A Non-Precision Instrument Approach Procedure with Vertical Guidance (IPV) for Aircraft Landing Using GPS

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In the near future, Spaced-Based Augmentation Systems (such as the Wide Area Augmentation System in North America) will become operational, permitting the use of GPS as a primary system for all phases of flight. Recently the International Civil Aviation Organisation (ICAO) has recommended the use of un-augmented GPS as a supplemental navigation system for all phases of flight including non-precision approaches. In this paper, the salient features of the Air Traffic Control (ATC) system in India, and the use of conventional navigational aids are described. A new landing procedure is proposed using un-augmented GPS known as 'a non-precision instrument approach procedure with vertical guidance (IPV)' for Hyderabad Airport, Runway 27. This procedure, if implemented, would be cost-effective and reliable for many airports in India. An algorithm has also been developed for determining the range and bearing between the departure and the arrival waypoints of an aircraft using the IPV.

KEY WORDS

1. GPS. 2. Air Traffic Control. 3. Approach and Landing.

1. INTRODUCTION. The Airports Authority of India (AAI) operates and regulates the Indian airspace system and is the authority for air traffic control (ATC) in India. Currently, about 5 international, 87 domestic airports and 28 civil enclaves at defence airfields are in use in India, but only about 45 airports (37·5%) have an Instrument Landing System (ILS) for aircraft precision approach and landing. There is a clear need for a reliable all-weather approach and landing system for all airports. The Global Positioning System (GPS) could provide such a system.

Civil aviation is one of the most important fields in which the use of GPS will have a dramatic impact. Space-Based Augmentation Systems (SBAS) for GPS, such as the Wide Area Augmentation System (WAAS), provide highly accurate position, velocity, and time for navigation and surveillance functions for all four phases of flight: enroute, terminal, approach and departure. Un-augmented GPS does not have the accuracy or integrity required to use as a primary navigation system for

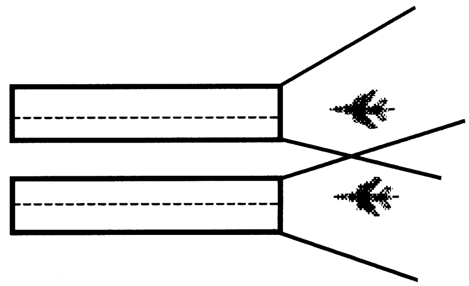

Figure 1. Angular approaches.

precision approach; however, in remote areas and over oceans, it can be used as a primary system for enroute and terminal navigation (Dewar, 1999).

Currently, there are two types of instrument approach: precision approach (PA) and non-precision approach (NPA). In contrast to PA where both lateral and vertical guidance has to be provided, NPA provides only lateral guidance (Houch *et al.*, 1999). ICAO is in the process of introducing a new type of approach 'a non-precision instrument approach procedure with vertical guidance (IPV)'. This is midway between PA and NPA and allows procedure designers to isolate obstacles that constrain the landing limits on a typical NPA. GPS/NPA is aimed at meeting this new type of approach and comprises a series of waypoints joined by tracks. The Federal Aviation Administration (FAA) of USA has already developed 1768 GPS non-precision instrument approaches and has published 925 of them. In this paper, a basic 'T' configuration procedure design for Runway 27 at Hyderabad Airport is presented. An algorithm is also presented for determining the range and bearing between the waypoints of an NPA procedure.

2. CURRENT APPROACH AND LANDING AIDS. The most common means of providing NPA capability uses either Non Directional Beacons (NDB) or VHF Omni-directional Range (VOR) with or without Distance Measuring Equipment (DME). VORs are primarily used as enroute navigation aids for operations that demand relatively precise guidance; but, where VORs are located in proximity to an airport, they can also provide approach guidance. VORs with DME can provide an aircraft with more precise positioning along approach paths, enabling obstacles behind the aircraft to be excluded from assessment. NDBs are also employed as enroute and approach navigation aids and, because of their comparatively low cost, their use is widespread. An NDB placed on the approach path of an airport requires obstacle assessment in an area that may extend to a radius of 15–20 nmi, but it is possible – though rarely achieved – to obtain a Minimum Distance Altitude (MDA) as low as 300 feet above the runway. If it is not possible to locate the NDB on the runway approach path, the situation becomes much worse because of the requirement to assess a very large area for obstacle clearance.

For Precision Approaches (PA), ILS is the standard civil landing system used in India. ILS provides a PA capability from Category I to Category III (ICAO – Annex 10, 1995/6). ILS consists of two components: the localizer beam for horizontal guidance and the glide-slope beam for vertical guidance. While ILS meets the PA requirement, it suffers from a number of problems including the angular nature of its radiating beams, typically 3 to 6 degrees wide horizontally and 14 degrees vertically.

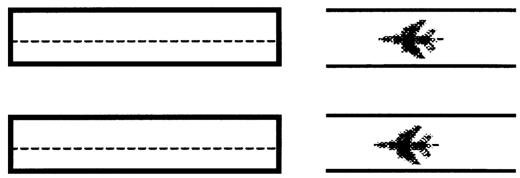

Figure 2. Corridor approaches.

Table 1. Required RAIM performance..

Parameter	Departure	Enroute	Terminal	Initial approach	NPA
Horizontal Accuracy limit (m)	220	740	740	220	220
Horizontal alert limit	555	1850	1850	555	555
False alarm limit (h^{-1})	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-5}
Probability of missed detection	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}

As a result, the farther the aircraft is from the runway, the lower the position resolution for a given needle deflection on the aircraft's course deviation indicator (CDI). During an approach, if the pilot exceeds a full-scale needle deflection, he or she must abort the procedure and execute a missed approach. As illustrated in Figure 1 for landings on parallel runways, the localizer beams of each runway will eventually overlap somewhere on the approach. For instance, if the runways were separated by 750 ft, the overlap at full CDI needle deflection would occur 1·2 nmi from the threshold. If the pilot were flying a 'good' one-dot approach, the overlap would occur 6 nmi from threshold.

3. THE USE OF GPS FOR APPROACH GUIDANCE.

Even though NDB and VOR/DME navigational aids are very reliable, they cannot be regarded completely as all-weather aids for approach and landing because their relatively poor accuracy imposes severe limitations on decision height. Moreover, costs of installation and maintenance of these aids is relatively high. In recent years, there has been widespread growth in the development of GPS, which is less expensive to use and available in all weather conditions. NPAs based on the use of GPS could provide better accuracy and therefore better all-weather performance than those based on NDB or VOR/DME.

There is also a need for completely separate, non-overlapping approaches to parallel runways; the ideal approach path would be a constant width corridor extending five or more miles from the runway threshold (see Figure 2). Un-augmented GPS position, or the augmented GPS position from SBAS, can be used to create these straight instrument approach corridors that are free from the angular dependence of ILS. These high-accuracy parallel approaches do not overlap and navigational separation is possible, even far from touch-down.

However, un-augmented GPS does not have the integrity required for approach guidance; thus, some form of monitoring is needed. Receiver Autonomous Integrity Monitoring (RAIM) has been developed by the receiver manufacturers to provide monitoring of the signals from individual GPS satellites and so give confidence for the use of GPS when not within the coverage area of a SBAS. RAIM operates by using

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Table 2. Accuracies required for NPA and PA landing phases.

Approach Type/Decision Height		Required Position Accuracy	
Non-Precision Approach		Horizontal	Vertical
DH = 76·2 m		0·3 nmi	500 m
Precision Approach			
CAT I	DH = 30·5 m	18·2 m	7·7–4·4 m
CAT II	DH = 15·2 m	6·5 m	1·7 m
CAT III	DH = 0 m	4·1 m	0·6 m

Table 3. Tolerances for the GPS NPA.

Parameter	Tolerance (FAA/ICAO)
IAS Segment	
True bearing to next waypoint	±2°
Distance to next waypoint	±0·5 nmi
FAS Segment	
True bearing to next waypoint	±2°
Distance to next waypoint	±0·3 nmi
MAS Segment	
True bearing to next waypoint	±2°
Distance to next waypoint	±0·5 nmi

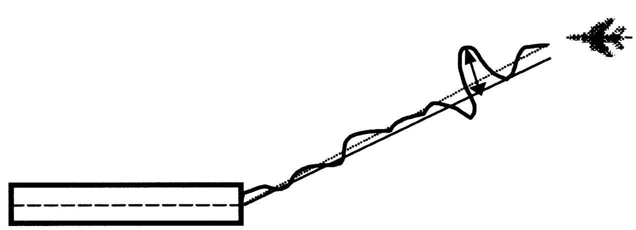

Figure 3. Total system error.

the signals received from redundant satellites (those over the four required for normal operation) to check whether all satellites in view are providing sensible and accurate signals. Table 1 shows the required RAIM performance, and Table 2 the accuracies required for NPA and PA landing phases.

3.1. *GPS Accuracy*. The primary errors to be quantified are navigation sensor error (NSE) and flight technical error (FTE) which combine to make total system error (TSE). NSE is the difference between the actual and measured aircraft position in space. FTE is a measure of how well the pilot or autopilot follows the indicated path through space. NSE is solely a function of the navigation systems in use, while FTE is primarily a function of the pilot or the autopilot. Figure 3 shows the pictorial representation of these errors. Using the carrier-smoothed, double difference GPS code-phase technique, NSE was determined to be approximately three metres for GPS approaches, effectively making FTE the primary error source of TSE (ICAO PANS OPS, 1993). Once more satellites are observed, the ambiguity factor can be fixed to its integer value, which is key to optimal use of double difference observations.

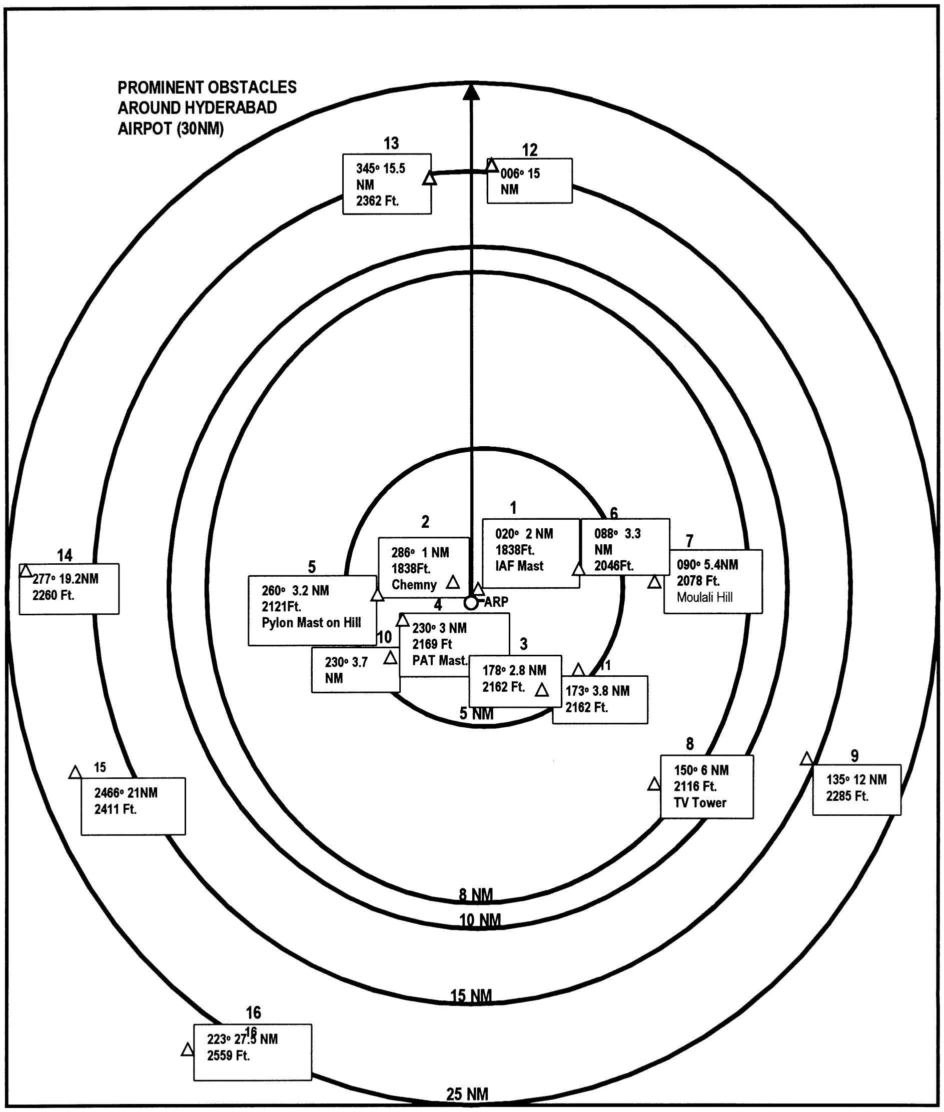

Figure 4. Prominent obstacles around Hyderabad Airport.

4. PROCEDURE DESIGN. A GPS/NPA consists of a series of waypoints (points on the ground defined by coordinates rather than beacons) programmed into a GPS receiver that will guide an aircraft to a point at which the aircraft can land safely. The series of waypoints that define a GPS/NPA comprise a number of terminal segments: the initial and intermediate approach segments (IAS), final approach segment (FAS) and missed approach segment (MAS). The IAS begins at the initial approach waypoint (IAWP) and ends at the final approach waypoint (FAWP), the FAS begins at the FAWP and ends at the missed approach waypoint (MAWP), and the MAS begins at the MAWP and may include turning or holding waypoints (MAHWAP) or fixes from ground-based navigation aids. The tolerances for both the FAA and ICAO for GPS/NPA are shown in Table 3.

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4.1. *Configuration*. Obstacle assessment areas are very important in the design of approaches. They are different for different navigational aids. Factors such as terrain, traffic pattern, noise sensitive areas, restricted zones and aircraft performance must be taken into account to achieve the lowest MDA consistent with safety. For GPS-based approach design, new guidelines have to be developed. Obstacles within 30 nmi of the Hyderabad airport have been assessed and plotted on the chart (see Figure 4).

GPS/NPAs can be configured in many ways; the most common configuration is referred to as the 'T' and is usually composed of five segments delineated by geographic waypoints. A typical 'T' configuration is shown in Figure 5. Each

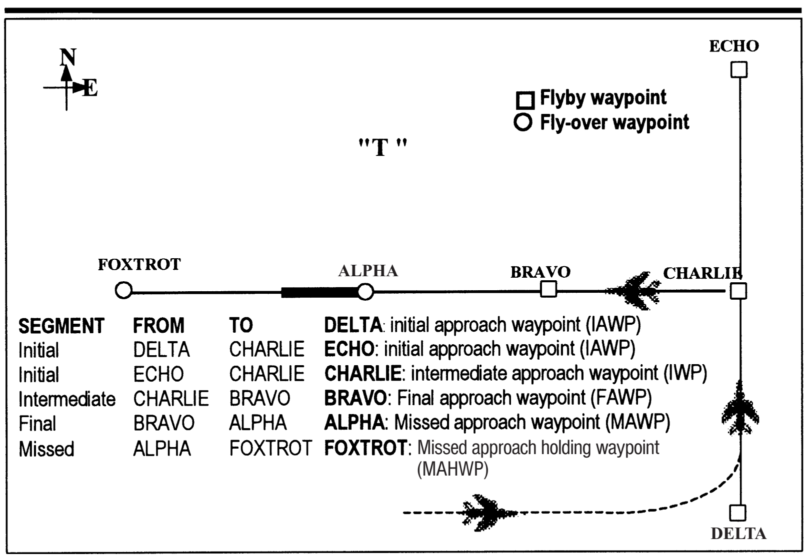

Figure 5. A typical GPS 'T' configuration.

waypoint is contained within an obstacle clearance area, and each obstacle clearance area has primary and secondary zones; the extremities of successive areas are joined to create a procedure's various segments.

The 'T' configuration designed for Hyderabad airport is based on the design guidelines given by Dewar (1999) but consists of four segments instead of five (see Figure 6). There is only one initial segment, from DELTA to CHARLIE, because there is an Air Force Base within 0·2 nmi (020°) and two hills: Moulali hill at 5·4 nmi (090°) and another hill at 3·3 nmi (088°). The starting point for designing most procedures is the first usable portion, or threshold, of the runway. Threshold portions and runway profiles are obtained from airport operators and plotted on the procedure chart.

4.1.1 *Initial Segment*. In the initial segment, an aircraft transitions from the enroute phase to the terminal phase. The initial segment starts at the earliest point of the initial approach waypoint obstacle assessment area and ends at the plotted intermediate approach waypoint (IWP) position. The segment has no standard length but should not exceed 50 nmi. In addition, alignment relative to the intermediate

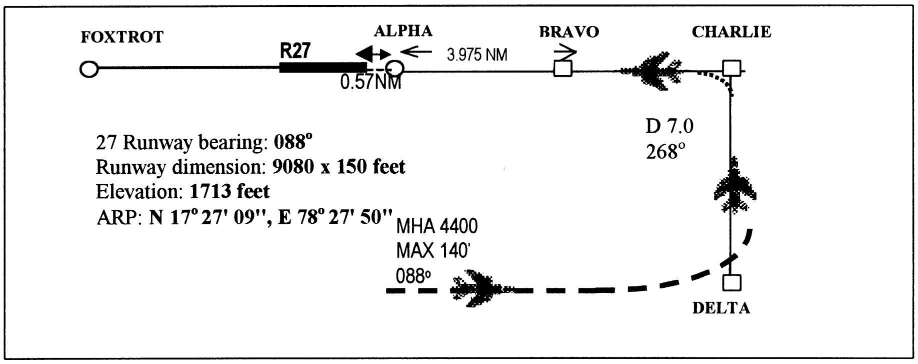

Figure 6. Designed GPS 'T' configuration for Hyderabad Airport.

segment should be 120° or less. In the primary area, 1000 feet of required obstacle clearance (ROC) is applied, and in the secondary area, ROC is 500 feet at the inner boundary decreasing to 0 feet at the outer boundary.

4.1.2. *Intermediate Segment*. The intermediate segment is designed to allow an aircraft to reduce speed and configure for approach and landing. The speed reduction can be significant, and the intermediate segment must be long enough to allow a gradual reduction of air speed. The intermediate segment starts at the earliest point of the IWP obstacle assessment area and ends at the plotted FAWP position. This transition between the terminal and the approach phases basically allows a reduction in air speed to that required for a descent rate of 300 feet per nautical mile. The intermediate segment length can be anywhere between 4·25 and 7 nmi.

4.1.3. *Final Segment*. At the start of the final segment, the aircraft stabilizes at the approach speed and descends towards the runway. The final segment (see Figure 7(a) and (b)) starts at the FAWP and ends at the missed approach waypoint (MAWP). The MAWP is usually located at the landing runway threshold. Locations of natural obstacles like Moulali hill (at 090° and 5·4 nmi), and positions of man-made obstructions in the general area of the runway approach, are plotted to determine the effect of those obstacles. The final segment is aligned with the extended runway centre-line with a length of 4·25 nmi effectively to narrow the areas and reduce ROC. In the primary area, a 250 foot ROC is added to the height of the highest obstacle within the final approach segment. In developing the final segment, the design has also taken into account the maximum allowable rate of descent to enable an aircraft to transition smoothly to level or ascending flight. This maximum rate is 400 feet per nautical mile, which corresponds to a glide-slope of about 4° with respect to a horizontal plane. Ideally, aircraft should descend at 300 feet per nautical mile (approximately 3° glide-slope). For Hyderabad, the altitude at the start of the final segment is 3270 feet and at the time of taking a decision for missed approach is 2020 feet. The obstacle clearance altitude is 1915 feet. These altitudes are above mean sea level (amsl) and the Hyderabad elevation is 1741 feet. The geodetic coordinates of the FAWP are 17° 27′ 13″ N, 78° 33′ 40″ E.

4.1.4. *Missed Approach Segment*. In the event a pilot does not obtain the visual references required for landing by a specified point along the final approach, he must fly the missed approach segment to the missed approach holding waypoint

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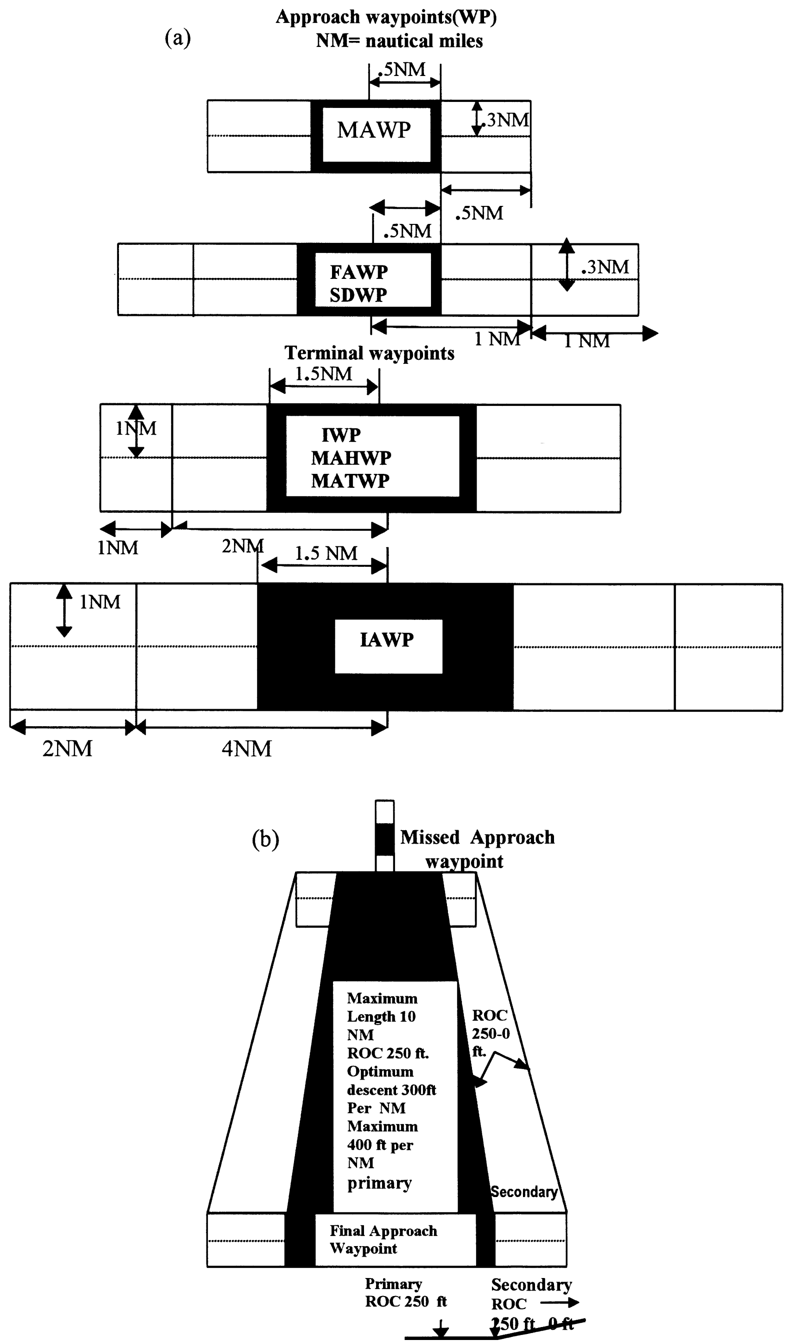

Figure 7 (a) Fix displacement tolerance areas (shaded) and obstacle clearance areas associated with the various waypoints used in a GPS procedure. (b) The primary and secondary areas plus operational parameters of a final approach segment.

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(MAHWP). The missed approach segment starts at MAWP and ends at the missed approach holding point (at Hyderabad, climb straight ahead to 4400 feet and turn left to join the VOR holding or as directed by ATC), where an aircraft either transitions to an enroute phase to another airport or enters a holding pattern while awaiting clearance to commence another approach. Here the MAWP is on the extended runway centreline and is 0·57 nmi from the runway threshold and location 17° 27′ 10″ N, 78° 29′ 30″ E.

5. WAYPOINT POSITION CALCULATION. From aerodrome runway data, position information is noted for our analysis. Runway 09 threshold: 17° 27′ 7·3″ N, 78° 27′ 22″ E, Runway 27 threshold: 17° 26′ 38″ N, 78° 28′ 55·9″ E and MAHWP: 17° 25′ 0·2″ N, 78° 27′ 47·2″ E. After the completion of the obstacle assessment of the final and missed approach segments, the next step is calculation of waypoint positions. Since the final approach and missed approach segments are aligned with the extended runway centreline, the position of the FAWP and MAWP are calculated using the Radar Operation Analysis Tool (ROAT) algorithm developed by the Westinghouse Corporation, USA and supplied to Airports Authority of India (AAI), Hyderabad Airport along with the Airport Surveillance Radar (ASR). This gives:

MAWP: 17·4528° N, 78·4917° E and 0·57 nmi from the runway threshold
FAWP: 17·4536° N, 78·5611° E and 4·25 nmi from the runway threshold

The IWP is calculated using the reciprocal of the final and intermediate segments. The MAHWP position is calculated using the missed approach segment length and the runway's forward bearing. The runway threshold is used as the reference for calculating the MAWP position, which is then used as the reference for calculating the FAWP and MAHWP positions.

6. GEODESIC RANGE AND BEARING ALGORITHM. One of the most important aspects to consider when designing a GPS/NPA is the coordinate system. The WGS-84 ellipsoid Earth model is used for the Aviation Information Publications (AIP) and air navigation. A pilot always reports his position in terms of radial and range with respect to a VOR or an airport rather than in latitude and longitude coordinates. Therefore, the accurate conversion of the latitude and longitude of two waypoints into azimuth and range between them is essential. Salient features of the algorithm to calculate azimuth and range from the given latitudes and longitudes are as follows (RTCA, 1999):

(a) Convert geodetic latitudes from degrees to radians,
(b) Compute the difference in longitudes (λ_k), in radians,
(c) Compute the 'reduced latitudes', (β) in radians,
(d) Compute the equatorial geodesic angular distance and azimuth and then perform the iteration $|\lambda_{\kappa+1} - \lambda_\kappa| < \epsilon$, where the value of the termination criteria ϵ used was 10^{-12},
(e) Then compute the range and azimuth of departure point.

For each departure point, range and bearing (at the departure point), the actual terminal point of the corresponding geodesic curve was computed by numerically

Table 4. Waypoints positions (from ROAT algorithm)..

GPS T configuration waypoint location	Calculated waypoint geodetic position	
	Latitude	Longitude
Runway threshold	17° 26′ 38″	78° 28′ 55·9″
ALPHA (MAWP)	17° 27′ 10″	78° 29′ 30″
BRAVO (FAWP)	17° 27′ 13″	78° 33′ 40″
CHARLIE (IWP)	17° 27′ 13·9375″	78° 30′ 47·03″
DELTA (IAWP)	17° 22′ 13″	78° 34′ 54·21875″

Table 5. Azimuth and geodesic range between the waypoints (from ROAT algorithm).

Arrival and Departure waypoints	With respect to Runway 27 calculated	
	Azimuth in deg.	Range in nmi
Runway threshold and ALPHA	269	0·57
ALPHA and BRAVO	269	3·9752
BRAVO and CHARLIE	269	2·75
DELTA and CHARLIE	180	5·0

integrating the following equations, which use the Runge-Kutta-Fehlberg algorithm of order (4, 5).

$$\frac{dB}{dt} = \frac{(1-e^2\sin^2 B)^{3/2}\cos\alpha}{(1-e^2)}$$

$$\frac{dL}{dt} = \frac{(1-e^2\sin^2 B)^{1/2}}{\cos B}$$

$$\frac{d\alpha}{dt} = (1-e^2\sin^2 B)^{1/2}\sin\alpha\tan\beta,$$

where B, L and α are geodetic latitude, longitude and bearing respectively at each point on the geodesic, t is the arc length along the geodesic divided by semi-major axis and e is eccentricity of the ellipsoid.

The distance between the actual terminal point and the desired arrival point is then calculated. Table 4 shows the waypoint geodetic locations of the designed GPS 'T' configuration, and Table 5 shows the azimuth and geodesic range calculated between the waypoints using the above algorithm.

The pilot enters the waypoints (latitude, longitude given in Table 4) in his airborne equipment database. Then, he defines a flight path by linking selected waypoints from the database. The airborne equipment computes the range and bearing between consecutive waypoints by using the above algorithm. As the aircraft using GPS/NPA reaches each waypoint, the current range and bearing to the next point is displayed on the airborne equipment (Table 5).

The Airport Surveillance Radar (ASR) display presents a combination of processed and smoothed primary and secondary returns. The returns are characterized by spatial (x, y, z) and temporal (t) components. The radar location is taken as the origin of the 3D coordinate system. The x and y components of the radar returns are function of rotating beam, z value corresponds to the barometer altitude reported by SSR Mode C from the aircraft.

When a flight plan is filed, information including date/time, aircraft type, flight number, destination, first waypoint etc., is entered into the ATC system so that information about a flight passing between two controlling stations can be tracked and guided according to the GPS NPA waypoint position. The ROAT software, which is incorporated in the system, provides interactive conversion of latitude-longitude to radar range and azimuth and vice-versa. The algorithm is based on both plane geometry and WGS 84 Earth model. The accuracy of calculations is inversely related to the range between radar site and target.

7. CONCLUSIONS.

In developing countries such as India, the majority of airports are not equipped with reliable approach and landing aids. Therefore, a cost-effective and reliable all-weather system is needed. At small airports, where traffic is low, un-augmented GPS using RAIM can be considered as a supplemental navigation aid. Initially a GPS/NPA was designed for Runway 27 of Hyderabad Airport. The procedure was validated using the ASR display to monitor the aircraft's actual landing data. A similar GPS approach procedure could be designed for Runway 09 (where there is no ILS landing facility at present) and for other airports with lower traffic where installation of ILS is not commercially viable. If so implemented, this procedure would increase the number of airports capable of supporting all-weather operation and could enable new airports at remote locations. This would also open more runways for all weather operations and also help solve the radio interference problems suffered by ILS.

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