spatial analysis shows that 96% of the U.S. population lives within 30 statute miles from the selected SATS airport set (1). In contrast, only 34% of the U.S. population lives within 30 mi of the large airport hubs (31 airports in 2004).

FAA WAAS APPROACH PROCEDURE

The instrument landing system continues to be the primary form of precision approach procedure in the United States. In 2004 there were 685 U.S. airports with full instrument landing system capability (4). This fact implies that many thousands of airports in the SATS set do not have precision approach capabilities. One goal of the SATS Program is to develop airborne technologies (e.g., displays and aircraft controls) aided by WAAS that would allow LLM approaches down to 30.5 m (100 ft) and 1/2 mi visibility. The use of GPS and WAAS approaches is the first step in assessing the benefit of LLM tech-

nologies in the SATS Program. Technically, SATS aircraft equipped with GPS- and WAAS-enabled technologies can execute precision approaches to airports at which conventional precision approaches are unavailable. However, the approach procedures using WAAS and GPS are restricted by specific FAA criteria related to the size of the WAAS qualification surface (WQS) and OCS (Figure 2, 5). The dimensions and clearance criteria of those surfaces determine important approach characteristics such as glide path angle (GPA) and the feasibility of the approach procedure. The FAA criteria to determine the size of WQS and OCS are well documented in FAA technical notes (5–8).

CRITICAL OBSTACLE LOCATIONS AND TYPES

Critical runway obstacle information for this study was obtained from the FAA airport database (4). Runways with available obstacle information were extracted for the SATS candidate airport database. The position and type of critical obstacles are identified in Figures 3 and 4, respectively. The analysis shows that 92% of the critical runway obstacles are found inside the WQS–OCS final approach segment. For this reason, the rest of analysis presented here focuses on the final approach segment only. Figure 4 shows that around 60% of the critical obstacles are easily removable objects such as trees, woods, and bushes. However, the possibility of direct removal depends on whether the removable obstacles are inside the airport perimeter. The fact that they are removable but still constitute obstacles (according to the FAA) suggests that they are either unreachable or too costly to remove.

FIGURE 1 SATS candidate airports in the United States (1).
FIGURE 3  Position of critical obstacles at 3,416 airports (obstacle positions at base end).

FIGURE 4  Types of critical obstacles at 3,416 runways: (a) base end and (b) reciprocal end.
OBSTACLE CLEARANCE METHODS

Other than direct removal, four obstacle clearance methods are proposed to achieve LLM capability and yet satisfy FAA approach design criteria (Figure 5): (a) raising the approach GPA, (b) displacing the runway threshold, (c) reducing the WQS, and (d) offsetting the final approach segment. Excluding reduction of the WQS, all the other methods can be applied to airports that meet the minimum WQS-OCS criteria. The obstacle clearance method of reduction of the WQS is justified by advances in aircraft controls and displays. Better flight deck navigation displays and controls provide improved pilot situation and lower workload. This improvement could reduce total flight technical errors (FTEs) during execution of WAAS-aided approaches. This subject will be investigated further in the SATS Program and has been demonstrated by the use of three-dimensional predictive displays.

Problematic airports can be identified at which GPS-WAAS approach criteria cannot be met after each method of obstacle clearance has been applied. In the following sections, the results are described of applying the four obstacle clearance methods to the set of 3,416 airports.

Raising GPA

The most intuitive way to clear obstacles is to raise the GPA. Recent general aviation pilot simulation research reveals that instrument-rated pilots have difficulty flying stabilized approaches in actual instrument meteorological conditions beyond 5 degrees with current flight deck instrumentation (9). SATS aircraft are expected to be equipped with improved navigation displays, but it is uncertain whether these displays could improve the GPA limit in instrument meteorological conditions. The transition from instrument navigation to the acquisition of the runway at the decision height seems to be a limiting factor driving the GPA limit. Anecdotal experience in the same pilot study suggests that under visual meteorological conditions pilots could fly steeper approaches.

The SATS aircraft considered in this study are very light jets, turboprop- and piston-powered aircraft with approach speeds up to 121 knots. For air traffic control purposes these aircraft are classified according to Terminal Area Procedures (TERP) Groups A and B. According to existing FAA rules, the maximum allowable GPA is 6.4 degrees for 81 knots or less, 5.7 degrees for 81 to 90 knots in TERP-A aircraft, and 4.2 degrees for TERP-B aircraft (5).

Figure 6 shows the gain by raising the GPA to clear obstacles at 3,416 airports for both (a) base and (b) reciprocal approach ends. Base-end results represent runways labeled from 00 to 18, and reciprocal runways include identifiers 19 to 36. By using recent general aviation pilot simulation study results, the 5-degree GPA is chosen as the critical safety threshold in this analysis (9). The results in Figure 6 indicate that 46% of base-end and reciprocal-end runways studied meet the WQS criteria if the GPA is 3 degrees. However, if the GPA is increased to 5 degrees, the percentage of runways in which the critical obstacle is cleared would increase to 78%. The observed trends for base-end and reciprocal-end runways are very similar. In the rest of this paper, only the results for base-end runways are discussed. However, reciprocal-end runways were also studied.

Displacing Runway Threshold

Another technique to remove runway obstacles is to displace the runway threshold. A displaced runway threshold of up to 305 m (1,000 ft) is now introduced as an obstacle clearance method. This threshold is coupled with GPAs of up to 5 degrees to test the gains in obstacle clearance. To satisfy runway operability and safety, the remaining runway length is set to be greater than 915 m (3,000 ft), which complies with runway length minima. Displacing the runway threshold offers...
the most cost-effective way to clear critical obstacles. A displaced threshold has little or no infrastructure investment needs.

The percentage of runway ends that benefited from threshold displacement is shown in Figure 7. With a 3-degree GPA as an example, 46% of the runways meet the WQS criteria. Displacement of thresholds up to 305 m resulted in 82% of the runways meeting the WQS criteria with at least 915 m of remaining runway. Figure 7 also shows that 152-m (500-ft) runway threshold displacement makes 75% of the runways studied compliant with the WQS criteria.

Reducing WQS

By conducting human factors research and applying new display technologies, NASA and NCAM are exploring the possibility of reducing FTEs, which are one of the primary drivers of WQS and OCS size. Large FTEs imply poor navigation-keeping ability in the final approach procedure and thus result in large vertical and lateral allowances in the design of the approach to keep the aircraft away from obstacles. If future pilot studies demonstrated that FTEs could
be reduced with improved aircraft controls and displays, the FAA might decide to accept smaller WQS and OCS. This change would only be possible if flight tests confirmed that the level of safety of the operations was not degraded. The foregoing possibility provided the incentive to study obstacle clearance by reducing the size of the WQS from its original dimension to an extreme case, a line with the same slope as the WQS–OCS surface. A reduction factor ranging from 1 to 0 is defined to indicate the normalized size of the WQS. A reduction factor of 1 implies the full size of the WQS. A value of zero implies that the WQS is a line.

The benefits of reducing the WQS are shown in Figure 8. With the same 3-degree GPA as the reference point with 46% of runway ends meeting the desired WQS criteria and with a reduction factor of 1 (making FTE zero), 80% of the runway ends would be in WQS compliance. The estimates of potential reductions in FTE here would suggest a reduction factor of no more than 0.5 in real applications. Recent flight simulation results using a Highway in the Sky display supported this conclusion. This finding would make the gains in obstacle clearance relatively small (4%). The results of this analysis indicate that navigation technologies can be made more precise and yet produce modest results in obstacle clearance.

Offsetting Final Approach Segment

Current FAA WAAS design approach criteria allow final approach segment offsets of up to 3 degrees provided that other criteria are met (5). Offsets up to 5 degrees are studied to illustrate the possible effect of new display technologies and aircraft controls in extending this limit. In this analysis a typical decision altitude (DA) of 91 m (300 ft) and a distance from the DA to the intersection of the runway centerline approach course of 351 m (1,150 ft) were used to comply with FAA rules.

Figure 9 shows the benefit of the offset method. Starting with a 3-degree GPA, if the maximum permissible offset of 3 degrees is applied to 3,416 runway base ends, the proportion of runways complying with WQS criteria increases from 46% (at zero offset) to 65%. If the offset angle is allowed increase to 5 degrees, the proportion of runways meeting WQS criteria would be 70%, a modest improvement but perhaps a worthwhile goal for the SATS LLM technology program.

RESULTS OF STANDARD PRECISION LANDING MINIMA

The FAA specifies precision approach landing minima contained in FAA Order 8260.48, Area Navigation Approach Construction Criteria (Table 1). On the basis of GPA analysis results obtained in the previous section and the available approach lighting system information obtained from the FAA airport database, the minimum HAT can be obtained for all runway ends studied (see Table 1). HAT defines the DH (in feet) or the minimum descent altitude above the runway touchdown zone elevation (TDZE). HAT defines a critical point in the approach at which a pilot initiates a missed-approach procedure if the runway is not in sight.

Two sets of HAT minima are presented in Figures 10 and 11 as a result of different dimensions and obstacle clearance criteria. The first set of results applies to the WQS and the second to the OCS. DA is the sum of HAT and TDZE. Presented in Figures 10 and 11 is a first-order analysis of the HAT values for every runway because the GPA for the critical obstacle and the approach lighting system at the runway end were the only variables considered in determining HAT. Under real-world conditions, other requirements such as the availability of taxiway, the size of the runway object-free zone and the runway safety area, and runway markings are to be considered whenever the information is available. An airport infrastructure inventory is necessary to understand the current status of the DA and the poten-

![Figure 8 Benefits of reducing size of WQS.](image-url)
tial to reach LLM at the 3,416 airports. Unfortunately, an airport database with all the necessary information is not readily available. To understand other factors that drive the current values of HAT, an informal airport instrument approach survey was conducted.

**SATS AIRPORT INSTRUMENT APPROACH SURVEY**

An informal survey was conducted of the top 500 airports from the selected SATS airport set that produces the largest demand according to the Virginia Tech air transportation decision support model \( (1) \). Approach characteristics surveyed were TERP group, type of approach, DA, RVR, real DA, and RVR considering TDZE, taxiway, and GPA. Among the 500 top SATS demand-producing airports, 85 have visual approach procedures only. The cumulative distribution functions of several TERP-A approach parameters are shown in Figure 12, and the TERP-B parameters are similarly distributed. A minimum HAT is assigned to each surveyed runway as its current best minimum (Figure 13). The survey acts as a starting point for a more comprehensive airport infrastructure inventory in future research. At the same time it provides useful data on actual approach parameters and how they compare with the minima contained in Table 1.

**APPLICATION OF OBSTACLE REMOVAL METHODS**

The effectiveness of the obstacle removal methods described here might depend on the views of various stakeholders. For example, an airport manager might have different views on how to remove obstacles than a pilot flying the approach or a technical analyst designing the aircraft controls to achieve safe operations for a challenged airport. On the basis of analysis of 3,416 runways in the United States, a family of sequential methods is proposed that rank in order of importance pragmatic approaches to the removal of obstacles. The same sequences can serve as guiding principles to rank LLM research in the SATS Program. The three ranking sequences to achieve obstacle removal are shown below in order from the best to the worst:

- Theoretical benefit: direct removal, raising the GPA, displacing the threshold, reducing the size of the approach surface, and offsetting the approach course;
- Approach safety: direct removal, displacing the threshold, offsetting the approach course, raising the GPA, and reducing the size of the approach surface; and
- Clearance cost: displacing the threshold, direct removal, offsetting the approach course, raising the GPA, and reducing the size of the approach surface.

Caution should be taken in the application of these clearance-method priorities. Use of the theoretical benefit approach means that only the gain of applying each method is considered, and costs and safety are neglected. The approach safety procedure analysis is airport site-specific. For example, runway length may raise the concern of threshold displacement safety, and the terrain around the airport may prohibit offsetting the approach course. The clearance cost approach should include the removal cost of the obstacles and the associated ground and airborne equipment costs.

The obstacle removal methods explained were applied to thousands of airports nationwide by using only the critical obstacle available for each runway end. The results from this analysis provide an initial assessment of the challenges in providing all-weather landing capabilities for the 3,416 airports. Once this assessment has been performed, a more detailed design procedure is to study each individual airport considering more detailed obstacle information (i.e., multiple objects) and the terrain information around each airport. A case study of
TABLE 1  Standard Precision Landing Minima (6, Table 2–2B)

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<thead>
<tr>
<th>Glide Path Angle (with approach light configuration)</th>
<th>Aircraft Category</th>
<th>Minimum Visibility</th>
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<tr>
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<td>Minimum HAT</td>
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<td>3.31°–3.60°</td>
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<td>3.61°–3.80°</td>
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<td>3.81°–4.20°</td>
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<td>5.01°–5.70°</td>
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★ = no lights; # = MALSR, SSALR, ALSF; $ = # plus TDZ/centerline lights; NA = not authorized.

Note: MALSR = medium-intensity approach lighting system; SSALR = simplified short approach lighting system; ALSF = high-intensity approach lighting system; TDZ = touchdown zone.

**FIGURE 10**  TERP-A HAT for runway base ends.
Blacksburg Airport is highlighted in the following section to illustrate the more detailed study of a GPS-WAAS precision approach procedure.

**CASE STUDY: BLACKSBURG AIRPORT (VIRGINIA TECH)**

Blacksburg, Virginia, is located in mountainous terrain that presents a challenge to design precision approaches. The airport has a partial instrument landing system approach with localizer information. To design an approach procedure, a U.S. Geological Survey 1:250K digital elevation model containing detailed topographic representation was used. Four existing approach fixes (PULASKI, ZOOMS, HAWTO, and SUNNY) were chosen for Runway End 12, and four pseudo-fixes were chosen for Runway End 30 to satisfy the FAA approach design criteria. Obstacle data were gathered from the National Geodetic Survey Universal Data Delivery Format for Runway End 12 (10). A resultant 4.2-degree GPA is necessary for this approach considering all the obstacles instead of the 3-degree approach obtained using the critical obstacle alone. The approach surface together with the terrain information for Runway 12 are shown in Figure 14. The analysis shows that a GPA of 4.2 degrees would meet
FIGURE 13 Cumulative distribution function of minimum HAT for each runway surveyed.

FIGURE 14 WAAS WQS with terrain information for Runway 12 at Blacksburg Airport.
the WQS clearance requirement for the three approach segments. The lesson learned from this detailed analysis is that a national-level analysis conducted with all four obstacle clearance methods provides the best-case scenario of the challenges to improve LLM capability at the airports studied.

CONCLUSIONS AND FUTURE RESEARCH

Four methods were presented to mitigate the effects of existing obstacles at airport runways using the critical object for every runway end. Other than direct removal of runway obstacles, the most promising methods to maximize WAAS approach compliance are raising the GPA and displacing the runway threshold. The SATS Program should continue investigating the safety implications of these methods.

A national-level study was done using the critical obstacle of every runway to identify challenges in providing LLM capabilities for the SATS Program. A detailed study of a challenged airport provided insight about the variations between the critical object analysis and more detailed consideration of terrain and obstacle databases for an airport. The obstacle removal methods presented here offer a first step to utilizing GPS and WAAS.

A further study of LLM costs and benefits is needed to find an optimum number of WAAS-capable airports to be part of the SATS Program that justifies infrastructure investment. SATS demand at candidate airports, weather patterns, travel time savings, ground and airborne WAAS equipment cost, and airport infrastructure inventory are the basic elements of a future cost–benefit model to identify the optimum set of airports needed for the SATS Program. The cost–benefit analysis requires knowledge of the demand function expected at the airport (to derive user benefits) and the infrastructure costs of every proposed LLM technology (both onboard and on the ground).

The SATS LLM operational technologies under development would provide safety benefits to the aviation community even if the SATS Program is not able to convince many passengers to switch to the air mode. The safety implications of LLM technologies should be studied using piloted and computer simulation studies. These technologies could well be one of the best legacies of the program.

REFERENCES


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