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USE OF ADS-B AND PERSPECTIVE DISPLAYS TO ENHANCE AIRPORT CAPACITY

J. David Powell, Stanford University, Stanford, CA
Chad Jennings, Nav3D, San Carlos, CA
Wendy Holforty, NASA Ames, Mt. View, CA

Abstract

As the growth in air travel continues over the coming decades, there will need to be increases in the capacity of the airspace system, especially airports. Technology associated with GPS, along with changes in procedures between air traffic controllers and pilots, has the capability to provide much of the required growth without sacrificing safety and without requiring wholesale expansions of airport land areas. The use of GPS to augment radar surveillance through Automatic Dependent Surveillance - Broadcast (ADS-B) provides a substantial improvement in surveillance accuracy and provides every pilot with information on neighboring traffic, information that does not exist now. Wake vortex turbulence of neighboring traffic is one of the limiting factors on parallel runway spacing and the in-trail spacing of aircraft. This paper shows how the impact of wake turbulence can be substantially reduced by the use of ADS-B and appropriate displays. The paper presents results of analyses, pilot simulations, and flight-testing that show the required runway spacing can be reduced from the current 4300 ft. to 750 ft., thus substantially improving landing capacity while minimizing cost and the effect on the environment.

Introduction

The capacity of the airspace system around the world is primarily constrained by the landing capacity of the busiest airports. Historically, world air traffic has been increasing at about 5 - 6% per year for many years and will likely continue that growth in the future. Therefore, increases in the number of aircraft landings will approximately triple in 20 years. In order to accommodate these landing rates, it will be necessary to increase the number of airports, increase the usable number of runways at existing airports, or both. A recent article [1] highlighted the coming crunch in Europe caused by the lack of airport capacity.

The current system for landing aircraft in cloudy weather (called Instrument Meteorological Conditions or "IMC") is composed of 1) the Instrument Landing System (ILS) for aircraft navigation, 2) airport radar surveillance to display the location of aircraft to the air traffic controllers, and 3) a set of procedures involving the responsibilities of the controllers and pilots. Under IMC conditions, the primary responsibility for maintaining separation between aircraft lies with the air traffic controllers. In good weather, (called Visual Meteorological Conditions or "VMC"), it is the pilots' responsibility to maintain separation from other nearby aircraft. Pilots often use the ILS in VMC to help guide the aircraft to a smooth landing during the last 5 miles of the approach; however, they have the option of looking out the window to line up the aircraft with the runway.

With the navigation and surveillance systems in primary use today, parallel runways must be separated by 4300 ft. for use in IMC. However, in VMC, parallel runways that are separated by as little as 750 ft. can be utilized. There are many airports around the world that have parallel runways where only one of the runways can be used in IMC but both can be used in VMC. This is the primary reason that delays usually occur in bad weather. Implementing technology that would allow for the usage of parallel runways with closer spacing in IMC would double the capacity of many airports in bad weather. For example, there are 22 airports in the U.S. with parallel runways separated by less than 4300 ft. but more than 700 ft.[2] Any of these airports would achieve a considerable increase in capacity if both their parallel runways could be used in IMC. Many other airports around the world also currently have parallel runways with insufficient spacing for use in IMC. Researchers from Honeywell and NASA Langley recognized this and demonstrated the ability to operate in IMC with reduced runway spacing in a program called Airborne Information for Lateral Spacing (AILS) [2], [3], and [4].

When runways are added to airports, the impact of the expansion is significantly affected by the required spacing of parallel runways. With the current requirement that parallel runways be separated by 4300 ft. for use in IMC, it is virtually impossible to add a second runway at existing airports without adding land area. Expansions now being planned for Chicago and St. Louis will require that a large amount of neighboring land is condemned and acquired by the airport, an expensive and difficult process. For San Francisco, a runway expansion project meeting current spacing requirements would require filling 2 sq. miles of S.F. Bay. Likewise, when new airports are created, the land required is significantly reduced as the spacing between parallel runways is reduced.

Thus, we see that there is a huge incentive to reduce the required spacing between parallel runways. It would reduce the cost, the amount of land required, and would ease the political process of obtaining the necessary permissions.

Another dimension of airport landing capacity is the separation between aircraft in-trail, i.e., aircraft that are following one another. Today, the required in-trail spacing varies between 3 and 5 miles, depending on the relative sizes of the aircraft. Larger separations are required when small aircraft are following large aircraft in order to avoid possible upsets due to an encounter with the turbulence from wake vortices (see Fig. 1) of the leading aircraft. Technology to enable pilots to avoid the wakes of preceding aircraft will, therefore, also lead to increased airport capacity. Furthermore, the need to avoid wakes of neighboring aircraft also affects the required separation between parallel runways. Rossow has extensively studied the behavior of wake vortices [5] and collaborated with Raytheon to devise a scheme whereby aircraft landing rates are improved by avoiding areas containing wake turbulence [6].

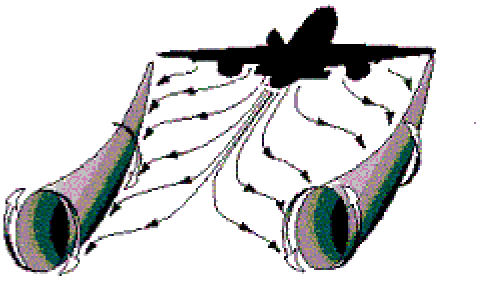

Fig. 1. Wake Vortices [7]

In summary, there will be a very large positive impact on the world’s ability to increase the landing capacity of airports if parallel runways can be used safely in IMC that are much closer together than the current minimum of 4300 ft. Further increases in capacity will be achieved if aircraft in-trail separation can be reduced safely by providing the pilot information about the location of wake vortices. This paper discusses new technology that has the potential to significantly improve the airport landing capacity by addressing both issues discussed above. However, difficult institutional issues need to be addressed in order for the technology to be implemented and accepted by all stakeholders in the airspace system.

Basis for Current Runway Spacing

The current requirement for parallel runway lateral spacing is 4300 ft. for use in bad weather (IMC). However, in clear weather (VMC) parallel runways are safely used today when spaced only 750 ft. apart. Clearly, when the pilot has good information about neighboring traffic, it is safe for two airplanes to land simultaneously on parallel runways that are spaced much less than 4300 ft. apart. The basis for the 4300 ft. requirement in IMC is partly due to the fact that the controller on the ground looking at the radar screen has responsibility for maintaining separation between the aircraft, and partly due to navigation and surveillance errors. More specifically, there is a normal operating zone that is 1150 ft. wide, a 2500 ft. buffer zone to allow an aircraft to escape should the neighboring aircraft blunder towards it, a 450 ft. margin that guards against a worst case error of the surveillance radar, plus 200 ft. representing the wingspan of the aircraft [8]. The 2500 ft. buffer zone is sized to allow time for the controller to recognize a blunder from the radar screen, to establish communication with the pilot for an alert of the danger, and for the pilots to react and divert their airplane.

Currently, navigation on the final approach is provided by the Instrument Landing System (ILS), a land based radio-navigation aid that provides a beam for the aircraft to follow as it approaches the runway. The aircraft receiver measures the angular deviation from the desired beam, thus any position errors in the system grow progressively larger as the distance from the airport increases. While the ILS is very accurate at the landing zone, it has an error of 385 ft. 5 miles from the airport [8] and an error of 770 ft. 10 miles out. These large errors are the primary reason that the normal operating zone described above is 1150 ft. Another factor in sizing this zone is the aircraft deviations from the proper course that may occur due to wind turbulence.

The surveillance radar used in the terminal area scans with a 5 second interval and provides an accuracy of approximately 3 mrad. Therefore, at 10 miles from the airport, their accuracy is approximately 180 ft.

The total required runway separation could be reduced with no degradation in safety if: 1) the navigation accuracy and control of the aircraft was improved thus reducing the size of the normal operating zone, 2) there was a reduction in the time required to recognize and react to a blunder of neighboring traffic, and 3) the surveillance accuracy was improved.

New Technology

There is technology available today that is capable of significantly improving the accuracy of aircraft navigation and surveillance. There is also technology that will allow for the improved knowledge of an aircraft's position to be transmitted to neighboring traffic and to the ground controllers. These all have major impacts on the required runway spacing described in the previous section.

Satellite Navigation

The GPS system provides much greater accuracy than has been available in past navigation systems. GPS is now augmented by 25 reference stations throughout the U.S and provides an accuracy of approximately 6 ft. (2 m) horizontal and 9 ft. (3 m) vertical (95%). It is called the Wide Area Augmentation System (WAAS) [9]. The system has been operational since July 2003. The augmented satellite navigation system substantially improves the navigation and surveillance accuracy and reliability over that being used by commercial aircraft and air traffic controllers today.

The satellite navigation data is available to the pilots and autopilots so that the normal operating zone can be substantially reduced. Furthermore, it does not grow as the distance from the airport increases; the error is the same no matter where the aircraft is. This navigation data can also be sent via data link to the ground controllers; therefore, surveillance accuracy can be substantially improved to the accuracy of WAAS. In addition, the data can be sent via data link to neighboring traffic so that each pilot can have very accurate information on where its neighbors are; essentially the same information available in VMC.

Data Link of Aircraft Navigation

Wireless digital data links are now well-accepted technology. Special versions have been developed and accepted for use by aircraft to broadcast their positions to one another and to the ground. The concept is referred to as Automatic Dependent Surveillance – Broadcast (ADS-B). Many prototype systems have been built and are currently being evaluated by approximately 200 airplanes in Alaska and on the east coast of the US. There are also evaluations ongoing in the Pacific Rim, Europe, and Russia, and the system has been officially adopted as the future surveillance system for Australia. The reason for the high level of interest is that it is substantially more accurate than radar and substantially less expensive. There is little doubt that, eventually, ADS-B will provide the world's surveillance [10].

The surveillance accuracy is the same as the underlying navigation accuracy, i.e., the augmented GPS. In the U.S. where WAAS is operational, the surveillance accuracy would be 2 m horizontal and 3 m vertical (95%). The data rates have some randomness due to the random nature of the protocol that enables hundreds of airplanes in a vicinity to share one frequency; however, the update period will normally be 1 second or slightly longer. It would be beneficial to restrict the update period to 1 second or shorter while used for parallel approaches.

Although current data link designs do not transmit the roll angle of each aircraft, it would be a relatively minor modification to add that quantity to the transmitted signal. In the following discussion, it is assumed that the roll angle of neighboring traffic would be available from the data link.

The wake visualization accuracy is enhanced if the data link also transmits the wind magnitude and direction from each aircraft, parameters not currently included in the ADS-B message. There are many other beneficial aspects of adding these quantities as well and the concept is being actively considered.

Synthetic Vision of Traffic

The position of neighboring traffic may be displayed to the pilot on 2-D displays or 3-D displays, sometimes called “perspective” displays or “synthetic vision”. Some researchers have concentrated on 2-D displays [11] while others have designed and evaluated displays that contained perspective portions [12]. An example of a synthetic vision display is shown in Fig. 2. The view at the top of the figure shows a synthetic view of what a pilot would see looking out the window. It shows a neighboring aircraft on a parallel approach and its proper approach “tunnel” in magenta; it also shows the pilot’s own tunnel in green. The bottom of the figure shows two 2-D views of the approach scenario: the center portion shows a top down view of the two aircraft as they are positioned on their respective approach paths. The two boxes in either side of the approach paths are a 2-D vertical slice that shows the vertical and horizontal position of each aircraft in their respective tunnels as well as the roll angle of the neighboring traffic. This particular mix of views was favored by a sample of pilots in a simulation study of various displays [12]. Human factors specialists are generally not in favor of displays that mix horizontal and vertical information on one display; however, pilots have given favorable evaluations for the mixed display on this study and others as well.

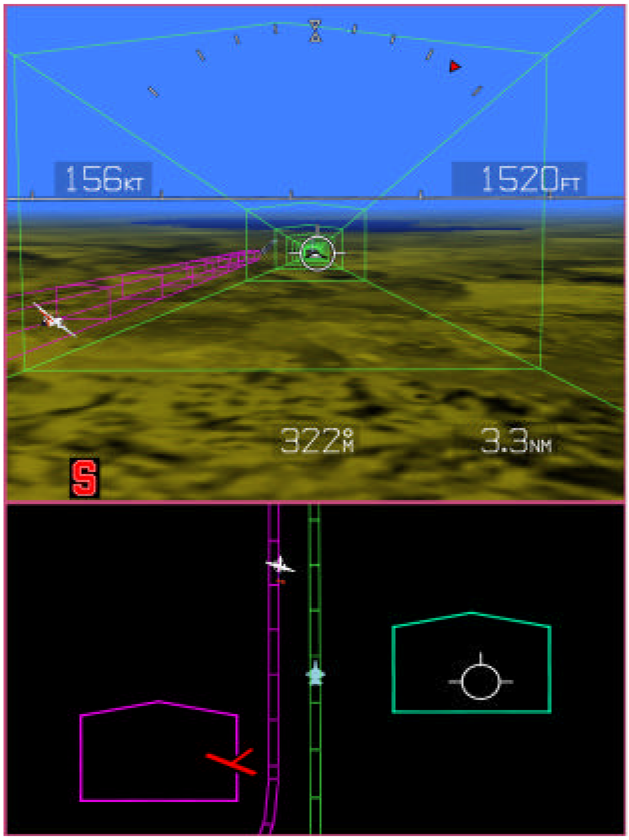

Fig. 2. Synthetic Vision Display for Parallel Approach with Traffic [12]

Note that the roll angle of the neighboring traffic is also apparent in the top perspective view. In this situation with the traffic on the left, a roll to the right (as shown) is a precursor to a blunder away from its assigned path into the aircraft on the right. Research has shown that the most important variable for pilots tasked with recognizing a blundering aircraft on a parallel approach is its roll angle [8], [13] and having knowledge of this angle minimizes the pilot’s reaction time to a threatening blunder by a neighbor.

It is also possible to determine the region around a neighboring aircraft in which it is unsafe to fly. This is accomplished by modeling the maneuvering capability of the two aircraft, assuming the neighboring aircraft will execute the worst possible maneuver, then calculating the boundary at which it is possible for the following aircraft to escape [14]. Fig. 3 shows an example of the boundary drawn around the traffic on the left. The red and yellow regions in front of the pilot on the right give more refinement to the danger. The red zone indicates that the pilot would have 4 seconds to respond to a blunder, while the yellow region indicates 6 seconds would be available.

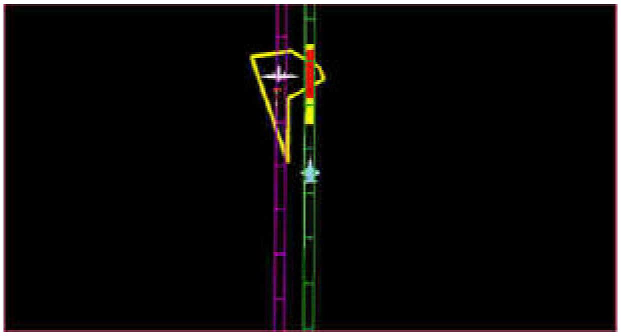

Fig. 3. Boundary of Safe Zone [12]

Synthetic Vision of Traffic Wakes

One of the key factors in determining the spacing of aircraft on final approach is the need to avoid the wake vortex turbulence caused by other traffic. It might be from prior departures, from an arrival immediately in front of the approaching aircraft, or from neighboring traffic on a parallel approach. The procedures and spacing requirements are substantially driven by the possible presence of wake turbulence. Today, the spacing is very conservative because there is no system in place to measure the location of the wakes nor to predict the location of wakes. An Airbus 320 class aircraft following a Boeing 747 is required to follow 5 miles behind in order to allow the wake to dissipate in case the wake is in the path of the oncoming aircraft. This extra spacing could be eliminated in most cases if the pilot had good knowledge on the location of the wake. Uncertainty about the location of wakes on the airport surface also causes delays in the release of a departing aircraft after an arrival on the same or crossing runway. Research into various methods of measuring the position of the wake is in progress. For example, pulsed lidar is being investigated in Europe [15] and NASA is investigating a suite of sensors in the Aircraft Vortex Spacing System (AVOSS) [16]. There is also extensive activity in predicting the position of wake turbulence [17] and to quantify the uncertainty of the position prediction. While these research efforts are ongoing, the ability to predict the position of the wake and to quantify its uncertainty is sufficient today to allow significant reductions in the spacing if the capability was implemented into the fleet.

Rossow's prediction methods were utilized to depict the wake in a synthetic vision display, installed in an aircraft, and flight tested [18], [19]. Fig. 4 shows a sample of the display from one of the flight trials. The experiments were carried out using two aircraft. One was used to generate a wake and to emit smoke so the wake could be found easily in flight. The other (larger) aircraft was equipped with the display driven by the wake location prediction. Both aircraft were equipped with a special version of ADS-B so that wind information could be exchanged between the two aircraft for better wake prediction. In all scenarios flight tested, the wake was located exactly where the predictions placed it. In Fig. 4, the wake is depicted by the series of disks located at the lower center portion of the display. The small circle in the middle indicates the flight path of the aircraft; therefore, the display shows that the wake is slightly below the aircraft. This fact was confirmed in the test flights by the presence of smoke from the preceding aircraft. Without exception, all pilots associated with the flight test program were very enthusiastic about the ability to visualize the presence of wakes from neighboring aircraft.

The 3-D perspective display such as shown in Fig. 4 is capable of depicting the wake's vertical and horizontal position in one view. It is also possible to show the horizontal position of the wake in a 2-D view [11] and its vertical position in another view. Whether the display is 2-D or 3-D, the implementation of a device that shows the position of the wake will be a significant safety feature for any flight regime. There have been many accidents over the years that were triggered by an encounter with wake vortex turbulence. It will also be a significant factor in allowing a safe decrease in the spacing on approach to airports.

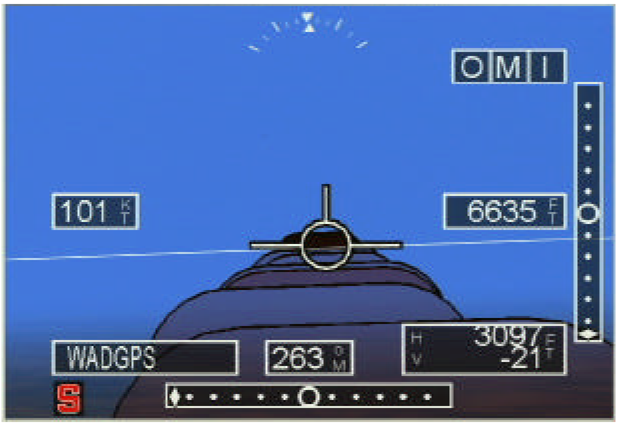

Fig. 4. Flight Trial Wake Display [18]

Impact of New Technology on Airport Capacity

As discussed above, the requirement that parallel runways be 4300 ft. apart for simultaneous use in IMC is influenced by the surveillance accuracy, navigation accuracy, and the delay time associated with the recognition and evasion of a blundering aircraft. All these quantities are significantly affected by the new technologies discussed in the previous section and that are now available.

Simply changing the radar from the current system (ASR-9) to a Precision Runway Monitor (PRM) increases the surveillance accuracy and update rate and will allow for a decrease in the required spacing from 4300 ft. to 3400 ft. [20]. Furthermore, adding better navigation than the angular ILS system will allow a further reduction to 2200 ft. with no other changes. The key is to have better navigation 5 to 10 miles away from the airport where ILS errors are at their largest [20]. These results were obtained using a statistical analysis that calculated the runway spacing that would yield the same level of safety that exists for the current 4300 ft. separation.

For evaluation of the effect of using displays in the cockpit that enable a pilot to “see” neighboring traffic on a parallel approach, a Monte Carlo statistical analysis was performed [13]. Based on the statistical variations of navigation accuracy, surveillance accuracy, longitudinal spacing, and pilot reaction times to recognize and react to a blunder, it was found that the required runway separation for the same level of safety was much less than 4300 ft. and a strong function of the longitudinal spacing (see Fig. 5). The figure shows that for longitudinal separations that vary between 1000 and 2000 ft, a runway separation of 1200 ft. yields a loss of separation probability of 10^{-7}. This is also the value of the probability that indicates a runway spacing of 4300 ft for today’s technology; therefore, use of this probability value (10^{-7}) results in the same level of safety as today’s runway separation. The same analysis showed that the required spacing is 750 ft. if the longitudinal spacing is increased to 3000 ft.; however, the curve for that case does not appear in Fig. 5 because the probability is less than 10^{-10} and falls off the bottom of the curve.

Taking advantage of increased longitudinal spacing introduces the possibility that the wake vortex from the neighboring aircraft drifts into the path of the oncoming aircraft. Fig. 6 depicts the situation and suggests that the size of the safe zone will depend on the strength and direction of the crosswind. In fact, to fully utilize the effect of longitudinal spacing, the leading aircraft should be placed so that the cross wind blows its wake away from the trailing aircraft. However, even without this complication for ATC, 750 ft. runway spacing would be safe for crosswinds less than 10 kts.

In summary, 1) if navigation and surveillance accuracy is improved as described, 2) if the pilot can “see” the neighboring traffic, 3) if the pilot can “see” the wake of the traffic, 4) if ATC can position the approaching pair of aircraft to maintain suitable longitudinal spacing, and 5) if ATC can place the lead aircraft on the down wind side, then a 750 ft. runway spacing would provide the same level of safety that is achieved now with 4300 ft. runway spacing. If ATC is unable to accomplish item 5, use of two runways with 750 ft. spacing in IMC would require that the cross winds be less than 10 kts.

Implementation Considerations

The advantages of improving airport capacity with a substantially reduced requirement for airport land are immense. The technologies required to bring about a reduction in required runway spacing from 4300 ft. to 750 ft. have, in large part, been prototyped and flight-tested. The hardware technology has been proven; however further development is indicated to arrive at the best displays, to refine the uncertainty of the wake prediction, and to establish ATC procedures. It will not be easy to implement the technology into the entire fleet so that it can be used routinely by the world’s airlines.

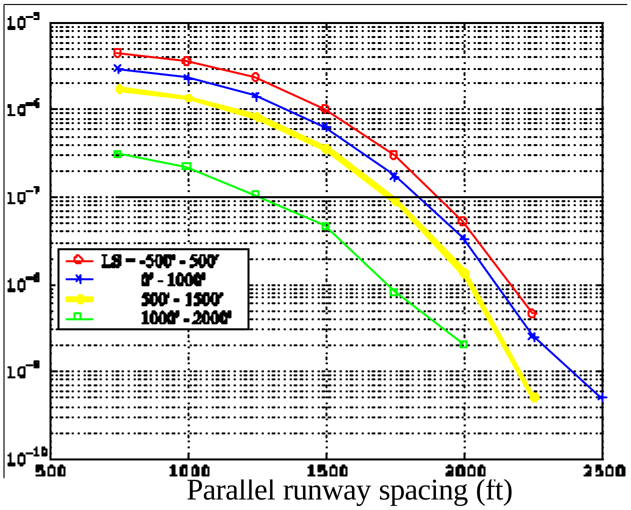

Fig. 5. Probability of Loss of Separation vs. Runway Spacing and Longitudinal Spacing (LS) [12]

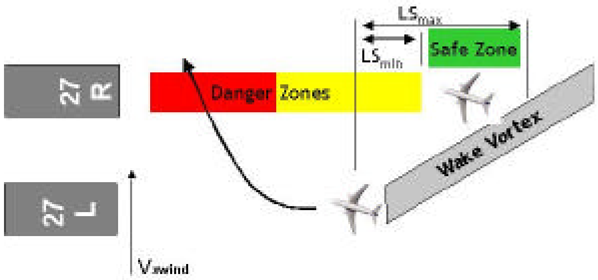

Fig. 6. Schematic of the Danger Zones and the Effect of the Neighboring Wake [12]

One difficulty is the allocation of costs. The cost of airport expansion is usually borne by the local or national government, and the cost to airlines is only partially recovered through landing fees. Implementing the ideas in this paper will reduce the cost of airport expansion and new airport construction by many billions worldwide [12], but will require airlines to re-equip their aircraft with a cost on the order of $200K per aircraft. In addition, the airlines would need to re-train their pilots in order to execute the modified landing procedures. Although a detailed cost analysis has not been carried out, it appears as if the total system cost of expansion will be significantly less by implementing the ideas in this paper. The difficulty is that large portions of the costs are shifted from the governments to the airlines, a situation that might cause barriers to the implementation of the ideas.

There will also be shifts in responsibilities between the air traffic controllers and the pilots. Today, the controllers have responsibility for separation in IMC. The technology discussed in this paper calls for shifting that responsibility to the pilots for approaches to closely spaced parallel runways. This kind of paradigm shift has been traditionally difficult to accomplish. There needs to be many simulations and flight tests of the procedures with the new technology so that all parties are comfortable with the new roles and responsibilities and the resulting safety level. In addition, the responsibilities of the controllers for lining up and pairing the approaching traffic are made more complex. In order to fully utilize the runways, the aircraft pairs need to be within certain bounds on longitudinal spacing and the lead aircraft is best located on the downwind side of the two runways. This is well beyond the scope of what controllers are required to do today and extensive simulation and software tools will need to be used to ensure reliable and safe operation.

The safety of the system needs to be demonstrated to all stakeholders. If pilots are asked today whether it is acceptable to reduce the spacing of runways for parallel approaches in IMC, they will invariably answer, “the more spacing, the safer it is”. While this is true if the question is directed to the use of current technology, the answer is much different if you consider all the safety enhancements with the technology described here. There should be extensive simulations and flight tests with many different pilots so that they can experience first hand how the technology enhances safety. Those pilots then need to communicate the system advantages to their colleagues. Final development of a product can not be achieved until these simulations and flight tests are carried out and the concept is accepted.

In short, developing the technology may be the easiest part. The difficult part lies ahead in bringing about a buy-in by all stakeholders in the airspace/airport system: the airlines, pilots, controllers, airport managers, aircraft manufacturers, and the government agencies.

Conclusions

Technologies have been described that will be capable of substantially increasing the capacity of airports with little or no increase in land area for existing airports and will greatly reduce the required amount of land for new airports. Prototypes of the technology have, in large part, been built and flight-tested. It is shown that, with this technology, the lateral spacing between parallel runways could be reduced from the current 4300 ft. to 750 ft. for simultaneous use in bad weather. Furthermore, the technology will enable the reduction in longitudinal spacing in many cases from 5 miles to 3 miles.

Implementation of the technology will not be easy. It will require extensive simulation and flight-testing to ensure that all stakeholders accept the system and are confident that its safety will be equal to or better than the current system.

In the long term, however, implementation of the system described will result in easier public acceptance of airport expansions because of the reduced environmental impact. Furthermore, it is highly likely that the total system cost to the traveling public will be minimized.

The need for more airport capacity is approaching fast [21] and government agencies in the U.S., Europe, and the Far East should increase their urgency in how best to implement increased capacity.

Acknowledgements

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