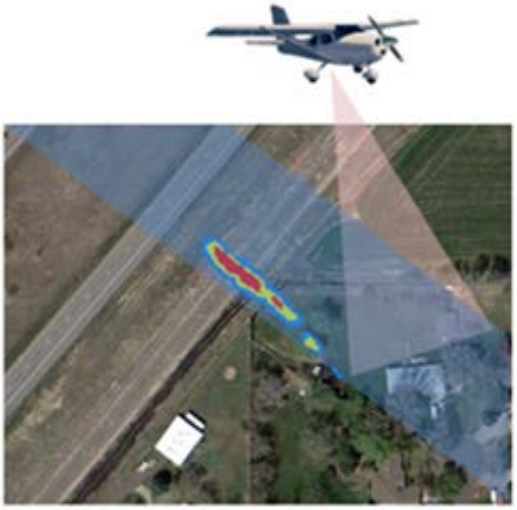
Advanced Leak Detection Lidar for Hazardous Liquids: Final Report

Prepared by:

Jarett Bartholomew, Principal Investigator
jbarthol@ball.com
(303) 939-5951

Phil Lyman, Project Manager
plyman@ball.com
(303) 939-6869



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Final Report, Public Version,
Advanced Leak Detection Lidar (ALDL)

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Project Title: *Advanced Leak Detection Lidar*

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Contact Information: *Philip C. Lyman, Project Manager (303.939.6869, plyman@ball.com)*
Jarett Bartholomew, Principal Investigator (303.939.5951, jbarthol@ball.com)

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1.0 Summary of Research Results and Conclusions vs. Project Objectives

Table 1, below, is excerpted from the R&D Proposal which Ball Aerospace submitted to PHMSA in 2013. It identifies the resulting benefits of successful development of the Advanced Leak Detection Lidar (ALDL).

Table 1, Targeted benefits of ALDL for hazardous liquids

Unmet Demands of End Users of Airborne Leak Detection Systems	Existing Gas Leak DIAL	Proposed Liquid Leak DIAL
Detects heavier (than methane) gasses and liquids evolving from liquid leaks (while retaining inherent flexibility to adapt for methane leak detection)?	**No**	**Yes**
Maps broad swath instead of narrow line to distinguish natural sources from pipeline leaks and point to a leak source to pinpoint leak location?	**No***	**Yes**
Has enough power and detection sensitivity to work from higher altitudes where FAA waivers are not needed?	**No**	**Yes**
Supports broad-area mapping needed to assess production, refining and storage operations as well as transportation?	**No**	**Yes**
Incorporates on-board processing and geo-location of data with hooks for real-time data link to customer operations center?	**No**	**Yes**
Overlays gas concentration data onto visible and LiDAR image data to help pinpoint leak source and cause?	**No**	**Yes**

To achieve the intended benefits, an instrument comprised of a broad set of components, as shown in **Figure 1** was developed. The system engineering process, undertaken during the >2 years of development included:

- **Requirements:** Defining target technical performance and functionality requirements with input/feedback from pipeline industry operators
- **Design:** Producing a design for the overall instrument and its subcomponents
- **Analysis:** Performing mathematical analysis to establish the likely performance of the overall instrument, when functioning in its planned operating environment (i.e. to confirm that the design can be expected to meet the intended performance and functionality.
- **Fabrication:** Manufacture, assembly and integration of the components (with component-level testing), plus assembly and integration of the overall instrument.
- **Test:** Ground and flight testing for final confirmation of the performance and functionality vs. the targeted characteristics.

Figure 1 shows the resulting ALDL instrument hardware with annotations. **Figure 2** shows a block diagram of the instrument. The project culminated in flight testing of the instrument and a detailed Flight Test Report is presented in Appendix A.

Figure 3 shows the very first differential absorption lidar (DIAL) data take in the near infrared, overlain on geo-located imagery of a test field where hazardous liquid leak simulations were established as targets. Ball Aerospace is now developing DIAL instrumentation for both hazardous liquid and natural gas leak detection. These are designated as ALDL-LQ and ALDL-NG, respectively.

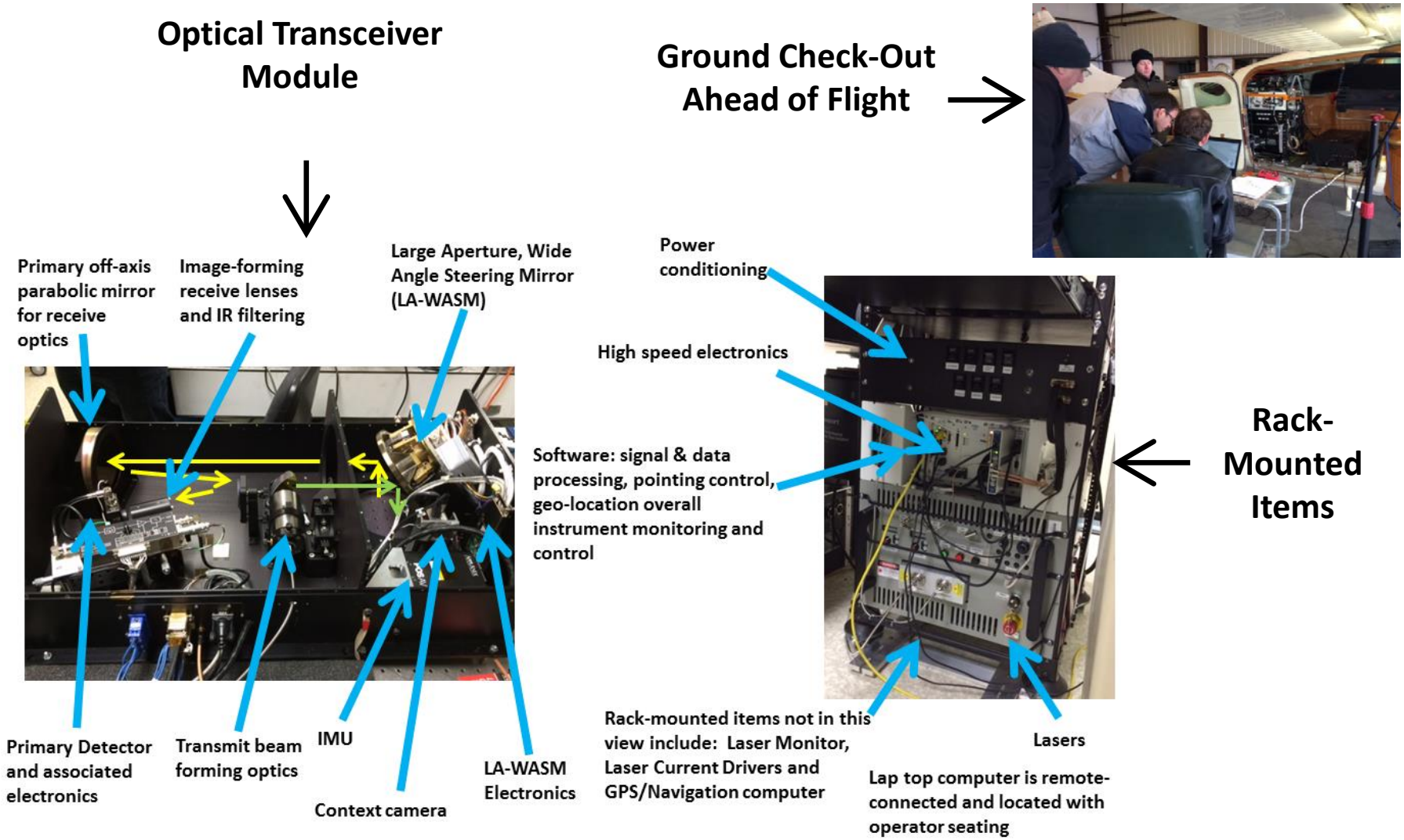


Figure 1, The ALDL instrument fits within a single engine, fixed-wing aircraft, the Cessna 206. The transceiver module on the left above contains all of the optically-aligned elements and the 19-inch rack on the right contains the remaining components of the system. Flight testing occurred in November of 2015 over simulated hazardous liquid leaks in Broomfield, Colorado.

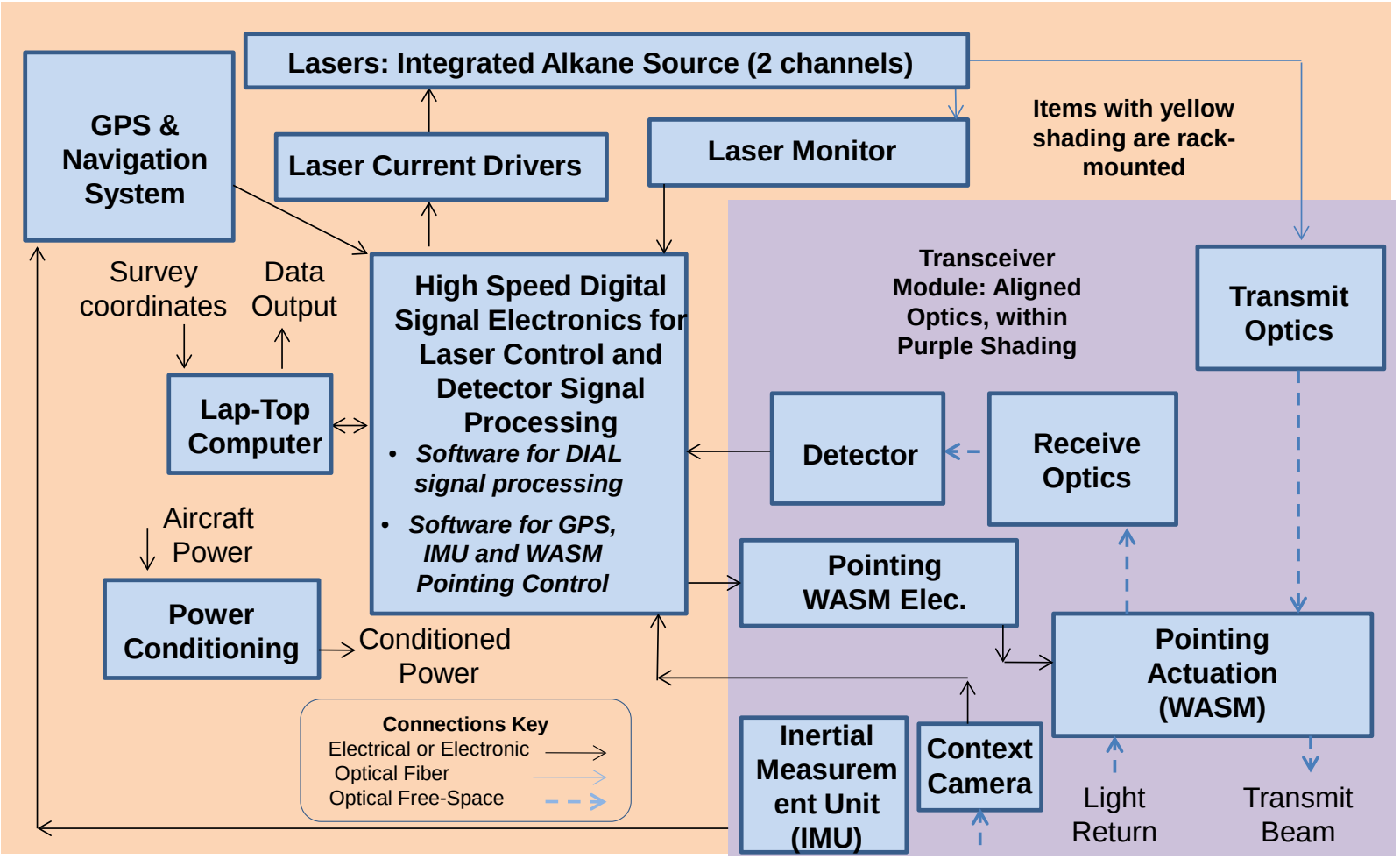
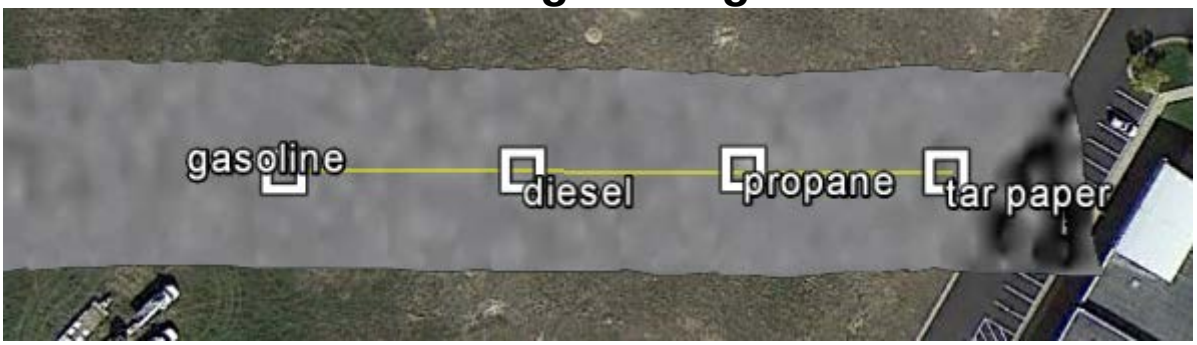


Figure 2, Block diagram of ALDL-NG instrument shows optically aligned elements of the Transceiver Module with purple background and the remaining rack-mounted components with yellow background

Overall laser return and target designations



DIAL concentration measurement/computation

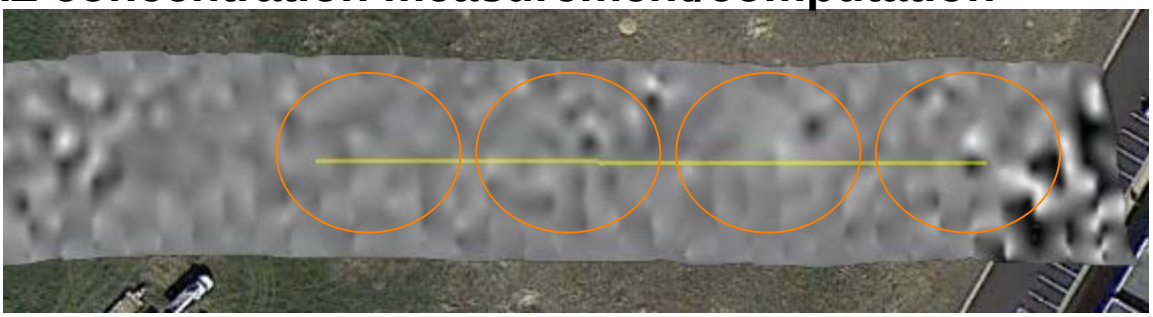


Figure 3a, Simulated hazardous liquid leaks are not discernable in data from the first flight testing of ALDL. While much of the instrument performed as expected, there are a few areas where improvements will be needed to achieve clear detection.

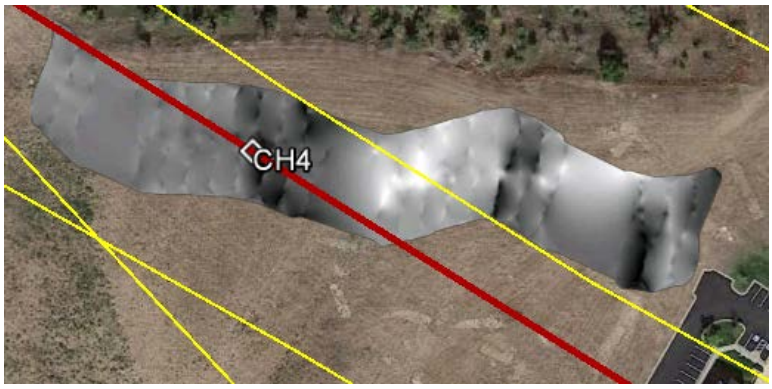


Figure 3b, ALDL was reconfigured with lasers at a wavelength to detect natural gas (methane) and was re-flown 6 weeks later. The methane plume was detected (bright zones in data).

Figure 3, ALDL has been flown for hazardous liquid leak detection (3a, top) and also for natural gas leak detection (3b, bottom). Performance during initial flights was below expectations. However, the data collected shows where upgrades can effectively improve the results.

1.1 Development Status - Progress Against Intended Objectives

A propane plume, simulating a hazardous liquid leak was successfully detected during horizontal ground testing with ALDL-LQ viewing ~1,000 ft across an open field. For flight however, inspection of Figure 3a, shows that plumes of propane or longer-chain alkane vapors evolving from hazardous liquids are not discerned by the ALDL instrument. Table 2 below describes the development status and shows that several of planned advancements have been achieved. The conclusions of post-flight data analysis are presented after the table: i.e. what would enable alkane plume detection.

Table 2, Several remote sensing advancements have been achieved by ALDL, but detection of vapor plumes of propane and longer-chain alkanes faces remaining technical challenges described below the table.

Unmet Demands of End Users of Airborne Leak Detection Systems	Development Status vs. Intended Benefit (as of the end of the PHMSA contract)
Detects heavier (than methane) gasses and liquids evolving from liquid leaks (while retaining inherent flexibility to adapt for methane leak detection)?	The sensor for liquids (ALDL-LQ) does not have a good enough signal to noise ratio (SNR) to sense longer chain alkanes from liquid leaks. Necessary improvements have been identified and are discussed in this report. The flexibility to adapt for methane leak detection has been demonstrated as shown in Figure 3.
Maps broad swath instead of narrow line to distinguish natural sources from pipeline leaks and point to a leak source to pinpoint leak location?	The ALDL sensor does map a swath, as shown in Figure 3 and can identify the pipeline as a leak source and reduce false-positives from other sources.
Has enough power and detection sensitivity to work from higher altitudes where FAA waivers are not needed?	This remains to be determined since the SNR is not yet sufficient.
Supports broad-area mapping needed to assess production, refining and storage operations as well as transportation?	The sensor swath width is adequate for mapping smaller facilities such as wells or storage tanks. It is probably not wide enough to readily map refineries, gathering pipe networks or gas distribution networks.
Incorporates on-board processing and geo-location of data with hooks for real-time data link to customer operations center?	The on-board algorithms perform gas concentration computations and geo-location on-board in real-time.
Overlays gas concentration data onto visible and LiDAR image data to help pinpoint leak source and cause?	Data output can be readily overlaid onto pre-existing, geo-located imagery such as that available from Google Earth. In addition, context imagery from the day of the leak survey can be viewed in parallel.

1.1.1 Successful Technology Advancements

Instrument Performance Modeling: Throughout the project a high-fidelity performance model was used to predict performance and aid with issue resolution. The functionality and performance of all hardware and software elements is included in the model: lasers, optics, detectors, signal processing algorithms, etc. As development progressed, the characteristics of the as-built components were used to update the Instrument Performance Model. When test data indicated unexpected performance of components was likely impacting overall instrument performance. The model could readily be updated to confirm analytically, the impact of component anomalies on end-to-end performance. Instrument Performance Modeling has proven to be very beneficial for ALDL-LQ development.

Novel Lasers: The lasers combine high-power solid state diodes with temperature-controlled Volume Bragg Gratings (VBG) to achieve narrow laser line-width and precise wavelength control. Continuous wave lasers are intensity-modulated at different frequencies for each of the Off-Line, and On-Line, wavelengths (On-Line being positioned at the particular absorption wavelength for propane and other longer-chain alkanes and Off-Line being positions slightly away from that spectral characteristic). The modulation frequencies are precisely chosen and controlled to allow signal separation and extraction for On-Line and Off-Line, thereby enabling the differential measurement of laser absorption.

Signal Processing: Signals from detectors within the Laser Monitor provide reference information for the outgoing laser light. The detector within the Transceiver Module captures returning light after its transmission through the atmosphere and reflection from the surface of the Earth. All of these signals undergo analog to digital conversion via high speed signal processing electronics. Thereafter, newly developed software algorithms isolate data for the two wavelengths, perform averaging, and differencing to establish the amount of target gasses in the atmosphere.

Swath Mapping – Pointing Control and Pointing Knowledge: The ALDL instrument adapts Ball's fast steering mirror technology for application to the DIAL instrument. The optics, electromechanical actuation and position sensors have been used on earlier instrumentation for the U.S. Department of Defense and NASA. The pointing control system enables swath mapping with a single pixel detector in a "whisk-broom" instrument configuration. Accurate knowledge of the pointing position is one of the variables that allows precise position determination of the gas concentration data on the ground.

Laser Monitor: The laser monitor includes an on-board reference gas cell. Detectors are positioned upstream and downstream of this gas cell and a small fraction of the laser light is routed to the Laser Monitor. This element of the instrument allows:

a) For the laser wavelength and line-width accuracy to be continuously monitored
b) Provides reference phase information that allows determination of the range to the ground for the gas concentration measurement. This, in-turn, allows computation of the average path length concentration in ppm.
c) Provides laser intensity and attenuation reference information that allows computation of the gas concentration, integrated over the path length in ppm-m.

1.1.2 Remaining Challenges at the Conclusion of the Project

The test flight and subsequent data analysis indicates several technical factors that impacted the quality of the plume imaging in Figure 3a. Correcting all of these issues is expected create a dramatic improvement in the chemical sensitivity and cohesiveness of plume imaging.

Instrument timing and laser modulation: Specific improvements are targeted in the area of overall instrument timing and also the laser modulation.

Vibration sensitivity: Some specific elements of the instrument were shown to be susceptible to aircraft-induced vibration. These components need to be upgraded to eliminate vibration sensitivity.

IR response: A few optical and electro-optical components showed sub-optimal performance at the infrared wavelengths used by ALDL-LQ. Some customization is needed to improve their performance at the specific wavelengths of operation.

2.0 Development Project Performance vs. Project Plan

The overall project schedule is show in **Figure 4**. We started with a 24 month development plan through September 1, 2015. This was extended by 8 months via Modification 001, through May 31, 2016. Development phases are shown across the top of the schedule:

- **Requirements:** Defining target technical performance and functionality requirements with input/feedback from pipeline industry operators
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Modification 001 added 8 months to the project schedule and extended the period of performance through May of 2016. This Final Report and project completion is one month early: April 30, 2016. Individual tasks incurred delays as shown in **Figure 4**. Delivery delays on the solid state lasers and pointing control mechanism (WASM) had the largest impact on the schedule.

3.0 Resource Matching Report

Resource matching readily exceeded the amount agreed upon – by nearly 50%.

4.0 Final Delivery Milestones

Delivery Milestone D16. Task T20, Industry Conference Paper and Presentation (Accomplished): This milestone was accomplished on February 3rd, 2016. A "White Paper" had been submitted to the Pipeline Research Council International (PRCI) in mid-December, 2015. That resulted in a presentation being invited at the next, subsequent PRCI Research Exchange Forum which was held in San Diego on February 3rd.

Note that Ball Aerospace is also preparing an abstract for a paper to be submitted to the American Institute of Aeronautics and Astronautics. Additionally, a paper on the high speed signal processing for ALDL is being prepared for an electrical engineering conference. Other papers and presentation are likely after the end of the contract as the commercialization effort progresses.

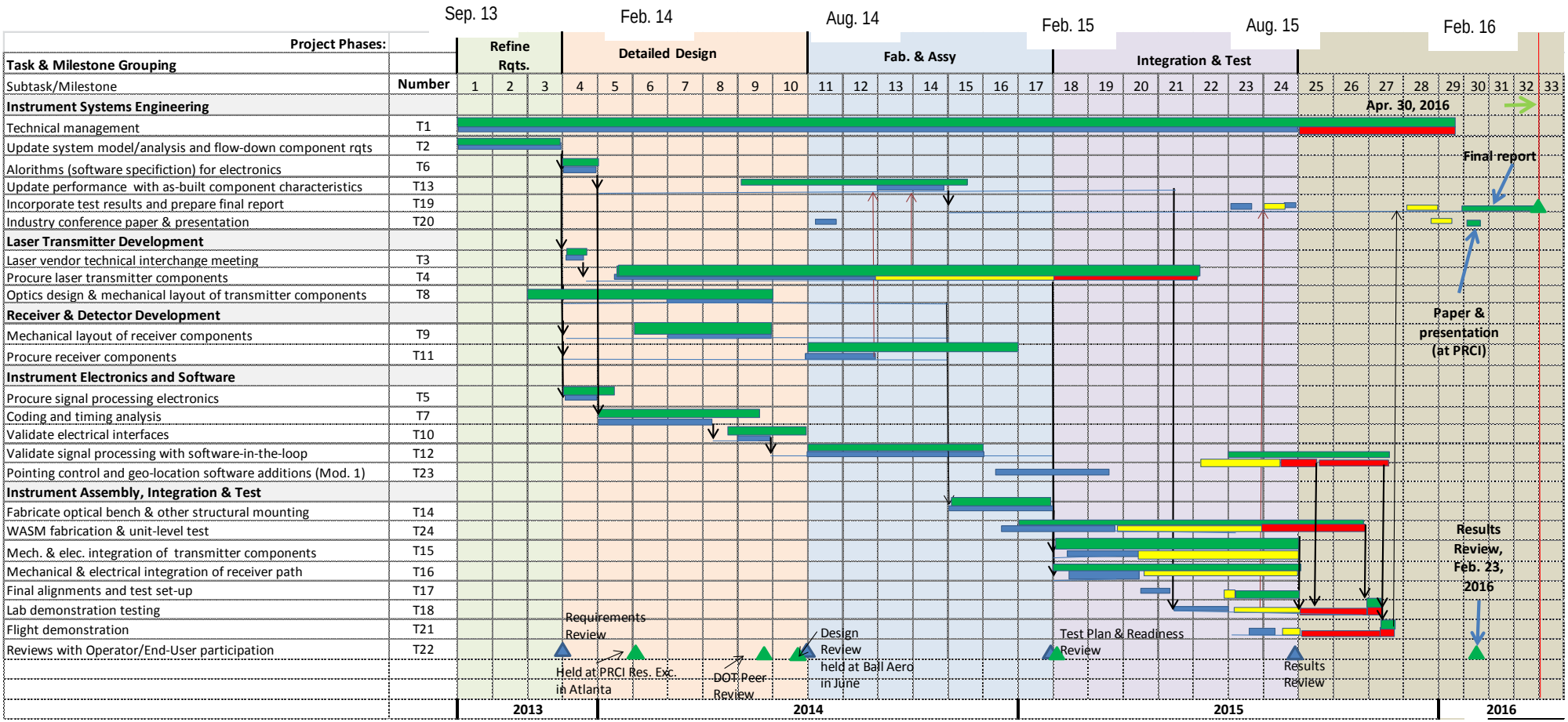

Figure 4, The original ALDL development schedule is shown by the blue bars. Yellow and red bars show re-planning with minimal and substantive schedule impact, respectively. Green bars show when the tasks were actually accomplished. Key schedule delays came from: A) late delivery of the laser assembly (Task T4), B) delays in completing the fabrication of the Wide Angle Steering Mirror (Task T24), and delays in completing the pointing control and geo-location software, which wound-up being dependent on the WASM being available for test (Task T23).

Delivery Milestone D30, Task T21, Flight Demonstration (Accomplished): As described in Sections 1 and 2, Flight Testing was accomplished in November, 2015 and the test report was submitted early in 2016..

Delivery Milestone D31, Task T19, Final Report (Accomplished): This document constitutes the public-version of the Final Report.

The final invoice for the project will be submitted after this final report and should include amounts associated with D16, D30 and D31.

5.0 Commercialization Update

Ball Aerospace has been building relationships with individual pipeline operators throughout the U.S. We've been supporting public pipeline meetings such as the GITA Pipeline Week and have pushed for invitations to meetings of pipeline operators that are normally reserved for paying members of the American Petroleum Institute (API) and the Pipeline Research Council International (PRCI). Through these meetings and contacts, there are several hazardous liquid pipeline operators interested in deploying ALDL-LQ, operationally, once the technology is further vetted.

We have also been in communication with government agencies regarding possible use of leak detection for government activities. These include the Environmental Protection Agency (EPA) and National Oceanic and Atmospheric Administration (NOAA). In both cases, the instrumentation is being considered for use in characterizing regional atmospheric composition as opposed to detection of specific sources of emissions.