Technology Roadmap for Deploying Operational Wind Lidar

Obtaining Global Operational Wind Profiles

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January 20, 2004

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1. Introduction

The need to for accurate, timely, and comprehensive global wind measurements is widely acknowledged. The Integrated Program Office (IPO)[1] which oversees the National Polar-orbiting Environmental Satellite System (NPOESS) identifies accurate direct measurement of wind velocity profiles as the greatest unmet observational need to improve global weather forecasts. The IPO's environmental data priorities reflect those of a broad national spectrum of users.

Technology advances are needed in lasers, detectors, low-mass telescopes, scanners, and momentum compensation to meet the published requirements. The GTWS reference designs required space-qualified lasers well beyond today's capabilities, large and heavy spacecraft, massive optical components, and very high electrical power consumption. Scanning and momentum compensation requirements are challenging. Three alternative DWL approaches are considered: direct detection, coherent detection, and hybrid detection. Each has unique advantages.

Hybrid DWL, combining coherent and direct detection subsystems, may make instrument development more tractable. The improvement is in the form of reduced demands on the DWL subsystems as compared to a coherent-only or direct detection-only instrument. The reduced subsystem performance requirements can be spread out end-to-end to optimize system design, affecting DWL laser power, telescope, optical efficiency, and detection. The results should reduce spacecraft mass, energy, and momentum compensation challenges. The current estimates for improvement factors are:

- Coherent Subsystem: 15 to 30 times
- Direct Detection Subsystem: 4 to 8 times

However, the hybrid instrument will complicate some mission and spacecraft issues because of the need to accommodate two complicated subsystems.

The IPO has sponsored a hybrid DWL feasibility study. NASA and industry activities are addressing high-powered flight-qualified lasers. Analysis of data requirements vs. benefits is recommended to identify any relaxation of data requirements that may reduce critical technology demands without excessive reduction of benefits.

<u>Background</u>

In October 2001, NOAA and NASA published draft global wind data requirements[2] and are exploring how these requirements might be satisfied. DOD is considering whether tactical military wind data requirements can be addressed as part of the same enterprise.

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[1] The IPO resides within the Department of Commerce's (DOC) National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data and Information Service (NESDIS) and is staffed with personnel from the Department of Defense (DOD), DOC, and the National Aeronautics and Space Administration (NASA).

[2] For more information, see *http://nais.msfc.nasa.gov/cgi-bin/EPS/synopsis.cgi?acqid=99220*

Other government agencies and commercial interests have expressed needs for wind data.[3]

Reliable wind data are presently available over North America, Europe, and other developed areas. They are obtained primarily by rawinsondes launched at 6 or 12 hour intervals from fixed stations. Wind profiles are also collected over the United States during aircraft ascent and descent at major airports,[4] providing flight level winds, but not profiles, along the paths connecting the same airports. Still, wind profiles are unavailable or inadequate over much of the oceans, tropics, and Southern Hemisphere.

The instrument class most likely to provide the required global wind profile data is the active remote sensors known as Doppler Wind Lidar (DWL) systems. Technology advancements are required before DWL can meet documented data requirements from space.

Interagency planning and commitment of resources and personnel are needed for a program to deploy an operational wind mission. This program will define and advance key technology areas, demonstrate new capabilities in laboratories, then surface-based, airborne, and finally space-based lidar systems, ultimately enabling deployment of an operational wind lidar mission.

Purpose and Scope

This paper outlines a technology roadmap to achieve mature technology and reduce technical risk for deploying DWLs to meet published data requirements.

Three DWL instrument approaches are considered (direct detection, coherent detection, and hybrid), with a technology roadmap for each.

The roadmaps in this paper are based on the hybrid approach. The hybrid approach encompasses the technology and roadmaps of the other two, and because it promises to reduce the most challenging lidar operating parameters, although at the cost of increased spacecraft and launch complexity.

For each alternative, technology development is needed in lasers, detectors, telescope, scanner, and momentum compensation.

[3] Wind data promises to support the missions of the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), Federal Emergency Management Agency (FEMA), Department of Defense (DOD), and the Department of Homeland Security (DHS).
[4] Instrumented by the ARINC (Aeronautical Radio Incorporated) Communications Addressing and Reporting System (ACARS)

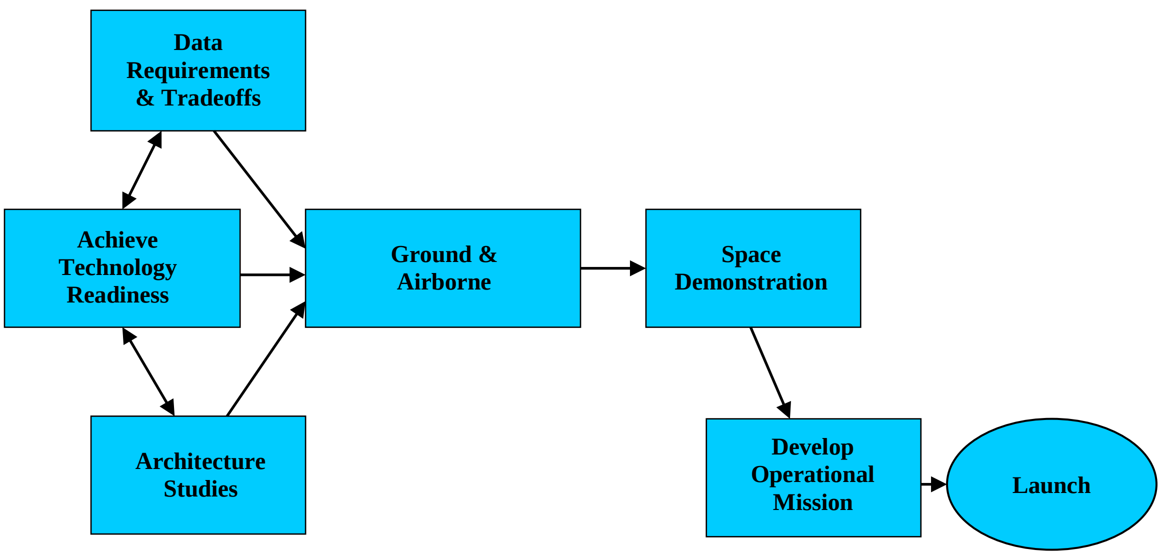
2. Program Overview

This paper anticipates that participating agencies will prepare and execute a long term plan for providing funding, staff, and other resources. This plan would advance critical technology areas and demonstrate capabilities in the laboratory, in ground observatories, on aircraft, and in space.

High level activities and dependencies are shown in Figure 2. When technology readiness and architecture are capable of meeting data requirements, the program will advance to space demonstration and then to an operational mission.

Some key instrument developments, such as flight qualified lasers and electro-optic scanners, may have long lead times.

Figure 2. Activities leading to operational wind lidar



The Data Requirements and Tradeoffs activities will quantify benefits, assess sensitivity of benefits to data specifications, develop DWL wind data assimilation techniques, and publish a revised data specification if justified.

The activity to Achieve Technology Readiness will advance capabilities in lasers, detectors, low-mass telescopes, scanners, momentum compensation, and other critical areas.

The Architecture activity will advance end-to-end systems engineering and architecture specifications to ensure that the data specifications are met in operations and to support acquisition.

Ground and Airborne Demonstration will test and demonstrate prototype subsystems, architecture, calibration, validation, and data products in a range of atmospheric conditions.

Space Demonstration will demonstrate the capability of the selected DWL instrument to meet data requirements from orbit. The platform may be the shuttle, the International Space Station, a DOD Space Test Program mission, or other platform.

The Operational Mission will acquire, launch, and operate the instrument, spacecraft, communications, operations center, data production facility, and other activities required to produce and distribute data products. A second instrument may be launched if required to meet temporal and spatial resolution requirements.

3. Benefits and Requirements Tradeoff Studies

Since lidars to meet the data requirements from space exceed the state-of-the-art, trade studies are needed between data requirements and societal benefits. The data requirements are based on needs of users concerned with weather prediction and atmospheric science, with limited input from those who design or acquire the corresponding hardware. Requirements will be searched for opportunities to reduce technology risk without incurring unacceptable impact on benefits.

Observing System Simulation Experiments (OSSEs) have been used to quantify potential benefits from wind observations in NASA and NOAA numerical weather forecast models. OSSEs can be used to evaluate potential modifications of data requirements. Development of new data assimilation methods for wind observations will be part of this activity.

For each data requirement, two questions may be explored:

1. Does the requirement drive technology beyond the state-of-the-art?
2. If so, can the requirement be relaxed without unacceptable benefit degradation?

If relaxation is justified, then a new version of the data requirements may be published.

Table 3 shows a preliminary list of requirements that drive the technology development and are candidates for further study.

Table 3. Requirements candidates for tradeoff study

Requirement (current threshold requirement)	**Technology Risk Impacts**	**Mechanism**
Vertical TSV Resolution (1 km)	Laser, detector, telescope	Increasing vertical TSV[5] dimension increases photon accumulation
Horizontal TSV Dimension (100 km)	Laser, detector, telescope, scanner	Increasing horizontal TSV dimension, combined with relaxing horizontal resolution would allow more shot accumulation and simplify scanner
Horizontal Resolution - Along Track (350 km),	Laser, detector, telescope, scanner	Increasing beyond 350 km increases time for shot averaging and scanner movement
Horizontal Resolution – Cross-Track (4 lines)	Laser, detector, telescope, scanner	Less Cross-Track observation lines increases time for shot accumulation and scanner movement
2 discrete perspectives in TSV	Scanner	Consider non-discrete method, e.g., conical scan
Wind Velocity Accuracy	Laser, telescope, detector	Reduced accuracy reduces laser, optics, and detector requirements

[5] Target Sample Volume (TSV) is the maximum volume of atmospheric motion to which sample averaging is to be limited for the expression of a single wind observation.

4. Architecture Studies

Systems engineering and architecture studies are needed to guide technology development. Early studies include:

- Develop a reference design for a hybrid lidar instrument and mission
- Perform trade studies among DWL alternatives and determine a course of action
- Determine how atmospheric properties, DWL alternatives, and spacecraft mechanics impact science data products
- Develop a calibration and validation approach

Selection of a DWL alternative is a major program decision. Reference designs for both direct and coherent detection resulted in large, expensive instruments that require significant technology advances. This has increased interest in a hybrid DWL that uses both direct and coherent detection. Hybrid may be the optimum solution, reducing cost, time, and risk. The hybrid technology roadmap is consistent with the combined roadmaps for direct and coherent, with the addition of developing shared technology, shared scanner, shared (or multiple) spacecraft and launch.

Hybrid DWL addresses the key technology challenges of lasers, detectors, telescopes and pointing by using coherent and direct lidars for different parts of the atmospheric depth of regard, for regions where they individually perform best. Coherent lidar performs better in parts of the atmosphere where direct detection lidar is weakest and vice versa. For either direct or coherent lidar alone to meet GTWS requirements, laser power, optics, and pointing are driven by conditions in the most challenging parts of the altitude range. Hybrid DWL promises to reduce technology demands on both. While use of two lidars instead of one adds some complexity, it also reduces the most serious technology challenges. The goal of hybrid DWL is to develop shared technology, scanners, spacecraft, and launch capability to reduce mission risk, cost, and time to launch date.

A Doppler Lidar Simulation Model has been used to simulate performance of different DWL concepts and prepare data product performance profiles.[6] Similar studies can verify effects on data products resulting from design alternatives, atmospheric variations (e.g. clouds, aerosol distributions, turbulence, jets, etc.), spacecraft mechanics (e.g. jitter, pointing error, etc.), and other variables.

Calibration and validation of an orbiting wind profiling instrument will be challenging. Methods are needed to check the orbiting DWL observations against independent observations to assure their validity. Since wind profiles can vary rapidly with time and position, new methods will be required.

[6] D. G. Emmitt, Simpson Weather Associates (SWA)

5. Direct Detection Roadmap

This roadmap discussion is based on target performance for the **direct detection subsystem** of a hybrid DWL. The roadmap activities for a DWL using only direct detection would be the same, but the performance targets are much more challenging.

Direct detection DWL measures wind profiles by transmitting a single frequency laser pulse (355 nm for molecular channel, 1064 nm for aerosol channel in the current point design) and measuring the Doppler shift due to the wind within range-gated altitude bins. Detected signal strength is proportional to the backscatter intensity (or number of photons) of the target altitude bin. High spectral resolution optical filters measure Doppler shifted frequency. Backscatter from aerosols or air molecules (or both) can be used, with molecular backscatter being the stronger signal. Two types of direct detection receivers are actively being tested, Fringe Imaging detection and Double Edge detection. Laser shots are accumulated to increase signal to noise ratios.

The NASA LRRP, funded by Code Y and Code R in 2002, is working to advance the critical laser technology.

Roadmap status shown in the following figures is as of early to mid 2003.

5.1 Roadmap for the Direct Detection Subsystem of a Hybrid DWL

Development begins with component technology improvements, followed by subsystem development, and then demonstration through field measurements, as shown in figure 5.1. Proven components and subsystems will then be incorporated into prototypes for ground, airborne, and space testing, as appropriate.

5.2 Direct Detection Subsystem Laser

The performance objectives for the direct detection subsystem laser are shown in Table 5.2. A technology roadmap in Figure 5.2 shows the development sequence and dependencies. The approach will utilize well developed, injection seeded, diode pumped Nd:YAG laser technology and focus development on efficiency, conductive cooling, and lifetime. The product will be tested in ground and airborne testbeds. Today a space qualified laser in GLAS delivers about 4% wallplug efficiency. TRW has demonstrated an efficient 100 W, all solid state, ruggedized laser.

Figure 5.1. Component and subsystem roadmap - Direct Detection Subsystem

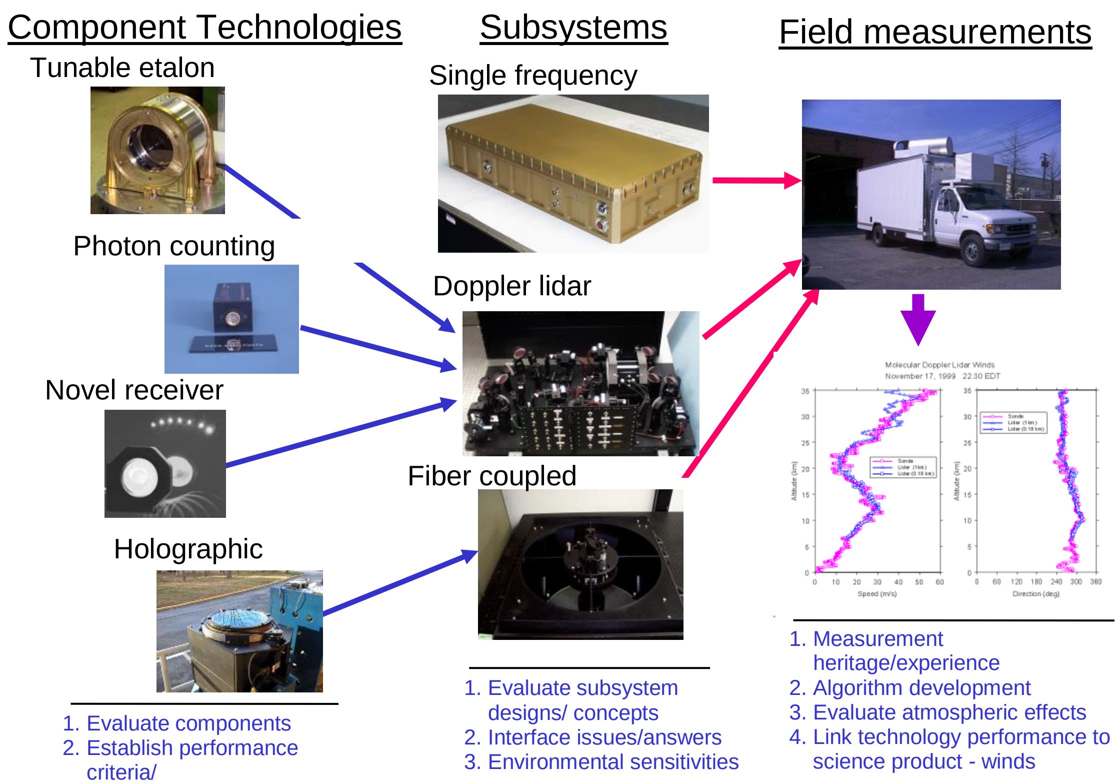
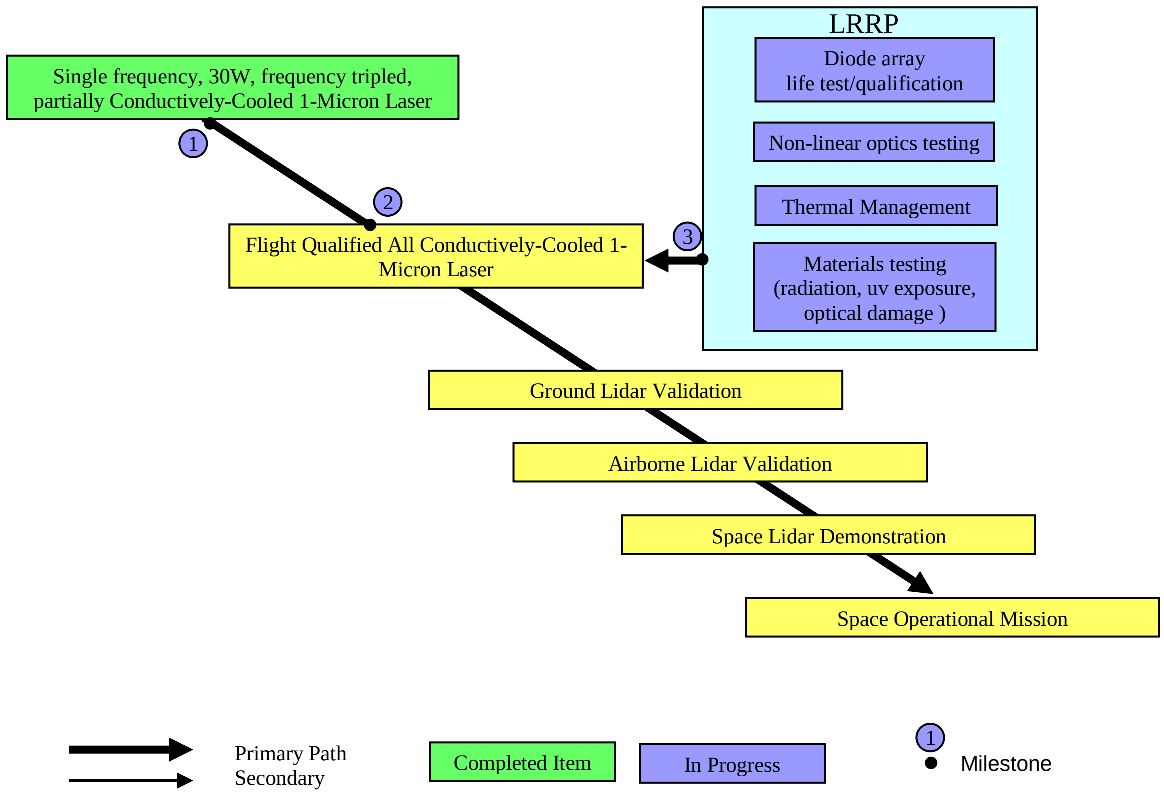


Table 5.2. Direct detection subsystem laser performance objectives

Material	All solid state
Pulse characteristics	1064 nm 1 to 3 J 20 ns pulse length 10-100 Hz < 200 MHz bandwidth @ 355 nm > 35% harmonic conversion to 355 nm
Lifetime	> $5x10^9$ shots
Mass	Low (tbd)
Power	Low (tbd)
Wallplug efficiency	6 to 8%
Cooling	Conductive

Figure 5.2. Laser roadmap – Direct Detection Subsystem



Milestone 1. TRW CAPPSL and Zephyr design study; SBIR Phase II studies (Fibertek, CEO, Litecycles, QPeak)
Milestone 2. GLAS, CALIPSO flight laser programs
Milestone 3. LRRP (NASA's Laser Risk Reduction Program)

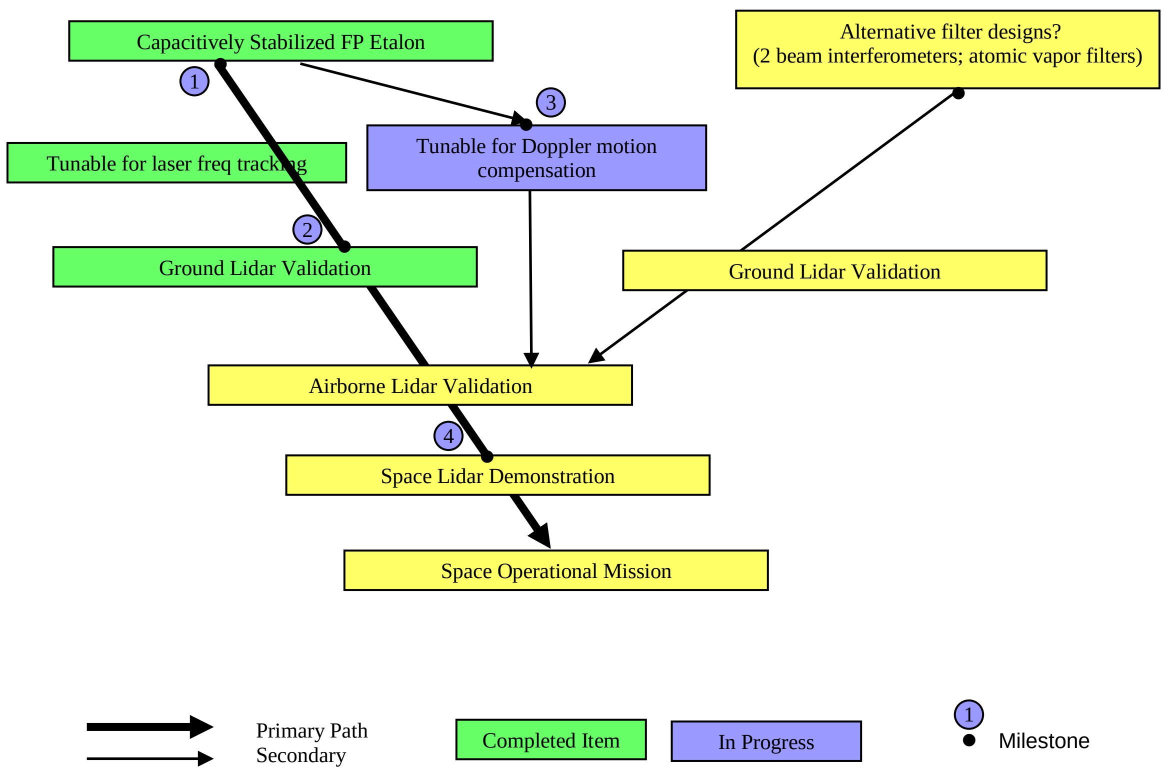
5.3 Direct Detection Subsystem Optical Filters

Optical filter performance objectives for the direct detection subsystem of a hybrid DWL are shown in Table 5.3 and a technology roadmap in Figure 5.3. The approach will use a capacitance stabilized piezoelectrically tunable Fabry-Perot etalon with prefiltering. Other technologies will also be assessed. Double Edge and Fringe Imaging filters are being demonstrated today in ground based lidar wind measurements. Capacitance stabilization is being used in space in UARS. A scalable engineering model was demonstrated in the CALIPSO program by MAC. The product will be tested in ground and airborne testbeds.

Table 5.3. Optical filter performance objectives – Direct Detection Subsystem

Bandwidth	100 to 1500 MHz
Wavelengths	355 nm and 1064 nm
Peak transmission	>70%
Tunability to compensate for spacecraft velocity	1 ms response time Frequency repeatability 6 x 10^{-10} (0.1 m/s)
Mass	Low (tbd)
Power	Low (tbd)
Active alignment stabilization	Support long term unattended operations (tbd)

Figure 5.3. Optical filters roadmap – Direct Detection Subsystem



Milestone 1. Michigan Aerospace/GroundWinds HI; Zephyr Engineering Model
Milestone 2. GroundWinds HI; NASA GLOW
Milestone 3. Zephyr Engineering Model demonstrated 3 ms tuning
Milestone 4. DE; HRDI; MAC CALIPSO prefilter

5.4 Direct Detection Subsystem Telescope/Scanner

The performance objective is to meet telescope, scanning, and pointing requirements as derived from the GTWS data requirements through minimizing telescope mass and developing new scanning and momentum compensation mechanisms. Performance requirements are shared with coherent detection except for round trip boresight requirements. The approach is to explore composite optics, deployables, holographic or diffractive optical elements, and other innovative techniques. A technology roadmap is shown in Figures 5.4a and 5.4b.

Figure 5.4a. Telescope Roadmap - Direct Detection Subsystem

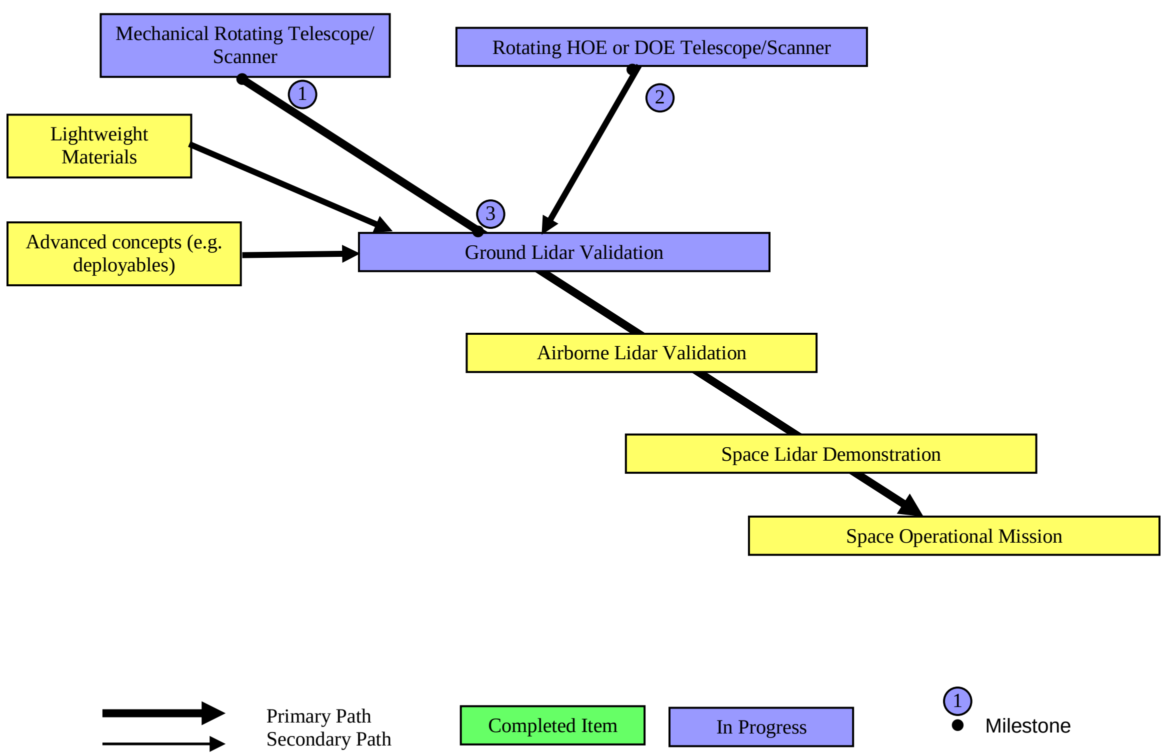
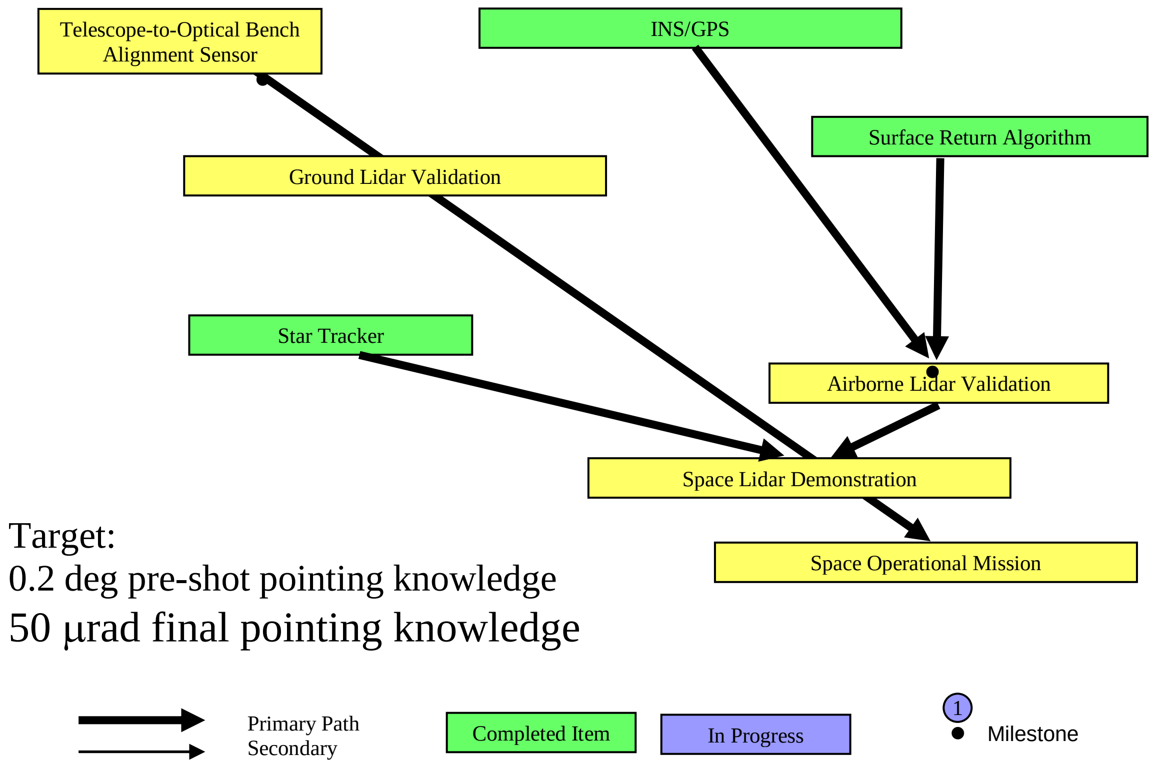


Figure 5.4b. Pointing technology roadmap – Direct Detection Subsystem



Milestones: None completed

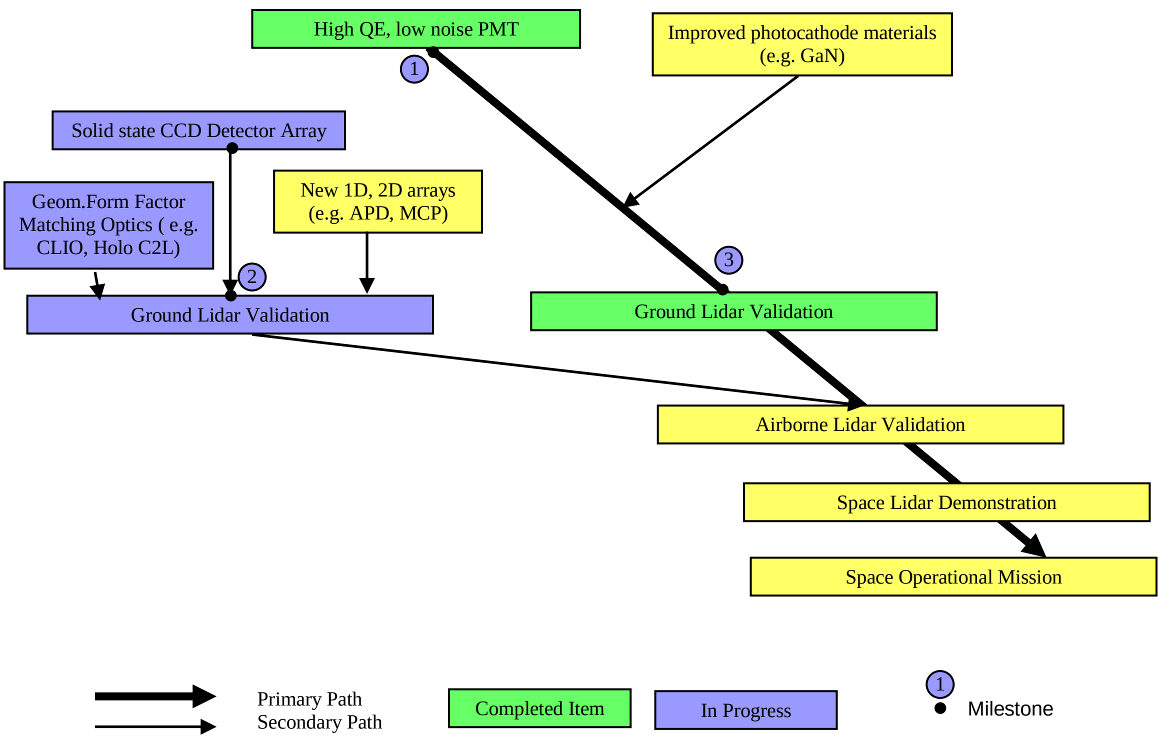
5.5 Direct Detection Subsystem Photon Counting Detectors

The performance objectives are shown in Table 5.5. Technology roadmaps are shown in Figures 5.5-1 and 5.5-2. The approach is to improve photocathode materials at 355 nm and to develop new solid state photomultiplier tube (PMT) photon counting detectors and arrays (e.g. CCD, microchannel plate, APD arrays). Space-qualified single-element PMTs are available with > 30% quantum efficiency photocathodes at 355 nm (Hammamatsu). Perkin Elmer developed an enhanced quantum efficiency Si APD photon counting module for GLAS.

Table 5.5. Photon counting detector performance objectives – Direct Detection Subsystem

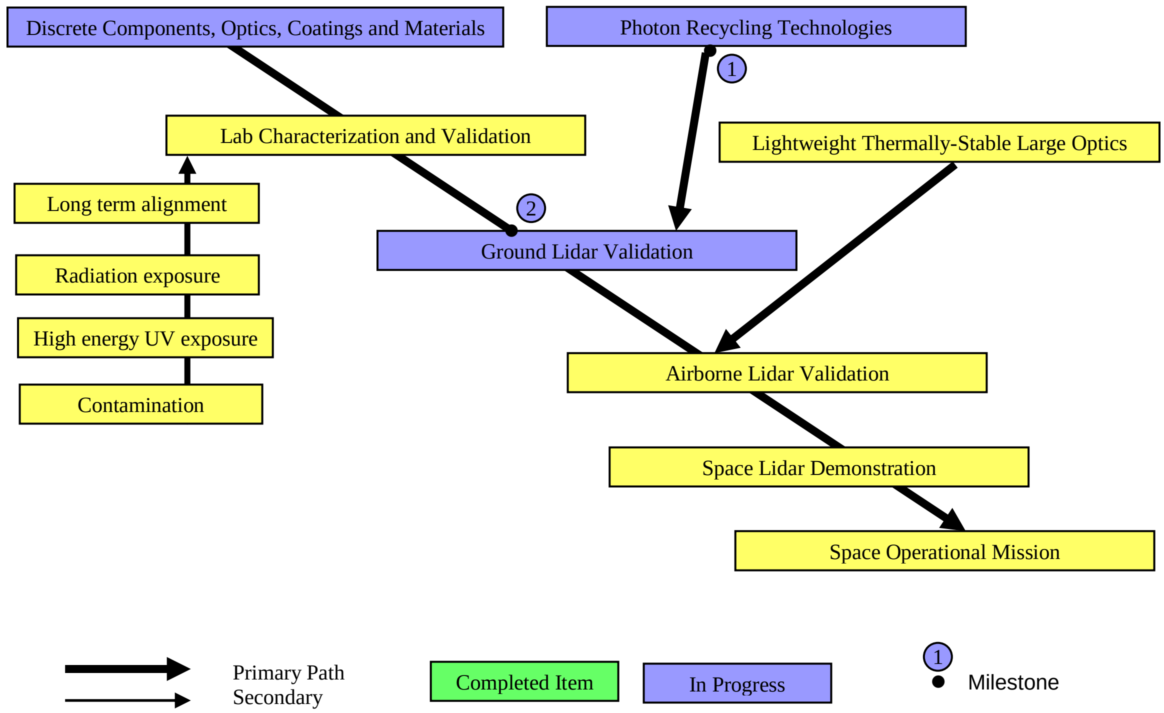
Quantum Efficiency	High (>30%)
Internal Noise (dark current, read noise)	Low (tbd)
Internal Gain	High (tbd)
Dynamic Range	>100 MHz count rate to accommodate clouds, ground return
Cooling	No cryogenic cooling
Stability and life	Compatible with long term operation in space environment

Figure 5.5-1. Photon counting roadmap – Direct Detection Subsystem



Milestone 1: Commercially available, e.g. Hammamatsu
Milestone 2: GroundWinds NH, HI
Milestone 3: NASA GLOW

Figure 5.5-2. Photon efficiency roadmap – Direct Detection Subsystem



Milestone 1: MAC/GroundWinds demonstrated fiber recycler concept

Milestone 2: Discrete component system efficiency measured – NASA GLOW; GroundWinds

6. Roadmap for Coherent DWL Subsystem Elements for Hybrid DWL

This discussion is based on target performance for the coherent subsystem of a hybrid DWL. The activities would be the same for a DWL using only coherent detection, but the performance targets would be much more challenging. Coherent DWL subsystem development will improve:

- Pulsed laser
- Scanner
- Tunable local oscillator laser
- Photon efficiency
- Autoalignment
- Pointing technology

Coherent DWL measures wind profiles by transmitting a laser pulse and measuring the average backscatter Doppler frequency shift within range-gated altitude bins using a coherent (optical heterodyne) receiver. Shot averaging is used to increase signal to noise ratios. Photons are scattered from atmospheric molecules and aerosols, with aerosol backscatter being the stronger.

The coherent DWL reference design is sensitive to pointing angle, requiring 2 microradian pointing accuracy over the round trip time from orbit. In the reference design, a step and stare scanning mechanism rotates the entire telescope, presenting pointing and jitter challenges in spacecraft design.

The key technology challenges (lasers, detectors, telescope, scanner, and momentum compensation) apply to coherent DWL. Technology readiness is low for vital components.

Coherent DWL has an extensive heritage. The MACAWS coherent DWL experiment flew on a NASA DC-8 aircraft in 1996. MACAWS used aircraft turns to simulate a conically scanning DWL and processed vertical wind profiles. Space Readiness Coherent Lidar Experiment (SPARCLE) was a New Millennium Program mission. It was being developed at the NASA Marshall Space Flight Center to test wind measurement from the Space Shuttle. The program was cancelled after completion of the Preliminary Design Review. LaRC scientists have extensive experience derived from SPARCLE, and also from ground-based DWL wind measurements. LaRC operates a mobile DWL.

Performance prediction for a coherent DWL requires assumptions about aerosol and cloud distributions. Velocity error is quite low above a threshold signal to noise ratio.

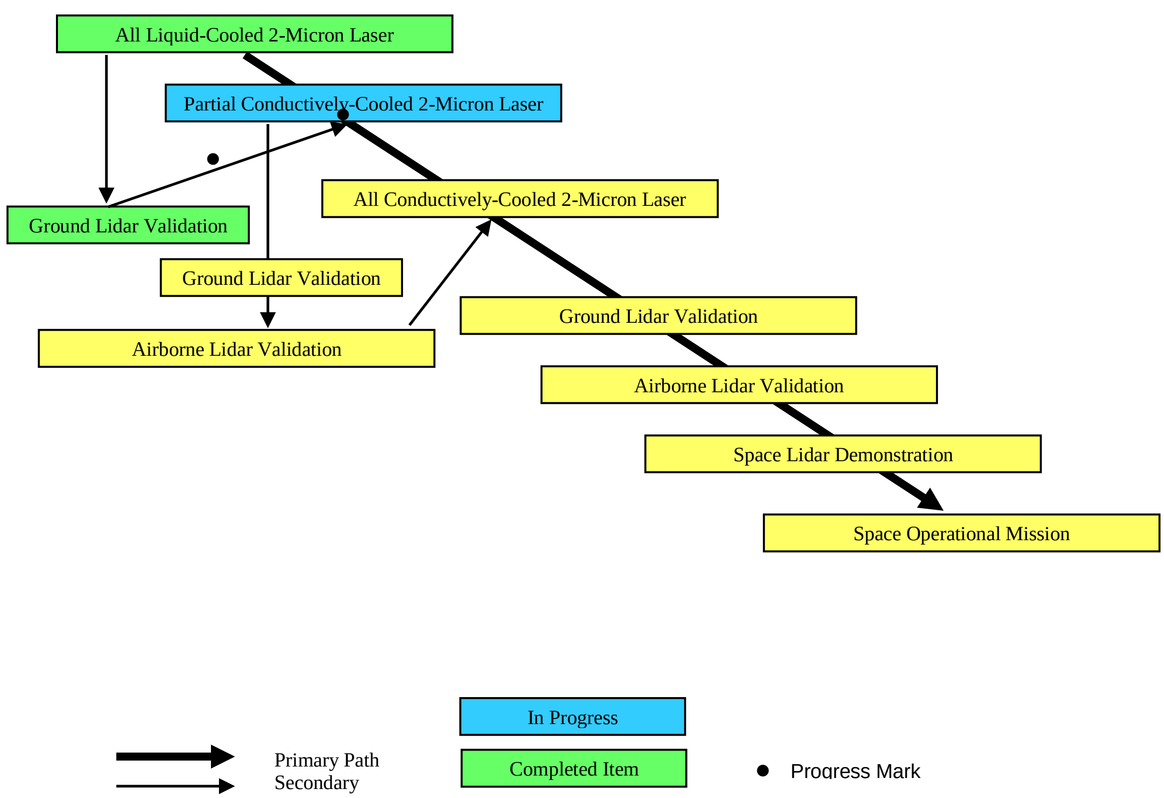
The NASA LRRP, funded by Code Y and Code R in 2002, is working to advance the critical laser technology. An Advanced Lidar Technology Project (ALTP) was formed in 2002 at LaRC. Its charter includes developing lidar technology; assembling a team with end-to-end lidar expertise (theory to hardware to field deployment); collaborating with industry, academia, and government; validating technology to reduce risk of space missions; and transferring technology to industry. Principal investigators are Upendra Singh, Michael Kavaya, and Farzin Amzajerdian. Activities include lidar development using a 2-micron laser source, solid state thulium lasers, 792 nm laser diodes, and optical parametric oscillator wavelength conversion (UV and IR).

Roadmap status shown in the following figures is as of early to mid 2003.

6.1 Coherent Subsystem Pulsed Laser

The lidar pulsed laser target is 0.5 Joules, 12 Hz, conductively cooled, with a lifetime of 5 years. The laser roadmap is shown in Figure 6.1.

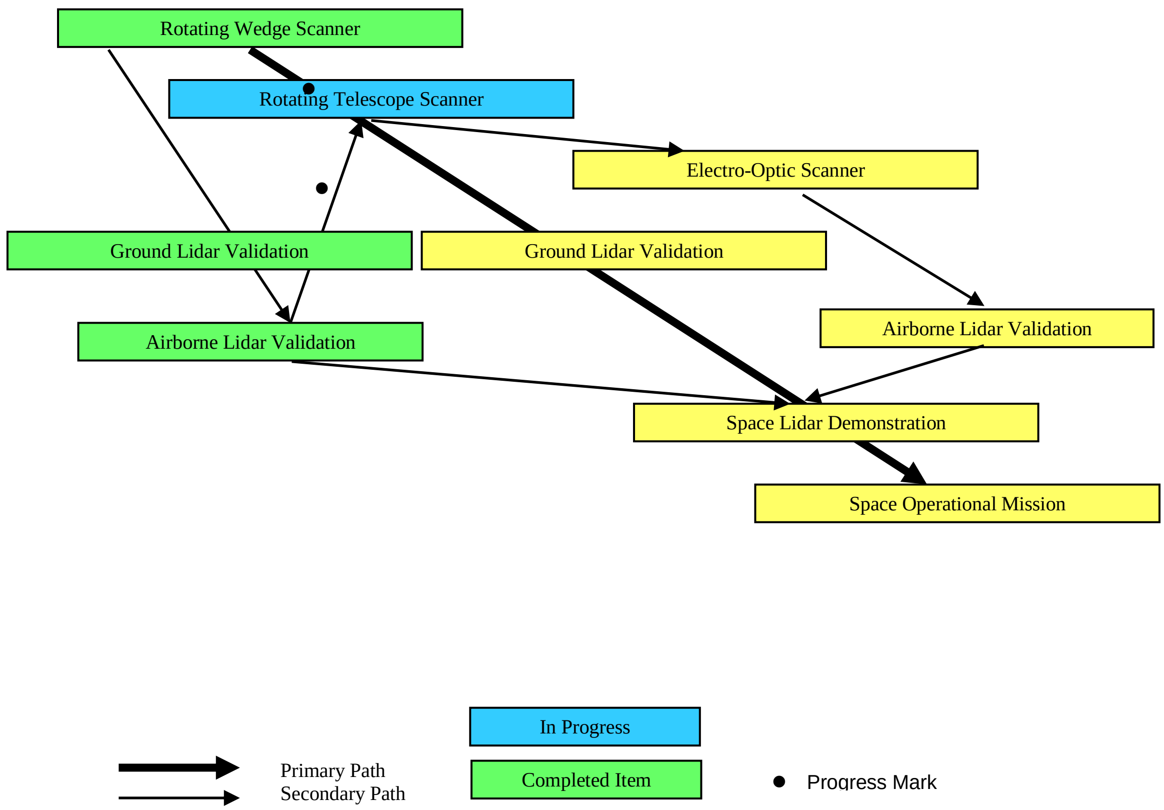
Figure 6.1. Laser roadmap – Coherent Subsystem



6.2 Coherent Subsystem Scanner

The target coherent DWL scanner is a 50 cm telescope with rapid step/stare pointing capable of meeting GTWS requirements. The scanner technology roadmap is shown in Figure 6.2.

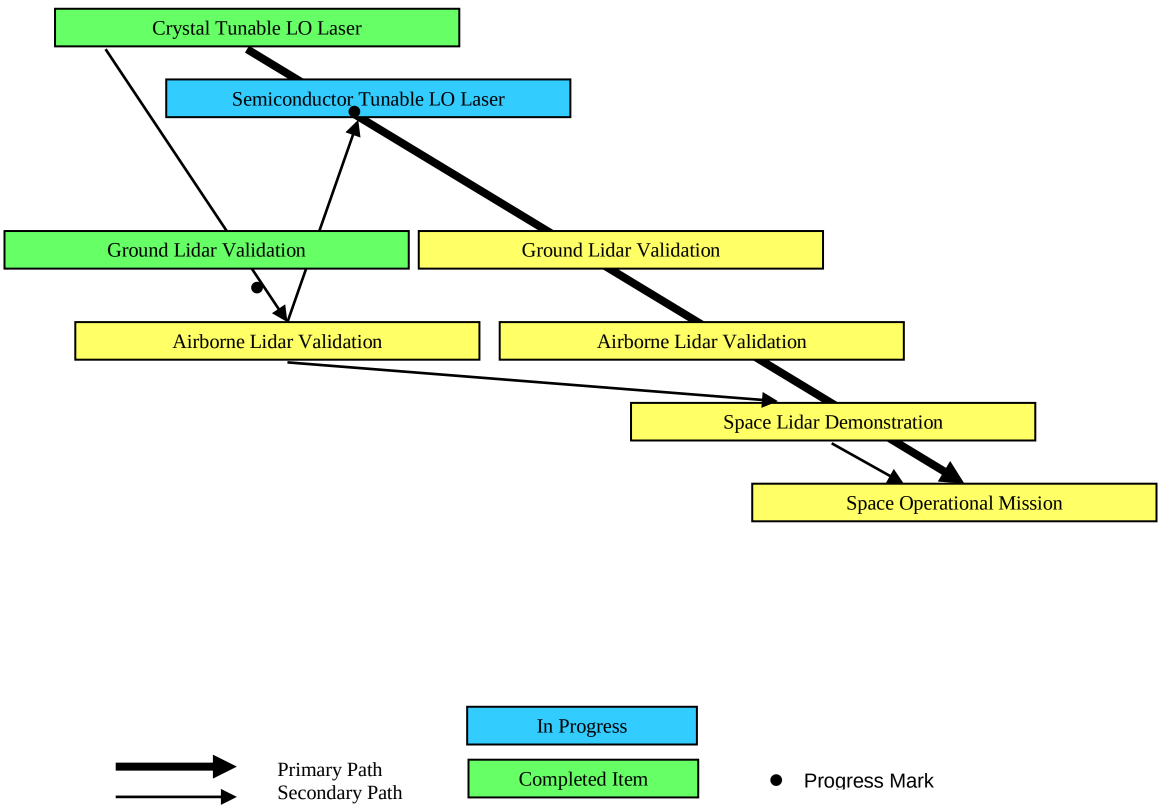
Figure 6.2 Scanner roadmap – Coherent Subsystem



6.3 Coherent Subsystem Tunable Local Oscillator Laser

The target coherent DWL tunable local oscillator provides 25 mW of power with ±6 GHz tuning range and less than 10 kHz/ms drift. The tunable local oscillator laser technology roadmap is shown in Figure 6.3.

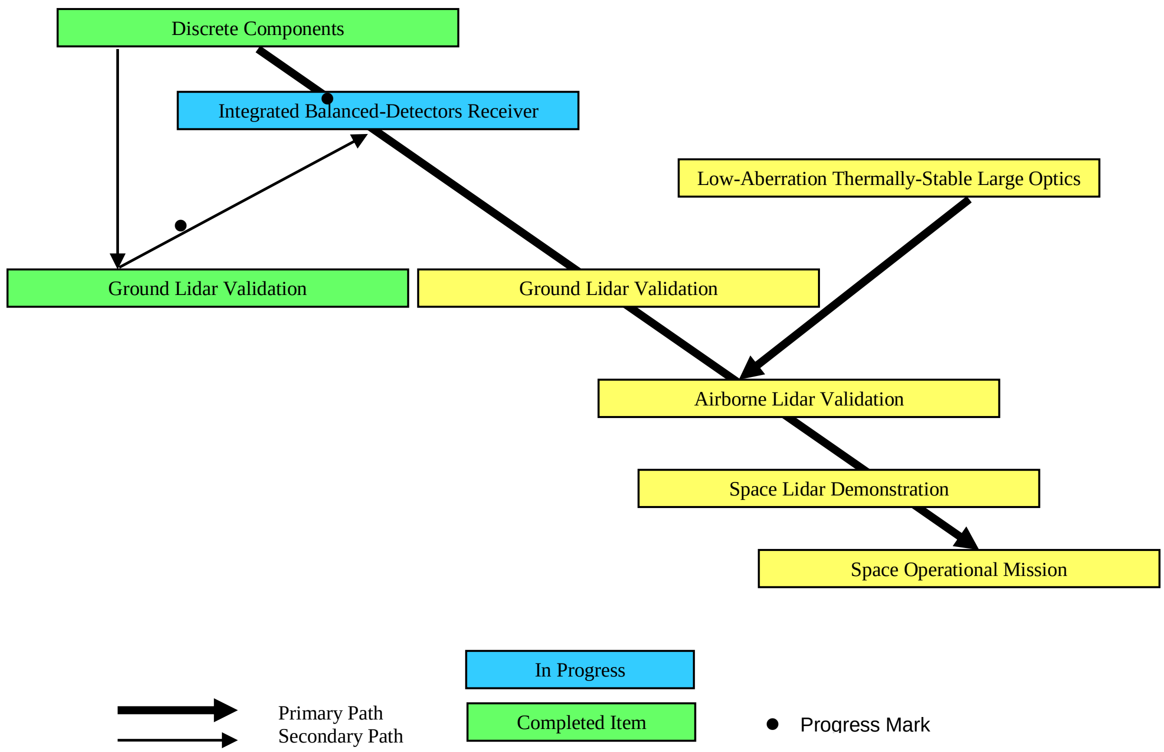
Figure 6.3 Tunable local oscillator laser roadmap – Coherent Subsystem



6.4 Coherent Subsystem Photon Efficiency Technology

The coherent DWL target efficiency is 12% lidar system (photon) efficiency. The technology roadmap is shown in Figure 6.4.

Figure 6.4. Photon efficiency roadmap – Coherent Subsystem



6.5 Coherent Subsystem Autoalignment Technology

Target performance for auto-alignment technology will depend on the instrument design and platform. For the ISAL/IMDC concepts, scaled to a 50 cm diameter telescope for the hybrid system, autoalignment must keep lidar components (before the telescope) aligned within 50 to 100 microradians. Telescope and scanner alignment tolerances reduce in proportion to the beam size, e.g. for a 50X telescope, the beam alignment requirement at the telescope output is 50X smaller (50 microradians/50= 1 microradian). Further, any angular or displacement misalignments of telescope mirrors will degrade beam quality and reduce SNR.

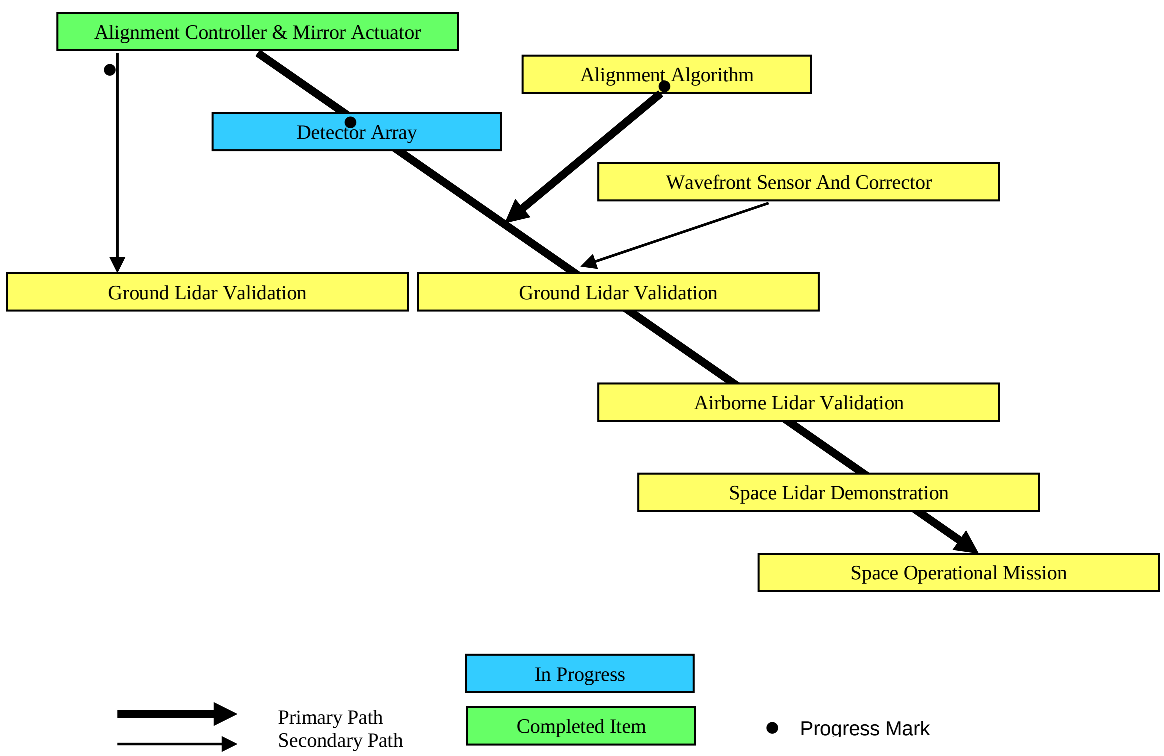
Autoalignment top-level performance requirements can be described by two parameters:

- Angular misalignment (say 50 microradians within the lidar instrument)
- Wavefront quality, which is a function of the telescope alignment

The autoalignment system must keep the telescope wavefront quality to better than 1/15 wave RMS at 2 micron wavelength or 1/5 wave RMS at 632 nm.

The technology roadmap is shown in Figure 6.5.

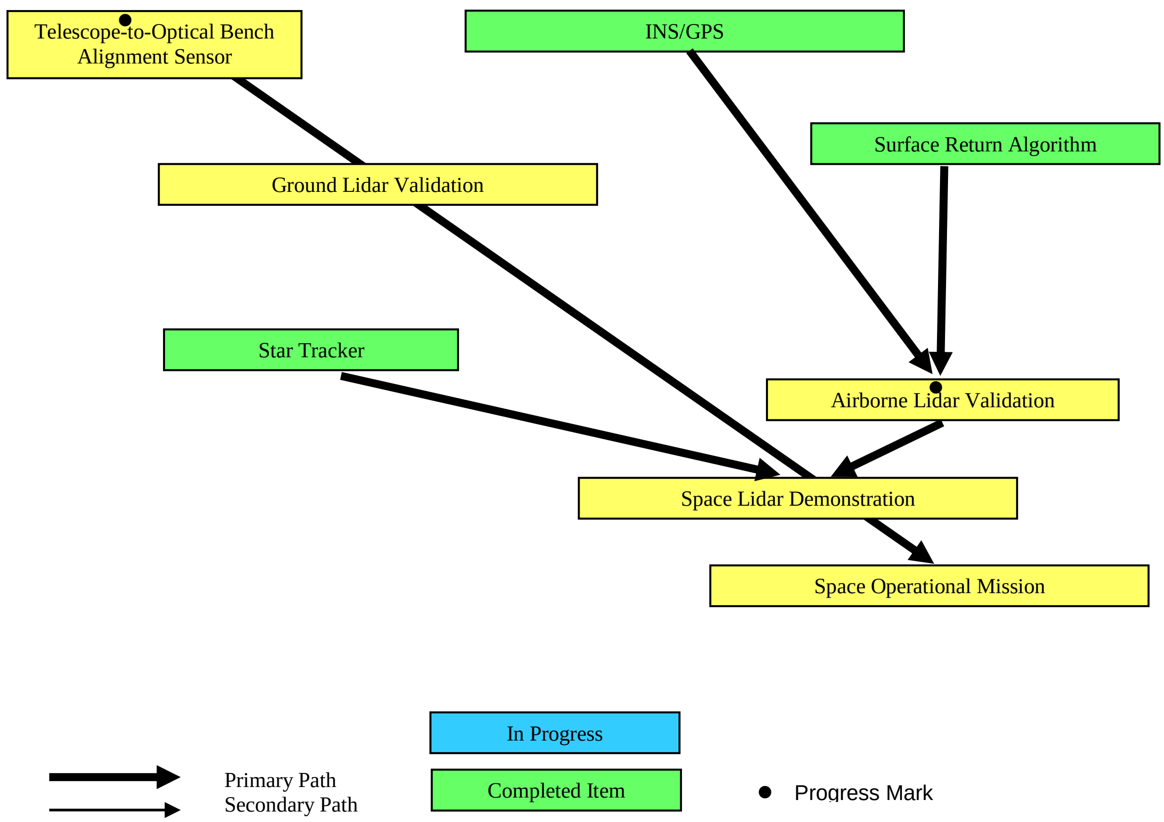
Figure 6.5. Autoalignment roadmap – Coherent Subsystem



6.6 Coherent Subsystem Pointing Technology

The pointing target performance is 0.2 degrees pre-shot pointing knowledge and 50 µrad final pointing knowledge. The technology roadmap is shown in Figure 6.6.

Figure 6.6. Pointing roadmap – Coherent Subsystem



7. Hybrid DWL Roadmap

Hybrid DWL addresses the key technology challenges of lasers, detectors, telescopes and pointing by using coherent and direct lidars for different parts of the atmospheric depth of regard, for regions where they individually perform best. Hybrid DWL may be the optimum solution, reducing cost, time, and risk to achieve operational global wind observations. The hybrid technology roadmap is consistent with the combined roadmaps for direct and coherent, with the addition of developing shared technology, shared scanner, a shared spacecraft, and launch.

Beyond issues already discussed for the coherent and direct detection subsystems, the two must be combined into an operational hybrid system. Studies are recommended to develop hybrid reference designs that integrate and deploy coherent and direct detection subsystems.

8. Summary and Recommendations

Some pre-operational development activities are underway, others can begin at an early date. Near term activities include architecture studies, requirements and benefits trades, technology readiness activities, conceptual design, and planning.

The technology readiness activity contribute to a number of future lidar missions in addition to wind.

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Glossary

ACARS	ARINC (Aeronautical Radio Incorporated) Communications Addressing and Reporting System
ALTP	NASA's Advanced Lidar Technology Program
DOC	Department of Commerce
DOD	Department of Defense
DWL	Doppler Wind Lidar
FAA	Federal Aviation Administration
GLAS	Geoscience Laser Altimeter System mission
GroundWinds	Ground based lidar observatory program, sponsored by NOAA, operated by University of New Hampshire
GroundWinds-HI	GroundWinds project in Hawaii
GroundWinds-NH	GroundWinds project in New Hampshire
GSFC	Goddard Space Flight Center (NASA)
GTWS	Global Tropospheric Wind Sounder
IMDC	Integrated Mission Design Center at GSFC
IPO	NPOESS Integrated Program Office, established to develop, acquire, operate, and maintain NPOESS. IPO organizationally resides within the Department of Commerce (DOC) National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data and Information Service (NESDIS) and is staffed with personnel from the Department of Defense (DOD), DOC, and the National Aeronautics and Space Administration (NASA).
ISAL	Instrument Synthesis and Analysis Laboratory (NASA GSFC)
JPL	Jet Propulsion Laboratory
LaRC	Langley Research Center (NASA)
Lidar	Light Detection and Ranging
LRRP	Laser Risk Reduction Project
MAC	Michigan Aerospace Corporation
MACAWS	Multi-center Airborne Coherent Atmospheric Wind Sensor
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data and Information Service
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Environmental Satellite System
OSSE	Observing System Simulation Experiment
SBIR	Small Business Innovation Research program
SNR	Signal to Noise Ratio
SPARCLE	Space Readiness Coherent Lidar Experiment
SWA	Simpson Weather Associates
TBD	To be determined
TSV	Target Sample Volume
UNH	University of New Hampshire
UV	Ultra violet

VCL	Vegetation Canopy Lidar mission
WOS/H	Wind Observing Satellite/