CANDIDATE REQUIREMENTS FOR MULTILATERATION AND ADS-B SYSTEMS TO SERVE AS ALTERNATIVES TO SECONDARY RADAR

Patrick J. Martone, US DOT Volpe Center, Cambridge, MA
George E. Tucker, NASA Ames Research Center, Moffett Field, CA

Abstract

The US Department of Transportation (DOT) Volpe Center is currently involved in a National Aeronautics and Space Administration (NASA) project to configure, deploy, and evaluate the capabilities of a transponder multilateration and Automatic Dependent Surveillance-Broadcast (ADS-B) system that will perform aircraft tracking in the Gulf of Mexico offshore area. The Helicopter In-flight Tracking System (HITS) is being assessed for use in an offshore area where several hundred petroleum industry helicopter flights occur daily, and where there is currently little secondary surveillance radar coverage. There are also over-flights by aircraft to/from Mexico and Central/South America.

Although multilateration has been extensively tested for airport surface applications, there is limited experience in the tracking of airborne aircraft. The HITS project provides an opportunity to evaluate multilateration and ADS-B technologies as potential alternatives to established secondary surveillance radar (SSR) as air traffic control surveillance systems. The project is described in more detail in a separate paper [9].

Evaluation Requirements

This section delineates the requirements — both capabilities and numerical parameters/values — that will be used to evaluate whether the HITS multilateration and ADS-B capabilities are equivalent in function and performance to those for the ATCBI-6 secondary surveillance radar. These criteria were developed expressly for this evaluation.

Due to differences in the technologies, comparing HITS and ATCBI-6 presents challenges. For example, radar measures target range and azimuth, while multilateration measures time of arrivals (TOAs) and provides a rectangular position, and ADS-B utilizes GPS position. Assuming that the ground sites have the same coverage (which is typically not the case), surveillance of a given volume using multilateration requires roughly three times as many sites as SSR. On the other hand, radar target report update rates are limited by the radar antenna scan period (5 or 10 seconds), while updates as frequent as once per second are achievable with multilateration. In contrast to the requirements differences, testing procedures for SSR and multilateration/ADS-B are quite similar.

The baseline radar standards upon which the HITS evaluation is based are those for the ATCBI-6, as documented in [1]. In order to perform the evaluation, many of the criteria listed in the ATCBI-6 specification are extracted from Section 3.2, and corresponding criteria are developed for the HITS multilateration and ADS-B capabilities. In many cases, the parameters have been transformed to account for the technology differences among the three technologies. In brief:

- SSR measures aircraft range and azimuth relative to a single ground location; a ground-interrogation/aircraft-transponder-response methodology is employed; and ground sites have mechanically-scanned high-gain directional antennas.
- Multilateration measures the times-of-arrival at three or more ground stations of both unelicited (squittered) or elicited transponder signals; aircraft location is computed in rectangular coordinates with respect to the geographic reference system used to define

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the ground station locations; and ground sites have omni-directional low-gain stationary antennas.

- ADS-B avionics obtain aircraft position and velocity from an onboard GPS receiver, and squitter this information to one or more ground stations over a digital data link; and ground sites use omni-directional low-gain stationary antennas.

In addition to the ATCB1-6 specification [1], several documents were consulted in developing the criteria herein. The Airport Surface Detection Equipment Model X (ASDE-X) specification [2] is the standard for multilateration/ADS-B systems designed for airport surface surveillance. The primary standards by which all Federal Aviation Administration (FAA) beacon radars are designed are contained in FAA Order 1010.51.A [3], developed for the Identification Friend or Foe (IFF) Mark X system, FAA Order 6365.1A ([4], developed for Mode S), and International Civil Aviation Organization (ICAO) Annex 10 [5]. ICAO Annex 10 has precedence over FAA Order 6365.1A when conflicts arise.

Table 1 compares many of the ATCB1-6 requirements of [1] with evaluation requirements developed below for the HITS multilateration and ADS-B capabilities. Italicized numbers in the headings for entries in the first column refer to sections in the ATCB1-6 specification. The paragraphs that follow address some, but not all, of the primary requirements included in the table, in greater detail, along with the rational used to develop them.

<table>
<thead>
<tr>
<th>ATCB1-6 (Heading Number = Ref. 1 Section Number)</th>
<th>HITS</th>
<th>ADS-B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3.1.1 Coverage Volume</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altitude: 0 to 100,000 feet AGL</td>
<td>Each RU: 0 to 100,000 ft AGL</td>
<td>Same as multilateration sub criterion for each RU.</td>
</tr>
<tr>
<td>Elevation Angle: Horizon to 40 deg</td>
<td>Elevation Angle: Horizon to 40 deg</td>
<td></td>
</tr>
<tr>
<td>Slant Range: 125 and 250 nmi</td>
<td>Slant Range: 50 nmi</td>
<td></td>
</tr>
<tr>
<td>Azimuth Angle: 360 deg</td>
<td>Azimuth Angle: 360 deg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HITS area: HDOP max 1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HITS area: Coverage by 1 RT</td>
<td></td>
</tr>
<tr>
<td><strong>3.1.2 Probability of Target Detection and</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probability of False Target Detection</td>
<td>99% detection of all targets;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ATCRBS false target detected 0.1%;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No false Mode S targets</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Processing for a minimum of 64 non-fixed and 64 fixed reflectors</td>
<td></td>
</tr>
<tr>
<td><strong>3.1.5 Interrogation Modes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One Mode S interrogation per scan</td>
<td>0.2 Hz average rate</td>
<td>Same</td>
</tr>
<tr>
<td>One target report per scan</td>
<td>3.2.3 Target Plot Report Update Rate</td>
<td></td>
</tr>
<tr>
<td><strong>3.1.3 Accuracy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range bias: ±30 ft</td>
<td>Bias: ±30 ft</td>
<td>Not applicable.</td>
</tr>
<tr>
<td>Range jitter: 25 ft rms</td>
<td>Jitter: 25 ft rms</td>
<td></td>
</tr>
<tr>
<td>Azimuth bias: ±0.033 deg</td>
<td>Azimuth jitter: 0.066 deg rms</td>
<td></td>
</tr>
<tr>
<td><strong>3.1.4 Target Resolution</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 ATCRBS targets with &lt;1.7 nmi slant range separation:</td>
<td>2 ATCRBS targets with &lt;1.7 nmi slant range separation:</td>
<td>Two closely spaced Mode S targets resolvable 100%</td>
</tr>
<tr>
<td>1.2 deg &lt; az &lt; 2.4 deg, detected 98%;</td>
<td>Detected 98%;</td>
<td></td>
</tr>
<tr>
<td>Az &lt; 1.2 deg, detected 90%;</td>
<td>Correct codes available 90%;</td>
<td></td>
</tr>
<tr>
<td>Correct codes available 90%</td>
<td>All other target combinations resolvable 100%</td>
<td></td>
</tr>
<tr>
<td>Two closely spaced Mode S targets resolvable 100%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of HITS Evaluation Criteria
<table>
<thead>
<tr>
<th>ATCBI-6</th>
<th>HITS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3.1.5 Interrogation Modes</strong></td>
<td><strong>Interrogation Modes</strong></td>
</tr>
<tr>
<td>Interrogate and process replies from ATCRBS and Mode S targets.</td>
<td>Same requirement.</td>
</tr>
<tr>
<td><strong>3.1.6 Multiple ATCRBS Reply Processing</strong></td>
<td><strong>3.2.7 Multiple ATCRBS Reply Processing</strong></td>
</tr>
<tr>
<td>Decode at least four replies simultaneously.</td>
<td>Same requirement.</td>
</tr>
<tr>
<td><strong>3.1.7 Code Reliability and Validity</strong></td>
<td><strong>3.2.8 Identity Code Reliability and Validation</strong></td>
</tr>
<tr>
<td>Modes 3/A codes correct 99%; Correct Mode 3/A codes validated 99%;</td>
<td>Modes 3/A codes correct 99%; Correct 3/A codes validated 99%;</td>
</tr>
<tr>
<td>Incorrect Mode 3/A codes validated 1%; Mode S ID correct 99.9%</td>
<td>Incorrect 3/A codes validated 1%; Mode S ID correct 99.9%</td>
</tr>
<tr>
<td><strong>3.1.8 Altitude Report Reliability &amp; Validation</strong></td>
<td><strong>Altitude Report Reliability and Validation</strong></td>
</tr>
<tr>
<td>Mode C code correct 99%; Correct Mode C code validated 95%;</td>
<td>Mode C code correct 99%; Correct code validated 95%;</td>
</tr>
<tr>
<td>Incorrect Mode C code validated 1%</td>
<td>Incorrect code validated 95%;</td>
</tr>
<tr>
<td><strong>3.1.9 Spectrum / PRF</strong></td>
<td><strong>Spectrum / PRF</strong></td>
</tr>
<tr>
<td>Max PRF 300 Hz (3 mode interlace); ATCRBS waveform and spectrum per</td>
<td>Max PRF 2.5 Hz at max range; ATCRBS waveform &amp; spectrum per FAA Order</td>
</tr>
<tr>
<td>FAA Order 1010.51A Section 2.4; Mode S waveform and spectrum per FAA</td>
<td>6365.1A, Section 2.4.1</td>
</tr>
<tr>
<td>Order 6365.1A, Section 2.4.1</td>
<td>Not applicable</td>
</tr>
<tr>
<td><strong>3.1.10 Target Capacity/Overload Processing</strong></td>
<td><strong>Target Capacity</strong></td>
</tr>
<tr>
<td>Process returns for 1400 beacon targets / 360 degree scan;</td>
<td>Each RU must process messages from 1400 transponders (all types) in 5</td>
</tr>
<tr>
<td>Peak 32 beacon targets / 2.4 deg wedge; Primary radar reports</td>
<td>sec Full HITS must process:</td>
</tr>
<tr>
<td>(standards are not relevant to HITS)</td>
<td>Average 1 target per 36 nm² in entire coverage area</td>
</tr>
<tr>
<td><strong>3.1.11 Data Timeliness</strong></td>
<td><strong>Data Latency</strong></td>
</tr>
<tr>
<td>For terminal use, detect, process and display transponder replies</td>
<td>Detect, process and output transponder replies within 0.450 sec of</td>
</tr>
<tr>
<td>between min 5/64 and max 3/32 of a scan period (approx. 0.375 sec</td>
<td>each transponder's transmission time.</td>
</tr>
<tr>
<td>min and 0.450 sec max)</td>
<td><strong>RU Clock Calibration</strong></td>
</tr>
<tr>
<td><strong>3.2.10.7 Beacon Parrot</strong></td>
<td>Multilateration subsystem shall include a means to synchronize the</td>
</tr>
<tr>
<td>System shall include a beacon parrot transponder capability to be</td>
<td>time of arrival clocks of the RUs.</td>
</tr>
<tr>
<td>located at two fixed locations</td>
<td>Not applicable</td>
</tr>
<tr>
<td><strong>3.2.12 System Calibration</strong></td>
<td><strong>Continuous Certification</strong></td>
</tr>
<tr>
<td>Shall have beacon transponders within coverage volume for automatic</td>
<td>Continuously certify that the multilateration subsystem is operating</td>
</tr>
<tr>
<td>North mark alignment (true or magnetic)</td>
<td>Similar criterion</td>
</tr>
<tr>
<td>Calibration of range and azimuth measurements</td>
<td></td>
</tr>
</tbody>
</table>

7.C.2-3
Coverage Volume

ATCBI-6 ([1], Subsection 3.1.1, "Coverage Volume") — The ATCBI-6 shall provide surveillance coverage for the area defined as follows:

- an altitude of 0 to 100,000 feet above ground level (AGL) as limited by the system elevation requirement specified herein;
- an elevation from the local radar antenna horizon as determined by the earth's curvature, atmospheric refraction and as further limited by the terrain screening, to 40 degrees with respect to the horizontal plane at the radar antenna;
- a slant range coverage from 0 nautical miles to at least 125 nautical miles for terminal applications, and a maximum of 250 nautical miles in en route applications;
- an azimuth of 360 degrees.

Multilateration — Multilateration system coverage is inherently a more complex issue than radar coverage, because multilateration surveillance requires that (a) multiple sites (at least three) be visible to the aircraft, and (b) the geometric arrangement of the sites must be taken into consideration. Accordingly, three subcriteria are selected for this evaluation:

1. Each location in the HITS coverage volume must be within the Remote Unit (RU) coverage volume (as defined by items 2a, 2b, 2c, and 2d) of at least three RUs, and the system must provide an associated horizontal dilution of precision (HDOP) of 1.5 or less.
2. Each RU, either Receive-Only (RO) or Receive-Transmit (RT), must provide reliable reception in a volume defined by:
   - altitude, 0 to 100,000 ft AGL;
   - elevation, horizon to 40 deg;
   - slant range, 0 to 50 nmi;
   - azimuth, 360 deg;
   Reliable reception involves reception in accordance with the detection probabilities defined below from transponders that comply with [6] and [7].
3. Each location in the HITS coverage volume must be within the RU coverage volume (as defined by items 2a, 2b, 2c, and 2d) of at least one RT which interrogates transponders that comply with [6] and [7].

The "geometry subcriterion" (first item) is taken from the ASDE-X specification ([2], Subsection 3.3.5), and is similar to requirements for most area navigation systems. HDOP is defined herein as the ratio of the horizontal position error to the TOA measurement error in range units. Generally, the HDOP criterion has an effect only at the edge of a region circumscribed by a set of ground stations. This is illustrated in Figure 1, which depicts HDOP contours at the minimum coverage altitude for seven RUs arranged in the form of a hexagon (or six equilateral triangles). These HDOPs correspond to an "all in view" target solution at the Central Processing Station (CPS).

The "RU coverage subcriterion" (second item) is similar to that for the ATCBI-6. The maximum range value is changed from that for the ATCBI-6, based on the power aperture product limitations of the multilateration technique. It is clearly inappropriate to use the more stringent radar range requirement of 125 nmi or 250 nmi for a HITS RU, because (a) the HITS RU antennas have much lower gain, and (b) the HITS RT transmitter power is significantly less. Modification of the range value may be advisable based on test data.

ADS-B — ADS-B coverage criterion is based on the need for reliable communications with a single ground site, and is similar to the multilateration RU subcriterion (second item) above. Each remote site must provide reliable reception from a transponder compliant with [8] in a volume defined by: range, 0 to 50 nmi; azimuth, 360 deg; elevation, horizon to 40 deg; altitude, 0 to 100,000 ft

Probabilities of Target Detection and False Target Detection

ATCBI-6 ([1], Subsection 3.1.2, "Probability of Target Detection (Pd) and Probability of False Target Detection") — The ATCBI-6 shall achieve target detection >99% for all aircraft within the detection volume as defined in Paragraph 3.1.1. The total of all ATCRBS false targets (reflections, multipath, splits, and false replies unsynchronized in time (FRUIT) disseminated by the Monopulse Secondary Surveillance Radar (MSSR) shall not exceed one for every 1000 real ATCRBS target reports disseminated (<0.1% of all ATCRBS targets

7.C.2-4
Figure 1. Multilateration HDOPs at Minimum Coverage Altitude for a Hexagon of 7 RU

disseminated can be false). The ATCBI-6 shall not report or disseminate any false Mode S target reports. This ability to detect targets and limit false targets shall be achievable in the presence of a steady state environment of up to 11,000 ATCRBS and up to 1000 Mode S FRUIT per second, of which 100 percent are in the main beam.

Multilateration — The probability of target detection, within 5 sec of penetration into the HITS coverage volume, shall be greater than 99 percent for all transponder equipped targets. The probability of an ATCRBS false plot report shall be no greater than 0.1 percent within the coverage volume, including the effects of reflections, multipath, splits, and FRUIT. (There shall be, at most, one false ATCRBS plot reports for every 1,000 physical ATCRBS plot reports.) There shall not be any false Mode S or ADS-B plot reports. As defined in Ref. 2, a false plot report is a plot report for a physically non-existent target, or a plot report position located more than 100 feet from a physical target’s true position (i.e., the location of the antenna on the aircraft at the time of transmission). This performance shall be achieved in the presence of the Radio Frequency (RF) environment defined at the end of this subsection.

ADS-B — The probability of target detection, within 5 seconds of penetration into the coverage volume, shall be greater than 99 percent for all airborne targets equipped with a 1090 MHz Mode S ADS-B transponder. There shall not be any false ADS-B plot reports. This performance shall be achieved in the RF environment defined immediately below.

RF Environment — The ability to detect targets and to limit false target generation shall be achievable with a steady state transponder message density at each RU of up to 11,000 ATCRBS FRUIT per sec, up to 1,000 Mode S FRUIT per second, and up to 1,000 ADS-B FRUIT per sec. The ATCRBS and Mode S FRUIT levels are specified in Ref. 4, which did not anticipate the introduction of ADS-B. The ADS-B FRUIT level for this evaluation is chosen to be equal to the Mode S level.

Target Plot Report Update Rate

ATCBI-6 — Reference 1 does explicitly not state an ATCBI-6 update rate requirement. The update requirement is implicit in the antenna scan period. Reference 1, Subsection 3.1.5, “Interrogation Modes” requires one Mode S surveillance interrogation per scan. Reference 1, Subsection 3.2.3.1, “ATCRBS Processor” requires one target report for each ATCRBS target per antenna scan.
Multilateration — This criterion is derived from the ASDE-X specification ([2], Subsection 3.3.9). The HITS multilateration subsystem average plot report update rate shall be at least 0.2 Hz (once per 5 sec) per target.

ADS-B — The HITS multilateration subsystem average plot report update rate shall be at least 0.2 Hz (once per 5 sec) per target. No credit will be allowed for a plot report that follows a credited report (for the same target) by less than 2.5 seconds in validity time. There shall not be any false ADS-B target reports.

Target Plot Report Position Accuracy

ATCBI-6 ([1], Subsection 3.1.3, “Accuracy”) — The ATCBI-6 shall achieve the following range and azimuth accuracy:

Range Accuracy. The ATCBI-6 range errors, measured utilizing beacon target reports, shall not exceed ±30 feet bias (including long term drift) and the standard deviation of the range errors shall not exceed 25 feet. Transponder delay time variations from the nominal values specified in FAA Order 1010.51A, Section 2.7.1 shall not be included in the ATCBI-6 range bias measurement.

Azimuth Accuracy. The long term combined sensor plus antenna azimuth accuracy shall not exceed the following values for the indicated antenna elevation angles:

- Bias: for elevation angles <2 degrees, the bias shall be within ±0.033 degrees for elevation angles equal or greater than 2 degrees, the bias will be permitted to change as a function of the elevation angle due to the antenna beam widening. The sensor and antenna reported azimuth bias component change shall not exceed the change attributable to the antenna only.
- Jitter: for all elevation angles less than 20 degrees, the standard deviation of the azimuth errors shall not exceed 0.066 degrees.

Multilateration — The HITS multilateration subsystem shall calculate either a 2D- or 3D-position for ATCRBS, Mode S and ADS-B transponder messages. The plot report horizontal position accuracy criterion is chosen to be the same as that for SSR range, specifically ±30 ft bias and 25 ft rms jitter when the all-in-view HDOP is 1.5 or less. As an area surveillance system, multilateration horizontal position error is measured with respect to the geographic reference system used to define the RU positions. Multilateration vertical accuracy shall be ±30 ft bias and 25 ft rms jitter when vertical dilution of precision (VDOP) is 1.5 or less. These criteria apply to all horizontal positions and altitudes within the coverage volume.

Even at the shortest usable distance from a radar site (typically 1 nmi), the multilateration horizontal accuracy criterion is comparable that for the ATCBI-6. At substantial radar ranges, the multilateration accuracy criterion is much more stringent than the ATCBI-6's. Figure 2 illustrates this situation, depicting the bias plus twice rms values. Selection of the more stringent standard for HITS is based on the even more stringent requirement of 20 ft rms imposed on the ASDE-X multilateration subsystem ([2], Subsection 3.3.11).

ADS-B — This requirement is not applicable to the ADS-B subsystem, because it does not measure aircraft position.

Target Resolution

ATCBI-6 ([1], Subsection 3.1.4, “Resolution”) — Two closely spaced ATCRBS equipped aircraft, with a uniform random distribution within a window described by a slant range separation less than 1.7 nautical miles and a simultaneous azimuth separation of less than 2.4 degrees and greater than 1.2 degrees, shall each be detected a minimum of 98% of the time. Two closely spaced ATCRBS equipped aircraft, with a uniform random distribution within a window described by a slant range separation less than 1.7 nautical miles and a simultaneous azimuth separation of less than 1.2 degrees, shall each be detected a minimum of 90% of the time. The code and altitude reported for each target detected in these closely spaced conditions shall be correct >90% of the time. Aircraft separated by greater than 1.7 nmi or greater than 2.4 degrees in azimuth shall be detected and reported >99% of the time while meeting the detection volume, false target dissemination and environmental conditions requirements described in Paragraph 3.1.2 ([1]).

7.C.2-6
The ATCBI-6, when interrogating Mode S equipped aircraft with discrete interrogations, shall resolve two Mode S equipped aircraft or one Mode S and an ATCRBS equipped aircraft 100% of the time.

**Multilateration** — Two closely spaced ATCRBS equipped targets, defined as having 1.7 nmi or less separation, shall be resolvable 98 percent of the time. The identity (ID) and altitude codes reported for each of these targets shall be correct greater than 90 percent of the time. ATCRBS targets separated by greater than 1.7 nmi shall be detected and reported 99 percent of the time. All other combinations of closely-spaced target pairs (i.e., one ATCRBS and one Mode S or ADS-B, or two Mode S, or two ADS-B, or one Mode S and one ADS-B) shall be resolvable 100 percent of the time. This criterion shall be satisfied in the presence of the Radio Frequency (RF) environment previously specified.

**ADS-B** — Two closely spaced ADS-B equipped targets shall be resolvable 100 percent of the time. This criterion shall be satisfied in the presence of the RF environment previously specified.

**Target Capacity**

**ATCBI-6** ([1], Subsection 3.1.10, “Target Capacity/Overload Processing”) — The ATCBI-6 shall provide target processing capacity as defined below:

<table>
<thead>
<tr>
<th>Case</th>
<th>Processing Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>1400 beacon (ATCRBS or Mode S) equipped aircraft targets (uniformly or non-uniformly distributed in range and azimuth) per 360 degrees antenna scan (See “Note” below); and</td>
</tr>
<tr>
<td>b.</td>
<td>in addition to (a) the ATCBI-6 shall process target reports from a collocated primary radar for at least 700 primary target reports targets corresponding to the beacon targets specified in (a) plus an additional 300 false primary reports per 360 degrees azimuth antenna scan. The primary target reports and false primary reports may be uniformly or non-uniformly distributed in range and azimuth; and</td>
</tr>
<tr>
<td>c.</td>
<td>a peak of 350 beacon targets plus 350 primary radar targets corresponding to the beacon targets and 200 false primary reports all uniformly distributed in a 90 degree sector; and</td>
</tr>
<tr>
<td>d.</td>
<td>a peak of 100 beacon targets plus 100 primary radar targets corresponding to the beacon targets and 100 false primary targets uniformly distributed across two contiguous 11.25 degree sectors; and</td>
</tr>
<tr>
<td>e.</td>
<td>a peak of 32 beacon targets per 2.4 degree wedge plus 32 primary targets corresponding to the beacon targets and 32 false primary targets per 2.4 degree wedge.</td>
</tr>
</tbody>
</table>

Note: Under the conditions described in paragraph a. above, the processing throughput.
reserve requirement of [1], Paragraph 3.1.12.3, shall be 33%.

Multilateration & ADS-B — HITS equipment shall have target processing capacity based on that for the ATCBI-6 when used in terminal operations (i.e., 5 sec period and 125 nmi range). The primary radar target aspect of the ATCBI-6 specification is not pertinent to the HITS. Separate subcriteria are established for individual RUs and the full HITS.

- Each HITS RU must have the capability to process returns from a total of 1400 transponder equipped targets (total of ATCRBS, Mode S and ADS-B) within a 5 sec update interval.
- The full HITS system, including inter-site communications and the CPS, must have the capability to process:
  - An average of one transponder target per 35 nm² within the full coverage area, and
  - A peak of one transponder target per 10 nm² within 1% of the coverage area.

Evaluation Procedures

The processes that will be used to assess HITS relative to these standards for each of the HITS evaluation requirements are contained in the test and evaluation plan. In this paper, we are limited to illustrating only a few examples of each requirement.

Coverage Volume

The coverage volume defined in the previous section shall be estimated by analysis and verified by test. Analysis can be used to illustrate that the HITS design and RU locations satisfy the coverage volume criteria but actual flight tests are also necessary.

Controlled and instrumented fixed and rotary wing aircraft will be employed for the coverage volume flight tests. Coverage must be established for instrumented aircraft with Mode A/C and S transponders and for ADS-B equipped aircraft. In the vertical dimension, instrumented aircraft will fly eight separate legs at altitudes of 100 ft, 500 ft, 1,000 ft, 5,000 ft, 10,000 ft, 15,000 ft, 20,000 ft, and 30,000 ft, while traversing the 10,000 square mile coverage from end-to-end for each leg. An illustration of these vertical flight profiles is shown in Figure 3. For example, the aircraft will fly at a constant altitude of 100 ft AGL for a complete and straight leg of approximately 200 miles, traversing the entire horizontal HITS coverage area from north to south. The next leg will begin when the aircraft

Horizontal dimension = 50 nm for East/West flights;
200 nm for North/South flights

Figure 3. Vertical Flight Profiles for Coverage Volume Tests
has turned around at the end of the HITS surveil-
ance volume and increased its altitude to 500 ft,
and now traverses the coverage area from south to
north remaining at 500 ft. This procedure is
continued with the two next legs at 1,000 ft and
5,000 ft. Another aircraft, more suited for higher
altitudes, could be used to fly the remaining four
legs at 10,000 ft, 15,000 ft, 20,000 ft, and 30,000 ft.

In the horizontal dimension (see Figure 4), the
vertical dimension flights will be conducted at the
boundaries of the coverage region and across the
center of the region (i.e., along 0, 25, and 50 nmi
north/south tracks and along 0, 50, 100, 150, and
200 nmi east/west tracks). Thus, eight horizontal
tracks at eight different altitudes for a total of 64
instrumented flights will be used to establish the
nominal coverage volume of the HITS. The GPS
grid will be used to lay out the specific tracks for
this set of flights.

During these flight tests, aircraft position data
will be collected and recorded both on-board the
aircraft and at the ground operations center for post
flight analyses. The flight crew(s) will be in
constant voice radio communications with the
ground test crew located at the HITS Operations
Center during all controlled and instrumented flight
tests.

Target reports from targets of opportunity can
be used to supplement the HITS coverage volume
by determining when these targets are first and last
reported to HITS and how continuous the reports
are within coverage. This information will be
valuable since the targets of opportunity have
different transponders with different characteristics
from those used in the instrumented tests. In
addition, these targets will fly different trajectories
than the instrumented flights in both the horizontal
and vertical dimensions and represent the actual
operational trajectories used in the flight test region.
Targets of opportunity will also show whether the
coverage volume determined by the instrumented
flight is valid for a large class of transponders. It
may reveal that the operational coverage volume is
equivalent to, less than, or greater than that
determined by the instrumented flights.

**Probabilities of Target Detection and False
Target Detection**

The probabilities of target detection and false
target detection standards defined in the previous
section for multilateration and for ADS-B shall be
evaluated by analysis and test. Analysis and
simulation can be used to illustrate that the HITS is
designed to satisfy the standards associated with
this criterion.

For testing, the use of built-in test targets,
targets of opportunity, and controlled and
instrumented aircraft shall be used to verify these
criteria. When using built-in test targets, the
required number of maximum targets (1400) must
be injected while measuring the probability of
target and false target detection. An appropriate
model for FRUIT (ATCRBS and Mode S) and
multipath must also be injected into the system
during these tests. The round reliability parameter
associated with the test target transponders must be
modeled and adjustable from 0.5 to 0.9 (in
increments of 0.1) during the laboratory testing.
The intent of the laboratory testing is to simulate
the operational environment to the maximum extent
possible. Laboratory data, with the use of the built-
in test target generator, can be collected and
analyzed to demonstrate the required performance
in a severe environment of high traffic loads,
including crossing target patterns. The
instrumented and target-of-opportunity flight data
collected for the assessment of the coverage volume criterion can also be used to evaluate this criterion. The probability of target detection can be calculated by determining the location of the first target report and comparing that to the boundary of the coverage region. HITS track information will provide an estimate of aircraft velocity vector that can then be used to determine the elapsed time between the nominal coverage boundary and the position given by the first target report. HITS track information can be derived based on the recorded target reports using data smoothing techniques. Data collected over the test period can then be used to calculate the target detection statistics for a large data sample that includes the instrumented flights and targets of opportunity. The results can then be compared with the standard of greater than 99% for all transponder equipped aircraft. Target reports can also be evaluated for each flight to determine the target report update rate average and standard deviation. All occurrences of target reports separated by greater than 0.5 seconds will be identified.

Using HITS track data coupled with the established coverage volume, one can also determine when false target reports are generated by correlating track data with target reports to determine if aircraft at the same position have a different identity (ID) or if aircraft at different positions have the same ID. In either case, these can be declared as false targets unless the targets at different positions have the same valid ID (e.g., code 1200). This false target data can then be statistically analyzed to determine if the HITS probability of false ATCRBS target detection is greater than 0.1% within the coverage volume. Any false Mode S target reports will also be identified since it is required that the HITS shall not report any false Mode S target reports.

**Target Plot Report Position Accuracy**

The multilateration subsystem shall calculate either a 2D- or 3D- position for ATCRBS, Mode S and ADS-B transponder messages. The plot report horizontal position accuracy shall be ±30 ft bias and 25 ft rms jitter when the all-in-view HDOP is 1.5 or less. Multilateration vertical accuracy shall be ±30 ft bias and 25 ft rms jitter when Vertical Dilution of Precision (VDOP) is 1.5 or less. The instrumented flight data provided during coverage volume testing can be used to determine HITS position accuracy. This is accomplished by first determining the nominal trajectory of the flight from the on-board and enhanced GPS data. Once this is accomplished, deviations between the nominal trajectory and the HITS target reports can be calculated. Standard statistical analysis can then be applied to determine the mean and the variance of these deviations. In addition, a confidence level in the result can also be determined using standard statistical analysis.

Targets of opportunity cannot supplement the instrumented flight test information concerning bias or mean deviation; however, this data can be used to supplement the jitter or variance information. This is accomplished by deriving an optimal estimate of the true trajectory of the aircraft using data smoothing techniques applied to the HITS target reports. Once the optimal estimate of the trajectory is determined, the deviations between the target reports and the smoothed trajectory can be calculated. These deviations can then be used to estimate the "jitter" or variance of the target reports from the smoothed estimate of the trajectory. The standard deviations for the set of processed flights can then be used to determine the jitter over all target-of-opportunity flights. In addition, a confidence level in the result can also be determined using standard statistical analysis.
Target Resolution

The requirements for target resolution can be verified by analysis and test. The analysis portion of this verification includes documentation and presentations to illustrate how the HITS system will meet these performance criteria.

For the test portion of this evaluation, two instrumented aircraft must be flown in a multiple crossing pattern configuration as illustrated in Figure 5. The first aircraft will fly straight and horizontal at a fixed altitude of 10,000 ft, while the second aircraft flies a zig-zag pattern also at fixed altitude but differing from the straight-flying aircraft by at least 1,000 ft and not more than 2,000 ft. The second aircraft will intersect (in the horizontal plane) the first aircraft on three separate occasions as the straight-flying (first) aircraft traverses 100 horizontal miles of HITS coverage area. Each zig-zag leg of the second aircraft will be approximately 30 miles long and will approach, intersect, and pass the straight-flying aircraft at an angle of approximately 30 degrees. The point of intersection of the two aircraft will be at the midpoint of each zig-zag leg (15 miles).

The turnaround point for the second aircraft from targets of opportunity by using optimal estimates of the target trajectories. The approach consists of determining the relative position of the targets using the optimal trajectories and identifying when these targets approach or are within 1.7 nmi separation. The target reports associated with these trajectories can then be examined in these regions to determine if they exist (i.e., have been resolved) during the times of close proximity.

Post-flight statistical analysis can then be applied to determine if these closely spaced targets (instrumented or targets of opportunity) have been resolved 98% of the time and if the ID and altitude codes reported for each of these closely spaced targets is correct at least 90% of the time. Further, for targets separated by more than 1.7 nmi, it can be determined if target reports exist more than 99% of the time while in the coverage volume. In addition, Mode S, ADS-B and combinations of these with ATCRBS target reports can be analyzed against the optimal estimate of their trajectories to determine if...
they are resolvable 100% of the time when closely spaced.

**Target Capacity**

Target Capacity will be evaluated by analysis to include documentation and presentations illustrating how the HITS design satisfies these standards; i.e., each HITS RU target capacity per 5 sec period shall be 1400 total (ATCRBS, Mode S and ADS-B). The number of targets of opportunity can be determined as a function of time during the test period. It is not expected that the actual number of targets will approach the 1400 requirement; however, if the HITS saturates during the test period at a certain target level, then it can be stated that it does not meet the requirement. Alternatively, it can be stated that the HITS demonstrated that it can process a given number of targets.

It is possible that the standards associated with one transponder target per 35 nm2 within the full coverage area, and a peak of one transponder target per 10 nm2 within 1% of the coverage area may be validated during target-of-opportunity testing and instrumented flight tests. Since it is unlikely that the maximum number of targets will be available during field testing, the use of test targets (modeled with round reliabilities from 0.5 to 0.9), FRUIT targets, and multipath, can be used during factory demonstration to verify the HITS target capacity. While simulating the operational environment to the maximum extent possible, HITS performance will be observed and recorded for test targets levels of 250, 700, 1400, 3000, 5000, and 10000 per 5 sec period. The HITS processing capabilities and limitations will be characterized as a result of this testing and the maximum target level at which the processor performs without degradation will be determined.

**Conclusion**

We anticipate completion of the HITS evaluation by mid 2002, and will publish those results at that time. The ability of the HITS to perform the mission of helicopter flight following as well as how multilateration performance compares with that of the ATCBI-6 will be presented.

**References**