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# A HUMAN SUBJECT EVALUATION OF AIRPORT SURFACE SITUATIONAL AWARENESS USING PROTOTYPICAL FLIGHT DECK ELECTRONIC TAXI CHART DISPLAYS

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# 1. Introduction

The advent of Instrument Landing Systems has allowed aircraft to safely takeoff and land in low visibility conditions. However, the lack of a means by which pilots can safely navigate on the ground in poor visibility conditions has been the cause of many runway incursions and several fatal aircraft accidents.

Currently flight crews use paper chart depictions of the airport surface and out-the-window visual cues to navigate on the surface. In addition they can be provided some feedback about their position on the surface from ATC. In clear, daylight environmental conditions flight crews can correlate airport features and navigation signs from the out-the-window view with the chart features to maintain airport surface situational awareness. In conditions of fog and darkness however, out-the-window cues are less available and it becomes a difficult task for flight crews to maintain situational awareness. Low visibility conditions also prevent ATC from tracking aircraft position on the airport surface from the tower.

Airport surface situational awareness is a flight crews awareness of their location with respect to airport surface features such as runways and taxiways. In conditions of low visibility, the lack of airport surface situational awareness may lead an aircraft to enter an active runway without proper ATC clearance. This was the case in a ground collision incident at Detroit Metro Wayne County Airport in 1990. A DC-9 mistakenly entered and proceeded to back-taxi down the same runway on which a B727 was cleared for takeoff. The 727 proceeded with the takeoff roll and a head-on collision resulted. Due to foggy environmental conditions tower controllers were not able to see the DC-9 taxi onto the active runway and therefore were not able to warn either of the flight crews. This incident resulted in 8 fatalities and 21 injuries [Harrison 1991].

To provide some background on the difficulty in maintaining situational awareness during low visibility taxi tasks as compared to other phases of flight, an informal survey of 19 airline pilots was conducted. The pilots had an average flight experience of 10250 flight hours. Pilots were asked to the rate the difficulty of 6 phases of a typical commercial flight in terms of maintaining situational awareness on a scale from 1 to 5. The results shown in Figure 1.1 indicate that ground taxi was the most difficult phase of flight to conduct in low visibility conditions, followed by landing and takeoff. The ground taxi difficulty rating was greater than the difficulty ratings of the other phases of flight at a 5% significance level (t test).

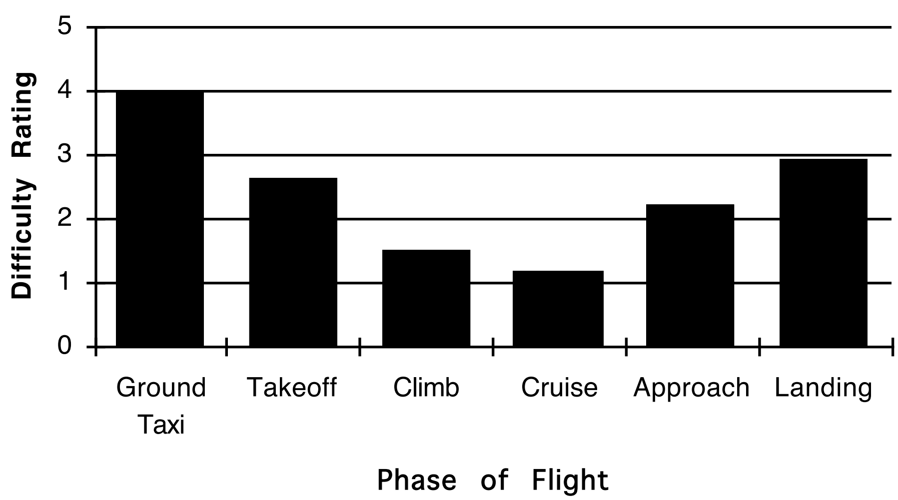

**Figure 1.1 Plot of Difficulty of Maintaining Situational Awareness in Low Visibility Conditions vs. Phase of Flight. 1=Not Difficult 3=Moderately Difficult 5=Very Difficult.**

Currently there are no displays in commercial airline cockpits which show the aircraft location with respect to local airport features to help crews determine their location on the airport surface in low visibility conditions. However the advent of high precision GPS navigation and display technology has enabled flight deck electronic displays of the airport surface with aircraft position information. Aircraft position can be determined using the Global Positioning System (GPS) to better than 100 meters or to even higher accuracy using Differential GPS (DGPS). Also a study on airport surface operations requirements performed by the Boeing Commercial Airplane Group for NASA Langley recommended the use of flight deck taxi displays with ownship position as a component of a global solution to low visibility surface operation difficulties [Groce et al. 1993].

The objectives of this study were as follows.

- Determine the benefit of displaying aircraft position on a north-up electronic taxi chart in terms of airport surface situational awareness.

- Determine what effect position accuracy degradation has on pilot Situational Awareness using a north-up electronic taxi chart. This data can be used to determine position accuracy requirements. Four levels of position error were tested ranging from 4.5 to 90 meters.

- Determine the benefit of graphically displaying real time knowledge of position accuracy as opposed to the knowledge of worst case position accuracy of the position sensing system.

In order to measure the impact of an electronic taxi chart on airport surface situational awareness, prototypical electronic taxi charts were developed and a test method was developed which involved asking airline pilots a series of situational awareness probe questions. The charts were designed from a Jeppesen Sanderson airport surface chart, Federal Aviation Administration (FAA) standards for airport markings, and feedback from airline pilots. The effect of the electronic taxi charts on Situational Awareness was tested by asking 12 airline pilots a series of situational awareness probe questions in static "snapshot" scenarios with restricted out-the-window visibility. Independent variables were aircraft position error and position uncertainty symbology. Dependent variables were situational awareness probe question response accuracy which was a measure of situational awareness and response time, as well as pilot subjective measures.

## 2. Background

This chapter will provide a section on runway incursions and the global positioning system (GPS). In addition, background will be offered on electronic taxi chart presentation issues, paper airport surface charts, and low visibility taxi procedures.

### 2.1 Runway Incursions

> ***Error! No index entries found.***" *Any occurrence at an airport involving an aircraft, vehicle, person, or object on the ground that creates a collision hazard or results in loss of separation with an aircraft taking off, intending to take off, landing, or intending to land.*" [Harrison 1991]

Runway incursions are normally caused by human error, either by the ATC controller or the pilot or controller of the surface vehicle. When a human error is committed by the pilot it is often due to a loss of airport surface situational awareness.

Runway incursions are categorized as operational errors, pilot deviations, and vehicle/pedestrian deviations. Figure 2.1 shows a breakdown of the number of incursions for each category during the 4 year period from 1989 to 1992.

It is not unusual for airline pilots to be involved in a runway or taxiway incursion. In order to provide some background on runway incursions an informal survey was conducted of 19 active airline pilots with an average flight experience of 10250 hours. When asked if they had been involved in a runway or taxiway incursion or close call, 13 of the 19 pilots replied yes.

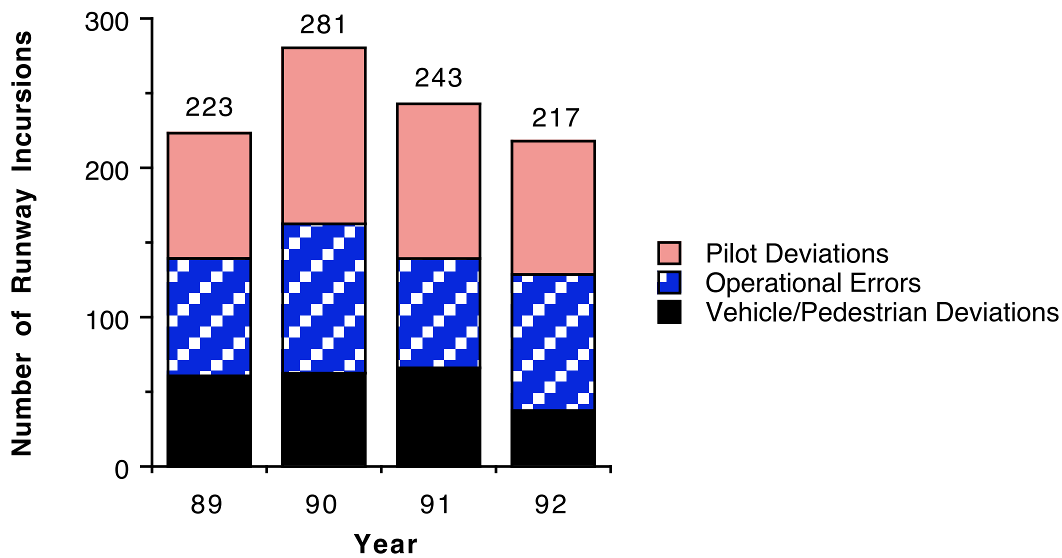


Figure 2.1 Runway Incursions Broken Down By Category for the 4 year period beginning in 1989 [Kasner 1992].

### 2.2 The Global Positioning System

One of the key ingredients of the implementation of a flight deck electronic taxi chart with ownship position is an accurate position sensing system. The Global Positioning

System (GPS) is a satellite based navigation system which transmits ranging signals to receivers which then calculate an estimate of position. GPS has currently been certified by the FAA for limited use as a position sensor for approaches [Nordwall 1994] and is a likely candidate for use in surface operations. Issues that arise in a discussion of GPS are satellite coverage and position error. It is not clear what value of position error will be acceptable for a flight deck electronic taxi chart. It is one of the objectives of this experiment to provide insight into this issue.

GPS position error is defined as the distance from the GPS predicted position to the actual position. For a position sensing system, an estimate of the position error is typically expressed as a level of position accuracy or uncertainty. This position uncertainty is typically expressed as $2\sigma$ value which means the position error is within this range 95% of the time. For aircraft in flight a typical error estimate is given in vertical and horizontal components. However for surface operations only a horizontal estimate of position is required.

GPS position error depends on two primary factors: the geometric configuration of the satellites from which the receiver is accepting ranging signals from and the precision with which the GPS receiver can measure the ranging distance to each satellite. Normally 4 satellites are needed to obtain a position fix: 3 to obtain latitude, longitude, and altitude coordinates and 1 to cancel out clock errors due to the difference in time between the expensive precise clocks on the satellites and the cheaper less precise clocks in the GPS receivers. However for surface operations, only three satellites are needed because altitude will be known. Position error is lowest when the satellites are widely spread out with large angles between them [Logston 1992]. The Geometrical Dilution of Precision (GDOP) is a numerical measure of how well the satellites are mutually positioned.

GPS satellites transmit on two L-band carrier frequencies: L1 and L2. The L1 frequency is modulated with the course acquisition (C/A) code and with the precise (P) code. The L2 carrier is modulated only with the P code. The C/A code is available to all users while the P code is restricted to military use. The Department of Defense (DOD) intentionally degrades the C/A code ranging signals for civilian use by method of Selective Availability (S/A). The horizontal $2\sigma$ accuracy of GPS for civilian use is considered to be 100 meters. This level of position accuracy was established as a compromise between the FAA (Federal Aviation Administration) and the DOD for civilian use. S/A is not consistently active. It was turned off during the Gulf War to allow coalition forces to obtain the best GPS positioning accuracy [Logston 1992]. Currently it is not clear whether it will remain on in the future.

Experimental tests have shown different levels of position accuracies. A study was completed in which a ground vehicle fitted with a GPS receiver was used to determine GPS static position accuracy at Chicago O'Hare International Airport in 1992. The GPS data was shown to have a $2\sigma$ accuracy of 41.32m for 2489 trials [Hoffelt et al. 1992]. It is important to state that these are position accuracy values for the time and location stated. Position error will vary with the number of satellites in view which is dependent on time and location, as well as the integrity of the ranging signal.

A method for improving the position accuracy is Differential GPS (DGPS) (Figure 2.2). This method provides a stationary receiving station on the ground at a known location. This differential station receives the ranging signals from the satellites and calculates the difference between the position predicted by triangulation and its known position. This correction factor can then be transmitted to local aircraft for improved user position accuracy. DGPS has been shown to provide a $2\sigma$ position accuracy of 4 to 5 meters [Hoffelt et al. 1992]. A limiting factor of DGPS is that it is limited to use only at airports or regions which have a differential receiving station.

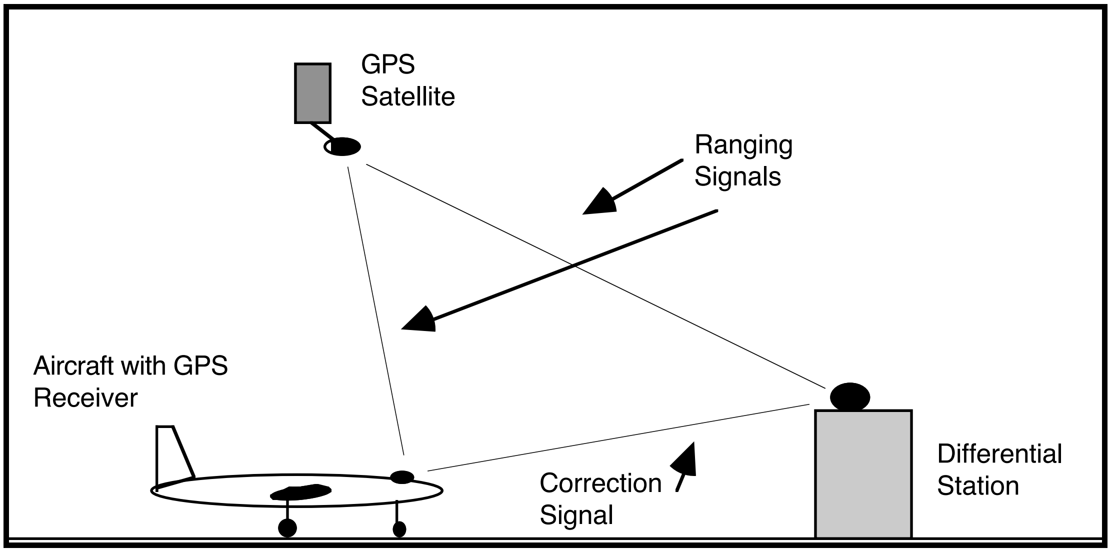


Figure 2.2 Schematic of Differential GPS. **For an accurate position fix 3 to 4 satellites are required.**

The typical output of GPS receivers is a position fix consisting of a latitude, longitude, and altitude. In addition some receivers will calculate Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP) and display an estimate of position accuracy.

GPS or DGPS could conceivably be used to provide position information to display aircraft location on an electronic taxi chart. It is also likely that the position accuracy estimate could be displayed as a measure of position confidence.

## 2.3 Electronic Taxi Chart Presentation Issues

Electronic displays first appeared in aircraft in order to replace conventional electromechanical instruments. The three primary advantages of using an electronic display is the ability to systematically use color coding, the ability to display a mixture of pictorial, text, and numeric formats, and the ability to have the pilots call up a variety of formats on the same piece of display hardware [Wiener and Nagel 1988]. An example of an electronic display currently used in glass cockpit aircraft is the Electronic Horizontal Situation Indicator (EHSI). The EHSI is a moving map display used to display navigation waypoints enroute. An EHSI developed at the MIT Aeronautical Systems Laboratory (ASL) based on a 757/767 display is shown in Figure 2.3. It is likely that an electronic taxi display could be utilized to provide navigation information and enhance pilot airport surface situational awareness using the same display hardware.

An issue when discussing electronic maps is whether to display the information in a north-up or track-up (moving map) format. A north-up format would display the airport surface in a north-up orientation. A track-up format would display the airport surface with respect to the ownship aircraft. Typically the ownship aircraft is placed horizontally at the center and vertically 1/3 of the way up the chart. Surrounding terrain would then be displayed. The advantages of a track-up chart include the ability to display surrounding terrain always with respect to the aircraft. This is helpful during taxi tasks because the pilot does not have to perform a mental rotation to orient the map to the aircraft heading. An advantage of a north-up format is that there are no text rotation problems because the map orientation does not change. For this study a north-up taxi chart format was developed.

Several organizations have been performing research in the area of Electronic Taxi Charts. NASA Langley has developed electronic displays of airports in Denver and Chicago in effort to investigate situational awareness and the benefit of electronic charts over currently used paper charts [Hunt 1993]. The Harris Corporation has also developed some electronic displays of the airport surface in an effort to find a solution to the runway incursion problem [Kulikowsi and Harvey 1992]. The Harris displays showed all runways and taxiways. In addition displays of the airport surface are being developed for use in the Airport Surface Traffic Automation Program (ASTA). A simulated surface radar display has been developed and is in use on a demonstration basis at Boston Logan International Airport [MIT Lincoln Laboratory 1993]. The display shows runways, taxiways, and ramp areas as well as surface traffic.

Figure 2.3 Electronic Horizontal Situation Indicator (EHSI)
Based on B757/767 Display. **Actual display is color.**

An issue which arises in a discussion of displaying aircraft position on an electronic taxi chart is how to display the position accuracy associated with the position sensing system. The worst case accuracy of the position sensing system can be displayed, or alternatively the real time position uncertainty can be displayed. A real time display of position accuracy would take advantage of increases in position accuracy due to better satellite coverage or other methods of improving accuracy such as DGPS.

### *2.4 Paper Airport Surface Charts*

Current charts are plan view depictions of the airport surface and surrounding features. They are used by flight crews to plan and navigate taxi routes at unfamiliar airports. Two organizations produce airport surface charts: the National Oceanic and Atmospheric Administration (NOAA) and Jeppesen Sanderson, Inc. Both organizations distribute the airport surface charts in conjunction with Instrument Approach Plates (IAP's). NOAA charts are contained in bound booklets and redistributed every 58 days [Hansman and Mykityshyn 1990]. Jeppesen Sanderson charts are contained in a ringed binder and are distributed individually every 2 weeks .

An example of a Jeppesen Sanderson airport surface chart is shown (Figure 2.4). The main portion of the Jeppesen chart contains a plan view schematic of every runway and taxiway on the airfield as well some features of the surrounding terrain such as railroad tracks and objects of altitudes which may be dangerous to local air traffic. Most of the airport surface diagrams are presented in a north-up format. The top portion of the charts contain the name of the airport and the city in which it is located as well as necessary radio frequencies.

### *2.5 Low Visibility Taxi Procedures*

Currently navigation on the airport surface is accomplished using the cockpit out-the-window view, a paper airport surface chart, and advice from ground and ramp controllers. In low visibility conditions follow-me trucks and tugs are sometimes used to guide the aircraft to the gate once it has landed. Flight crews use the paper chart of the airport surface to provide a reference to the flight deck window visual cues. On approach the chart is typically retrieved from its binder within an hour from touchdown at unfamiliar airports. On departure it is typically reviewed at the gate.

Ground taxi operations are broken up into movement and non-movement areas. The movement area covers all taxiways and runways and is governed by ATC ground control. The non-movement area expands the ramp and terminal areas and is governed by local airline ramp controllers at more congested airports.

Low visibility surface operations for transport category aircraft are normally governed by takeoff and landing restrictions. A decision to takeoff is governed by Runway Visual Range (RVR) which is a measure of the visibility longitudinally along the runway surface in feet. RVR may be measured at the runway touchdown, midpoint, and

Figure 2.4 Example of Jeppesen Sanderson Airport Surface Chart. **Reproduced with permission from Jeppesen Sanderson, Inc.**

rollout locations. Landing decisions are based on RVR and a decision height at which the runway must be in sight. Takeoff decisions are based on RVR. Approach and landing RVR minimums depend on guidance equipment a the particular runway and on the a particular aircraft. Typically 600 feet RVR has been the minimum although some aircraft and runways are certified for 300 RVR.

## 3. Development of a Prototypical Electronic Taxi Chart Format

In order to test the effect of an electronic taxi chart on airport surface situational awareness it was necessary to develop a prototypical electronic taxi chart format. The term electronic taxi chart refers to an electronic display of the airport surface to be used for taxiing purposes.

### *3.1 Electronic Taxi Chart*

The overall layout of the prototypical electronic taxi chart format resembled that of a Jeppesen Sanderson paper airport surface chart. One of the prototypical electronic taxi charts developed for this study is shown in Figure 3.1. The top portion of the chart contained radio frequencies necessary for approach and departure and the name and location of the airport. The geographical layout of the airport lies in the center and is a scale view. It included a plan view presentation of the runways and taxiways with ID's and airport buildings. In addition, the runway lengths in feet were also displayed.

Although the electronic chart resembles the Jeppesen paper chart some features not present on paper charts were incorporated. For example runway centerlines, edgelines, and threshold markers were included on the electronic charts as well as taxiway centerlines. The lengths and widths of the runways and taxiways, as well as the runway and taxiway markings, were depicted to scale.

Color coding of the electronic taxi chart resembled the real world to the extent possible. Runway, taxiway, and ramp areas were dark gray to be consistent with the actual pavement color. Similarly, runway centerlines, edgelines, and threshold markers were white and taxiway centerlines were yellow. The buildings were colored blue. A black background was used to provide contrast.

Figure 3.1  Example of Electronic Taxi Chart.  **Actual size shown.**

Although the approach was to have the basic layout resemble a standard paper airport surface diagram, some modifications were taken to facilitate using an electronic media for presentation. For example the scale was increased by a factor of 1.13 to allow the airport surface depiction to be as large as possible but still fit the constraints of the standard EFIS display size (5.625” by 6.75”). In addition the airport runway ID symbology (Figure 3.2) remains horizontal regardless of the orientation of the runway in order to avoid aliasing effects where the runway ID symbology on Jeppesen charts is oriented perpendicular to the respective runway centerline.

Figure 3.2 Example of Runway ID Symbology on the Electronic Taxi Charts. **The larger font is the actual runway ID while the smaller is the runway heading with respect to North. This symbology was modeled from the runway ID symbology on Jeppesen Sanderson Airport Surface Diagrams. This is the ID for “Runway 18”.**

Taxiway ID markings were similar to the Jeppesen paper chart's convention. The taxiways were identified by an individual letter from the English alphabet and presented on the electronic chart in capital case. The ID was placed as close to the taxiway as possible without obstructing it.

Text on the electronic taxi chart was sized according to Society of Automotive Engineers (SAE) standards. SAE recommends that electronic display letters and figures subtend not less than a minimum vertical angle at the design eye position of the pilot who normally uses the instruments. SAE recommends a visual angle for three types of data [Society of Automotive Engineers 1988]:

| | |
|---|---|
| Primary data | 6 milliradians |
| Nonessential and Secondary data | 4 milliradians |
| Minor descriptive legends | 3 milliradians. |

The runway ID symbology text as well as the taxiway ID text and runway length text were considered to be primary data for this experiment and were sized so that they would subtend an angle not less than 6 radians. A viewing distance of 30 inches was used as a reference value for this experiment (Figure 3.3). The font size used for the aircraft heading in the runway ID symbology was 9 point (this was the smallest of the primary data text). The visual angle for the aircraft heading text was 6.25 milliradians.

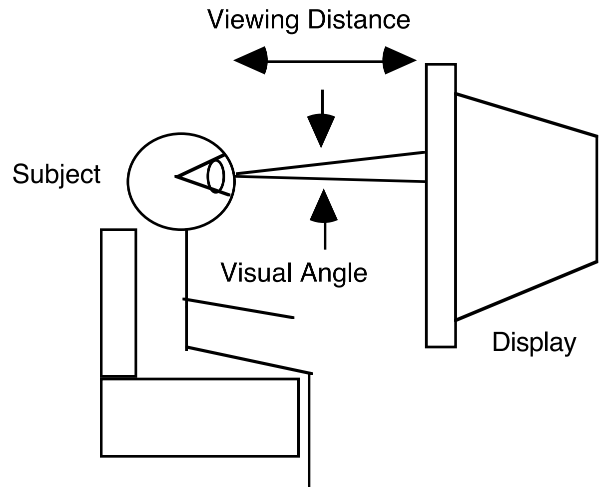


Figure 3.3  Schematic of Subject Viewing Distance and Visual Angle Subtended When Viewing Electronic Taxi Chart Text.  **Visual angle subtends height of electronic taxi chart text.**

### *3.2 Aircraft Position and Heading Symbology*

The position of the aircraft on the airport surface was depicted by overlaying ownship aircraft symbology onto the electronic taxi chart.  Three things were displayed with this symbology:  the predicted location of the aircraft, the uncertainty of the predicted location, and the aircraft heading.  The predicted location was indicated by the apex of a triangular icon.  The aircraft cockpit was used as the aircraft reference location.  The position uncertainty was indicated by an uncertainty circle centered at the apex of the triangle (Figure 3.4).  The uncertainty circle defined the disc within which the cockpit of the aircraft was located.  The aircraft heading was indicated by an imaginary bisector of the base of the triangle pointing towards the apex.  It should be noted that for this study the heading was assumed to be accurately known.

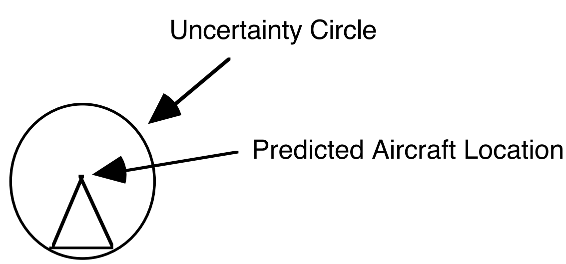


Figure 3.4  Aircraft Triangular Icon and Uncertainty Circle. **The uncertainty circle defines the disc within which the cockpit of the aircraft was located.**

Two types of uncertainty circles were used as shown in Figure 3.5. The constant radius uncertainty circle indicated the worst case system position accuracy while the variable radius uncertainty circle indicated the actual position uncertainty. The constant radius uncertainty circle was intended to provide the pilot knowledge of the worst case system uncertainty while the variable radius uncertainty circle was intended to provide the pilot with knowledge of the current position uncertainty as a measure of position confidence.

The variable radius uncertainty circle had 4 different radii: 5 meters, 25 meters, 50 meters, and 100 meters. These were chosen to reflect the four different levels of position error used in the study. The constant radius uncertainty circle had only 1 radius: 100 meters. This value was chosen to emulate the 2σ GPS position accuracy level of 100 meters.

The colors of the aircraft symbology were selected after prototype testing to be clearly visible to the pilot. It was also desired to provide contrast between the uncertainty symbol which represented aircraft location and the triangular icon which represented aircraft heading. Green was selected for the triangular icon and yellow was selected for the uncertainty circle to provide good contrast between each other and the other symbology on the chart.

Figure 3.5 Ownship Aircraft Symbology. **Values shown are radii of the uncertainty circles in meters. The 5m uncertainty circle collapses to a point**