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Introduction

Acquisition, tracking, and pointing (ATP) are complex system-level operations that require robust integration of several related technologies. The 1999 Acquisition, Tracking, and Pointing Conference provided the 13th SPIE program to integrate sensors, image processing algorithms, electronics, modeling, simulation, and systems architectures. The technology's richness and the broad applications of this field have produced one of the longest running of SPIE's successful conferences. The 1999 conference included the following topics:

SYSTEM-LEVEL APPLICATIONS

System-level applications for this year's conference include ground support equipment and image processing for the High-Altitude Balloon Experiment (HABE), as well as a description of the pointing and stabilization system for a hovering helicopter "sky hook" application.

SENSORS FOR ACQUISITION, TRACKING, AND POINTING

Sensor presentations included a data compression technique to reduce high-resolution imagery (for subsequent processing by a low-resolution tracker), a laser communications sensor, multiple sensor configurations for reconnaissance applications, and an analytic boresight technique to maintain sensor alignment (to replace expensive mechanical approaches).

STABILIZATION AND CONTROL

Stabilization and control topics include stabilization problems encountered during gunshock, practical pulse width modulation (PWM) motor control techniques, the use of dynamic tuned gyros (DTG) for stabilization, hydrostatic bearings, influence of base movement in gimbal systems, and advanced control procedures for stabilization and missile guidance.

SIGNAL PROCESSING

Tracking of multiple targets is a complex operation; this year's papers include extensions of prior results to ever more difficult situations, e.g., sensor fusion, in which the sensors are asynchronous with different communication delays; a comparison of PHMT and PDAF algorithms; and a perception-net-based technique suitable for maneuvering targets. Other papers treat an integrated INS and GPS positioning algorithm and an investigation of the use of commercial TV and FM signals for covert target tracking.

IMAGING TRACKERS

Target trackers are essential for the ATP process. Presentations included a successfully fielded reconfigurable IR video tracker (capable of easily switching between tracking modes) and several papers that use multiple tracking modes, e.g., a real-time, multistage tracker that uses feature-based algorithms to assist correlation tracker reference updates, a leading edge-correlation-polynomial correlation tracker, and handoff algorithms between track-while-scan and image-based trackers. These papers also include multimode trackers for IR point targets and an IR seeker emulation designed for countermeasure evaluations.

IMAGE PROCESSING

Other related presentations included techniques for detection and tracking of multiple IR targets in clutter environments, electronic image stabilization, and a treatment of the fundamentals for tracking of vehicles which follow on-road constrained routes. Another paper treats a reconfigurable target acquisition and tracking algorithm patterned from biological foveal vision characteristics; another discusses human-factor considerations for ground-to-ground target trackers.

Overall, the 1999 SPIE Acquisition, Tracking, and Pointing conference provided an excellent interchange of applications and technologies related to the ATP problem. We want to thank each of the authors, and their sponsoring organizations, who are the contributors who provide the hard work necessary to make this conference successful. We also want to thank the Program Committee for their work and encouragement. As usual, the SPIE staff made this event both professional and enjoyable.

Michael K. Masten
Larry A. Stockum

Contents

SESSION 1

System-Level Applications

Ground support equipment (GSE) for testing precision ATP payloads

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ABSTRACT

The High Altitude Balloon Experiment (HABE) is being developed by the U.S. Air Force Research Laboratory (AFRL) to investigate technologies needed to perform acquisition, tracking, and pointing (ATP) functions against boosting missiles in near-space environments. The HABE control system architecture is based on establishing an inertially stabilized LOS for active missile hardbody tracking through the use of a pulsed illuminator laser. The payload optical system uses a large 60 cm telescope as its primary viewing/receiving aperture for the payload's tracking and pointing functions. A 5 cm secondary aperture provides transmission of the illuminator laser. Ranging and self-scoring functions are implemented with reflected optical signals received in a 20 cm aperture. The primary optical bench, the Inertial Pseudo Star Reference Unit (IPSRU) subsystem, the autoalignment system (AAS), the active fine track (AFT) camera, and multiple high speed digital processors work in concert to implement the payload's precise active imaging and target image tracking. Real-time digital image processors derive tracking and pointing errors from the laser illuminated images of the missile nose. Fast steering mirrors controlled by other digital processors align the optical paths for the cameras and the transmitted illuminator laser to the IPSRU generated and stabilized reference laser. A marker laser is pointed to a designated missile aimpoint by use of digital image processing algorithms operating on the AFT images. The goal for marker laser pointing errors is to be below 1 microradian RMS in jitter, drift, and accuracy (two-axis, one sigma metric). This is a requirement that stresses ground support equipment and test capabilities.

This paper focuses on the ground support technologies, instrumentation, and the analysis approaches employed to verify that the HABE ATP payload is correctly performing its state-of-the-art alignment, stabilization, and tracking functions. A specially constructed Laboratory Test Component (LTC) includes scoring sensors that measure the payload's LOS pointing errors by receiving and measuring the motion of the transmitted marker laser. Motion sensors with high sensitivity and broad bandwidth provide signals that are recorded simultaneously with other payload telemetry signals from the stabilized reference platform, the fast steering mirror alignment systems, and from the image track loops. The combined signals facilitate understanding and evaluation of the payload's tracking and pointing errors. With properly constructed laboratory tests and full instrumentation of the vibration and atmosphere contributed disturbances, it is possible to confirm that a sophisticated ATP payload like HABE is able to operate with residual pointing errors under a microradian.

Keywords: acquisition, pointing, and tracking; lasers; verification of alignment, stabilization, and tracking functions

1. INTRODUCTION

The HABE payload recent activity has been to step from the rigorous laboratory testing to the hangar facility for the Active End-to-End (AETE) tests of the precision acquisition, pointing, and tracking capabilities. The primary goal of this phase of integration, testing, and verification is to provide assurance that the many electro-optical components, tracking cameras, electronics, and associated software are ready to demonstrate the ATP functions needed to engage and defeat near-space missile targets. The overall concept of the HABE, its design and equipment features, and the plans for balloon-borne tests against typical boosting missiles are described elsewhere in the conference[1]. During laboratory testing, the imaging and tracking systems were identified for upgrade and replacement due to processing and acquisition latency problems. Additionally, it was found that the original cameras needed to be replaced to overcome issues of excessive vibrations and electronic noise. The tracker has since been replaced with a Real-Time Image Processor (RIP). The system hardware and software and benchmark verifications are identified and described by Krainak[2]. This unique system design allows HABE to overcome a variety of the latency errors and processing delays previously encountered. The upgraded cameras and newly designed isolation mountings provide enhanced sensitivity to target scenes and lower jitter from the cryogenic coolers. HABE includes a number of innovations in relation to the task of developing and testing ATP technology that merit presentation to the community of ATP developers and users.

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In Section 2, a summary description of the HABE ATP flight software design is provided. The flight software is designed and implemented on a distributed set of modern, fast, commercial off-the-shelf processors. The software implements the interface communications with sensors and actuators, performs the control loop compensations, and transfers data needed by other cooperating processors of the payload. In concert, the set of processors accomplishes all of the functions typically required and attributed to a sophisticated ATP system, including LOS stabilization; target detection, acquisition and tracking; and LOS alignment and pointing. Since HABE is concerned with missile targets at ranges of 50–200 km, the performance errors of the payload are necessarily in the submicroradian class. To achieve these precisions, HABE employs an illuminator laser that enhances the signature of the missile hardbody and makes its image visible to the Active Fine Tracker.

The process of testing and verifying functions and performance for an ATP system like HABE is challenging. Sebesta[3] provides a description of the tests, test hardware, and data analyses processes that have been developed for and used in the context of developing the software and the flight equipment for the HABE ATP payload. This testing is accomplished in two stages: (1) the ATP software is developed and verified to meet its specified functional and operating characteristics in the HABE Real-Time Emulator (HABERTE); and (2) final flight system integrity and performance is tested and documented during hardware testing. The HABERTE provides a duplicate set of flight processors and electronics combined with a set of hardware and software emulators to closely simulate the operating environment. The software developers use this to develop and test the software system. The emulators exhibit appropriate dynamics, input/output frequency response characteristics, and logical control so verification tests of the developed software are accomplished in a context that provides extremely high fidelity with the final flight payload. The all-digital nature of the HABE ATP payload enables flexible, in-situ tests of the complex control systems needed to perform the missile target acquisition, tracking, and pointing. Built-in-tests (BITs) are convenient to implement and evaluate in real time. Sections 3 and 4 describe the final stage of testing which employs ground support equipment generally referred to as a "range-in-a-box," or as it is designated here, "Laboratory Test Component." It provides simulated target sources and scoring functions that appear to be in the far-field for the payload optical sensors and laser transmitters. The most challenging test task during the final verification of the integrated software and hardware is measuring and verifying the performance of the stabilization, tracking, and pointing functions included within the payload. For HABE, the allocated error budgets involve terms that are on the order of a 100 nrad. Extracting and ascertaining the statistical validity of such measurements is only possible through use of advanced signal analysis techniques (for example, Sebesta[4] describes such an application of multiple input coherence analysis algorithms in the context of state-of-the-art ATP experiments, specifically, the Relay Mirror Experiment[5]). In addition to describing the ground test hardware, section 3 identifies the setup for the Active End-to-End (AETE) tests conducted using the LTC and its simulated targets.

Section 4 illustrates the details of applying HABE's innovative test processes to the AETE tests. The illustrations include (1) validation of the equipment used and the test setup; (2) the data collected during the AETE tests, including inputs/outputs and identification of the components contributing to the analysis; and (3) a summary of the test results and how they are used to verify the performance error budget. LOS stabilization is implemented in the HABE design by employing a state-of-the-art inertial reference denoted the Pseudo Star Inertial Reference Unit (IPSRU) and maintaining the alignment of the LOS to the pseudo star by means of a 16.2 kHz sample rate digital servo system which controls a fast steering mirror. Luniewicz[6] and Shen[7] report performance and technical details and features of the IPSRU and HABE fast steering mirrors, respectively. The summary of the HABE integration and test processes, along with conclusions about their applications, are provided in section 5.

2. HABE ATP SYSTEM DESCRIPTION

The ATP payload developed for the HABE is depicted as reported by Browning and Olson[1]. **Figure 1** illustrates the optical payload of the HABE. The payload includes the necessary functional capability to perform the entire sequence of modes, which transition from externally cued inertial pointing to tracking with an infrared acquisition camera, to passive intermediate infrared tracking, and ending in a precision tracking mode. This last mode, designated as active fine tracking, forms the primary subject of this paper. The control systems and the error budgets involved in this last stage of operation were illustrated by Sebesta[3]. **Figure 2** illustrates top-level HABE ATP functional modules.

The performance metric in this mode of operation is the capability of the ATP system to autonomously reach the condition of precision tracking and precisely pointing a marker laser (low-power scoring laser which is surrogate for a high-energy laser) at an aimpoint selected on the missile hard-body. The identification of the sources of errors and the mechanisms by which they contribute to the inaccuracy of holding the marker laser on the aimpoint is conventionally referred to as the

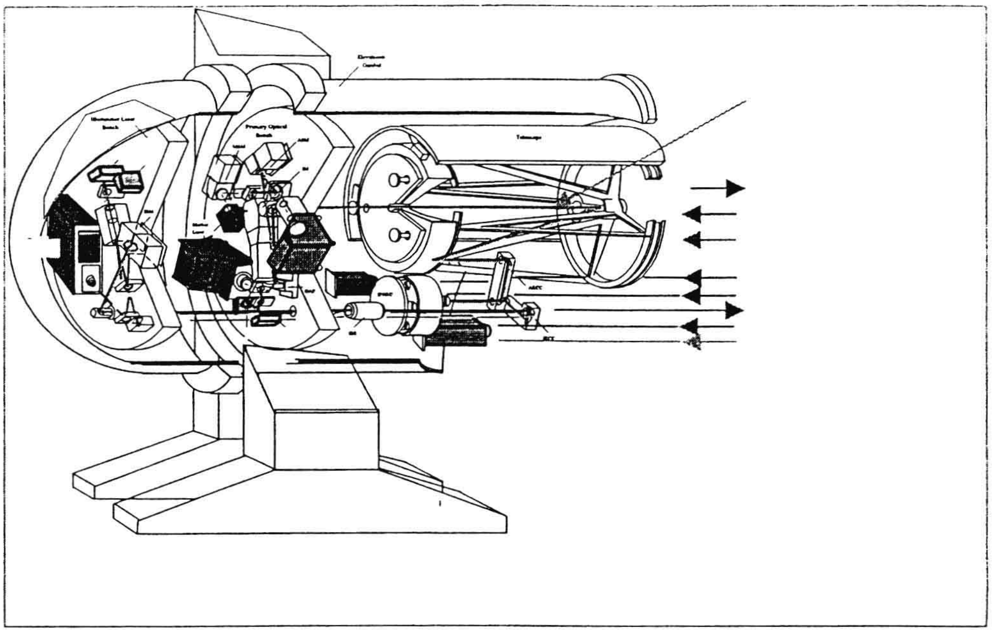

Figure 1. HABE ATP Payload

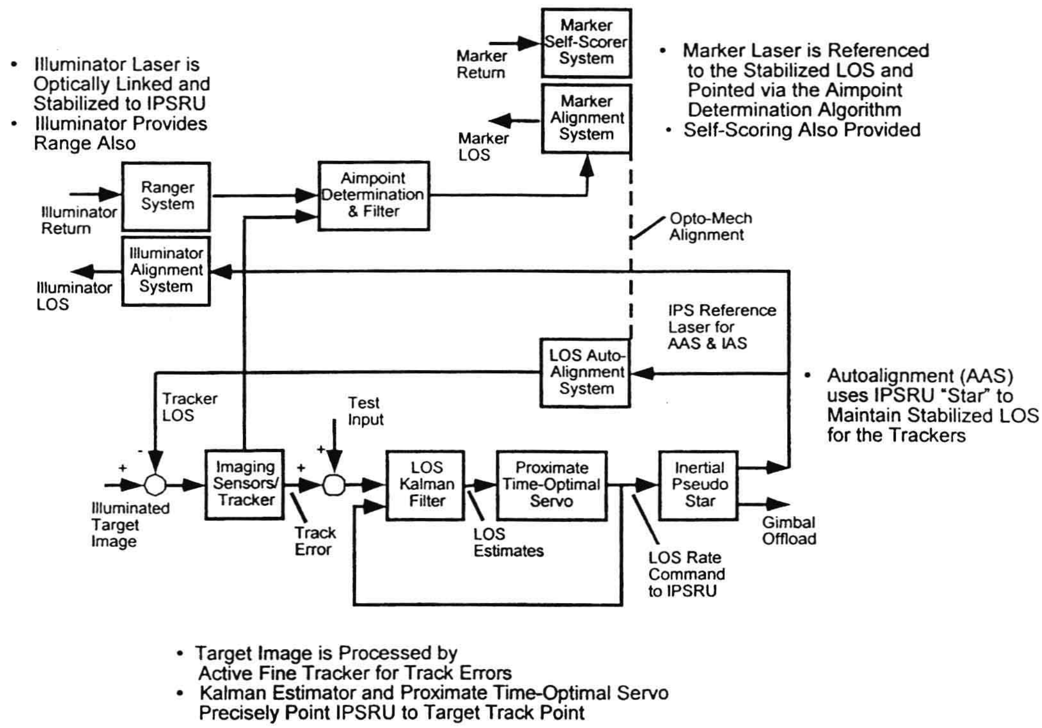

Figure 2. HABE ATP Functions

system error budget. Error budget models for the contributions which cause bias and drift have also been developed, but are not discussed in this paper. The jitter error contributors are identified in three categories: (1) LOS stabilization jitter; (2) active fine tracking jitter; and (3) aimpoint determination and pointing of the marker laser. **Figure 3** illustrates this combined HABE system metric for errors in placing the scoring laser on the aimpoint.

The first and least dominant category of error sources is that which is attributable to errors in the IPSRU creation of the stabilized inertial reference "star" or alignment laser and to errors of the autoalignment system in keeping the LOS aligned to the star. Internal sensor, implementation noise of IPSRU, and the unrejected base motion are factors that dominate star stabilization of the reference laser. Optical path jitter rejection and sensor and implementation noise are also key factors in the performance of the autoalignment system. The capability of IPSRU, its concept of active and passive stabilization, and the predicted performance with respect to noise sources and base motion rejection are documented elsewhere[3, 6]. The IPSRU and the autoalignment servo comprise the contributors to the error budget element, LOS Stabilization, shown in Figure 3. Reactions from IPSRU's base gyro and its actuators increase the vibrations on the optics bench and influence the performance of the autoalignment system. LOS Stabilization performance is 125 nrad with IPSRU inactive and 174 nrad with an active IPSRU. Section 4 will briefly describe the processes of collecting data and performing analysis to establish that the LOS Stabilization function is operating at these levels.

The second category of error sources is that which governs how precisely the tracking loop can place and hold the stabilized LOS on a specific missile track point. In HABE, the approach is to partially illuminate (subflood) the missile, create an image visible to the tracking camera, and apply a tracking algorithm to compute the LOS errors in relation to the selected track point. The error budget rollup for active tracking addresses the classical trade in order to optimize LOS control: (1) following the dynamics of the target LOS which implies higher track loop bandwidth; and (2) smoothing and filtering the track error sensor measurement noise, which implies lower track loop bandwidth. Modern control system design theory provides the rationale for selecting a small signal, linear regulator control system design. In addition, the design must also work robustly during mode transition events and simultaneously prevent LOS rate and acceleration commands that would

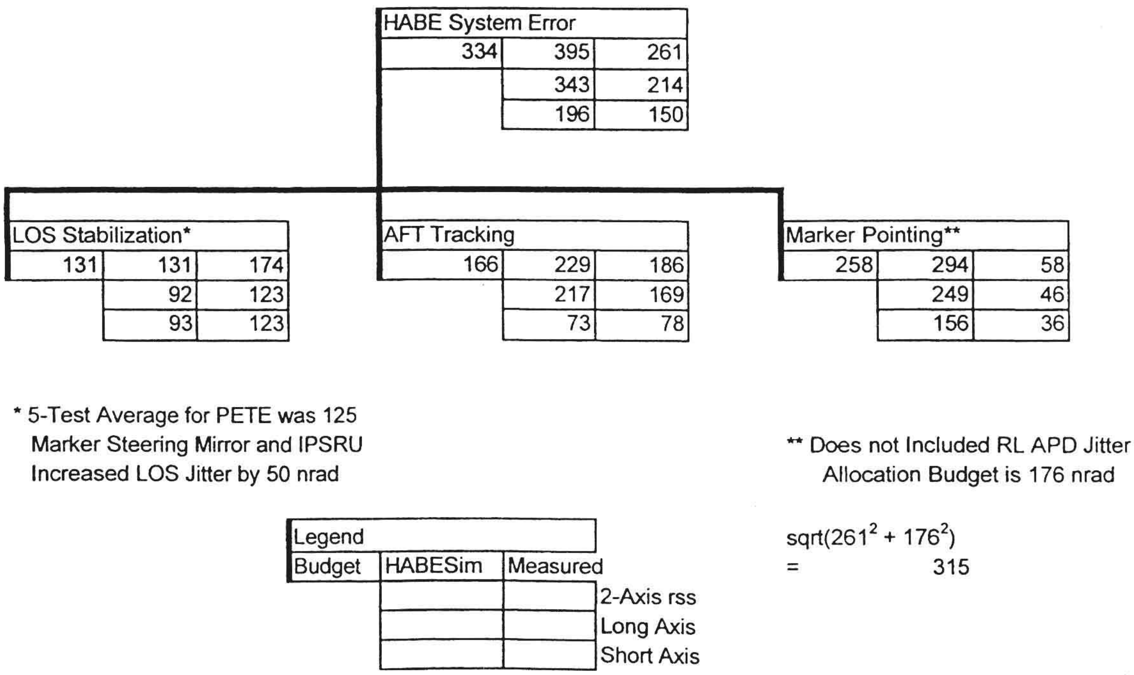

Figure 3. HABE Jitter Budget

exceed IPSRU safe operation limits of 2 deg/s and 1.15 deg/s^2. Minimum time settling during mode change transitions is achieved by employing residual error thresholds that cause gain adaptation to be reinitialized when large errors are sensed (as when a mode change occurs). Software algorithms that prevent commands to IPSRU that exceed its rate and acceleration constraints are based on the proximate time optimal servo design, for example, as reported by Liebst[8].

The last and most dominant category of error sources is that which determines how precisely the aimpoint for the marker laser can be determined and the marker pointed in response to this calculated aimpoint. The aimpoint determination (APD) algorithm is a separate software process from that which performs missile target tracking. However, it employs as inputs the same measured image from the active fine track camera plus other parameters such as range, range rate, and estimated LOS tracking error and LOS rate. The outputs from the APD algorithm are the calculated offsets measured in relation to the LOS of the active fine track camera and include noise from the image measurement and from the APD software algorithm. To reduce the marker pointing errors caused by the noise in the calculated offsets, the pointing offsets are processed through a relatively low-bandwidth smoothing filter before the aimpoint commands (offsets) are sent to the marker alignment system (MAS). The MAS operates with an alignment and pointing loop that is essentially the same as the Auto Alignment System, except that optical alignment errors are from a separate optical position sensor. Bias signals are added to the optical sensor signal to achieve the offsets necessary to account for the marker laser's time-of-flight and location of the aimpoint relative to the track point LOS. The marker laser is modulated with a 50% duty cycle at 16.2 kHz. This modulation permits the use of narrow-band AC detection electronics to enhance the signal-to-noise of the measured return marker signal from the target. This latter detection and signal processing is used within the self-scorer system for the payload.

As may be observed from the allocated, predicted, and measured jitter numbers listed in the error budget, the development of the HABE ATP payload is a challenging technology development, integration, and experimental program. The sub-microradian goals for LOS stabilization, active fine tracking, and marker pointing push the technology boundary for each area. For this and other reasons, the designers for HABE chose to exploit as much as possible the use of modern digital processors in implementing the payload. From a top-level view, the ATP control systems of HABE include four major digital processor suites: (1) the pointing control processor (PCP); (2) the tracker (TKR) or Real-Time Image Processor (RIP); (3) the data handling processor (DHP); and (4) the tracker mode controller (TMC). The terminology suite is used purposefully because within each suite a number of separate real-time microprocessors are used. For instance, the mirror control loops are implemented on a single 233 MHz co-processor to the PCP. High speed sharing of data and parameters between the processor suites is implemented by using a shared reflective memory network that operates with a fiber optic inter-processor communication system. The VME data bus is for interfaces between the numerous physical devices in the payload and the processors. The majority of the payload processor functions (CPU, memory, analog-to-digital, digital-to-analog, etc.) are situated in VME cards that are located in electronic chassis setups within the payload electronics canister (E-Can). The latter is maintained at environmental conditions compatible with commercial processors. Electronic boards that cannot be located within the E-Can and must be located close to the subsystems of the optical canister (O-Can) are deployed in a chassis mounted on the optical benches. The electronics located in the O-Can are designed to be compatible with the near-space environmental conditions that HABE will encounter at its operating altitude of 26 km (85,000 ft). The PCP and the DHP suites communicate from the E-Can over serial bus lines with the processors and interface boards in the O-Can. Video signals from the cameras that constitute part of the optical payload communicate over digital video lines to camera interface boards in a RIP chassis in the E-Can. The layout of the multi-processor system comprising the HABE payload was described by Browning[1], Krainak[2], and Sebesta[3]. While the HABE payload is designed to operate autonomously, the requirement to allow close monitoring and detailed recording of payload signals has resulted in the inclusion of telemetry uplinks and downlinks. The payload operations center (POC) includes a ground support processor (GSP) for handling the telemetry link interfaces. Consoles for the payload operator, the test director, the HABE laser safety officer, and tracker operator are provided and allow monitoring of the real-time functions of the payload during laboratory integration, ground, or flight tests.

3. GROUND SUPPORT EQUIPMENT (GSE) DESCRIPTION

The technical thrust of this paper is the ground support equipment (GSE) that has been developed to facilitate HABE integration and testing. A GSE item that has been denoted the Laboratory Test Component (LTC) has provided the means to validate functional and performance capabilities of the HABE control loops. **Figure 4** illustrates the mechanical and optical layout of the LTC. The configuration depicted in Figure 4 is the final and most complete evolution of the LTC. It provides a complete set of target scene interfaces for all of the tracking and pointing modes of HABE. The active target illumination and the transmit delay of the reflected light into the active fine tracker is simulated by use of a 3 km fiber optic coil. Additionally, the optics and sensors included in the LTC allow measurement of the marker laser's far-field motions relative to the aimpoint. In the paragraphs below, key capabilities and instrumentation of the LTC are described in more detail. The LTC provides a "range-in-a-box" that allows the HABE integration and test team to derive initial evidence that the integrated