COMMERCIAL DEVELOPMENT OF AIRBORNE LASER ALTIMETRY

A review of the commercial instrument market and its projected growth.

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ABSTRACT

Preliminary results of a study to estimate the instrument base required to support a competitive laser altimetry sector within the global remote sensing industry are presented. The recent growth of the commercial laser altimetry sector and the current breakdown of the installed instrument base are reviewed. Projections for future growth in the installed base are presented based on the current adoption rate and projected growth curves through 2005. A comparison to the established aerial camera market is used to set a constraint on the upper growth of the instrument base. The projection provides an estimate of the size of the market for commercial instrument sales and consequently a view of the future competitive environment for survey companies offering laser altimetry services. A significant gap is identified between the current installed base and estimates of the required instrument base.

1. INTRODUCTION

Airborne laser altimetry is an emerging technology in the commercial remote sensing industry that is capable of rapidly generating high-density, high-accuracy, digital elevation data. It is an attractive technology for a variety of data end-users in various survey applications since the cost to produce the elevation data, point for point, can be significantly less than other forms of traditional data collection. To a commercial survey company, laser altimetry offers unique technical capabilities, lower field-operation costs and reduced post-processing time and effort compared to traditional survey methods. While laser altimetry has been under investigation since the 1960s, the commercial development of the technology has been driven by the relatively recent availability of rugged, low-cost solutions for each of the core subsystems of the instruments. An increasing awareness of the unique advantages of laser-based survey instruments within the remote sensing community combined with the growing demand for cheap, accurate, timely, digital elevation data by the data end-users is also a contributing factor. Current commercial instrument designs are based on work done over the past twenty years by research groups such as NASA (Blair et. al., 1994; Bufton et. al., 1991; Krabill et. al., 1984;) and the Institute of Photogrammetry at the University of Stuttgart (Ackermann, 1999). Commercial off-the-shelf instruments can now be purchased or leased from several dedicated system manufacturers while various survey companies have designed and built proprietary sensors either alone or in conjunction with organizations in the laser/lidar industry. Reduced barriers to entry, including lower capital investment costs to acquire an instrument, the increasing availability of commercial off-the-shelf systems and the increased acceptance of the technology by the data end-users, are driving a significant expansion of the commercial market. Consequently, the number of survey companies operating instruments on a "for profit" basis has increased dramatically since 1995. To date strategic planning efforts within the commercial sector have focused on identifying the essential functionality of commercial laser altimetry instruments, defining the technology road map for future upgrades and estimating the potential demand for survey services based on the technology. Limited analysis has been published about the potential size of the market for commercial instruments based on the current growth and projected demand for instruments. Such analysis is an important factor for any forward-looking estimate of the impact of airborne laser altimetry on the commercial remote sensing industry, especially if further reductions in the barriers to entry are considered.

This paper presents preliminary results of a study to estimate the instrument base required to support a competitive commercial airborne laser altimetry sector within the global remote sensing community. The paper reviews the current commercial markets, the recent growth of the commercial industry and the current breakdown of the installed instrument base. Projections for future growth in the installed base based on the current adoption curve and a comparison to the established aerial camera market are presented. This projection provides a forward-looking estimate of the size of the market for commercial instrument sales and hence a view of the future competitive environment for survey companies offering laser altimetry services.

DEFINITIONS

For the purposes of this study, the following definitions are used to classify the various airborne laser altimetry systems in operation today:

Commercial: A commercial instrument is defined as any airborne laser altimeter that is used on a "for profit" basis or an off-the-shelf instrument bought from a commercial instrument manufacturer but used for non-profit purposes. Examples of the later include the systems operated by the U.S. Army Corps of Engineers Topographic Engineering Center, the University of Florida and the UK Environment Agency. Commercial instruments are further divided in to two categories; Off-The-Shelf or Proprietary.

Off-The-Shelf (OTS): An off-the-shelf instrument is defined as any complete laser altimetry system that includes all necessary hardware, firmware and post-processing software, and is available from a dedicated commercial instrument manufacturer. These instruments can be purchased by any company or organization wanting to acquire airborne laser altimetry capabilities. Currently the three major suppliers of off-the-shelf instruments are Azimuth Corporation (USA), Optech Inc. (Canada), and TopEye AB (Sweden).

Proprietary: A proprietary instrument is defined as any custom-designed system. The instrument may incorporate commercial off-the-shelf subsystems or components but must essentially be designed, developed and maintained as a unique proprietary system or systems, not available for purchase by a third party. For the purposes of this paper, proprietary instruments are only included if they are used for commercial "for profit" operations. Examples include John E. Chance's FLI-MAP and TerraPoint's ALTMS. Custom-built systems operated by government agencies, research institutes or universities for research applications, for example LVIS, are not considered as commercial instruments.

Only scanning laser altimeters are considered for this study as profiling systems have limited commercial applications and are generally not deployed in "for profit" operations. Other airborne sensors integrating a lidar for direct single-point elevation measurement were also not considered. Bathymetric laser systems such as SHOALS or LADS were also excluded as their design constraints, target applications, commercial markets and competing technologies are considered significantly different as to be outside the terrestrial mapping sector covered in this paper. It should be noted however that bathymetric lidar systems have been used for similar mapping applications as the terrestrial systems to be discussed below and there is growing interest in hybrid hydrographic-terrestrial lidar instruments for coastal beach mapping, especially working in the near-shore surf zone.

2. COMMERCIAL SECTOR

Unlike the research sector, which is primarily driven by scientific goals and objectives, the commercial sector is driven by the need to define and address profitable markets for the data products. In assessing the various market opportunities for laser altimetry, commercial organizations focus on areas that offer a demand for the data products that is large enough to support a profitable business. Ideally, such markets require the data capture and analysis capabilities provided by laser altimetry but not readily available from other survey technologies and are driven by various economic factors to place a significant value on the data products. Potential markets should also have an established client-base with the financial resources to contract for laser altimetry survey services at a reasonable and profitable price. Due to the relatively recent introduction of the technology to the commercial sector, many of these markets are still being defined.

2.1. Commercial Markets

Depending on the survey application, laser altimetry can be viewed as either a complementary or a competitive technology when compared to existing survey methods. For many applications, airborne laser altimetry is currently deployed in conjunction with other more traditional sensors including standard aerial film cameras, digital cameras, hyperspectral scanners or thermal imagery. In general, laser altimetry is best viewed as an addition to the remote sensing toolbox that can add significant value to the data products produced, either independently or in conjunction with other sensor systems. Deploying airborne laser altimetry within a field survey can provide additional value depending on project specific goals and deliverables. Since each individual client has particular needs and specifications that they expect to be met, laser altimetry may not meet these expectations without support from traditional survey methods. However, in certain applications, such as forestry or coastal engineering, laser altimetry offers unique capabilities not achievable with any other technology. A brief review of the main commercial applications is provided below. (Flood, 1999; Flood and Gutelius, 1997; Gutelius, 1998)

DTM Generation: Airborne laser mapping is a rapid, cost-effective source of high-accuracy, high-density elevation data for many traditional topographic mapping applications. The technology allows large area topographic surveys to be completed significantly faster and at a reduced cost compared to traditional survey methods.

Forestry: The use of airborne laser mapping in the forestry industry was one of the first commercial areas investigated. Accurate information on the terrain and topography beneath the tree canopy is extremely important to both the forestry industry and natural resource managers. Accurate information on tree heights and densities is also critical information that is difficult to obtain using conventional techniques. Airborne laser technology, unlike radar or satellite imaging, can simultaneously map the ground beneath the tree canopy as well as the tree heights. Post-processing of the data allows the individual laser returns to be analyzed and classified as vegetation or ground returns allowing DTMs of the bare ground to be generated or accurate representative tree heights to be calculated. Established techniques from the research sector using full waveform analysis of the return laser pulse to investigate details of canopy structure (Blair and Hofton, 1999) are also receiving greater attention as the technology gains acceptance in the commercial sector. Consequently, airborne laser mapping is an extremely effective technique for forestry companies when compared to photogrammetry or extensive ground surveys.

Coastal Engineering: Beach mapping or similar surveys of coastal regions are another area where airborne laser technology offers state-of-the-art type performance with significant advantages over existing survey techniques. Since traditional photogrammetry is difficult to use in areas of limited contrast, such as beaches and coastal zones, an active sensing technique such as laser altimetry offers the ability to complete surveys that would be too costly using other methods. In addition, highly dynamic environments such as coastal zones often require constant updating of baseline survey data. Airborne laser mapping offers a cost-effective method to do this on a routine basis. It is also used for mapping and monitoring of shore belts, dunes, dikes and coastal forests.

Corridor or Right-of-Way Mapping: Airborne laser mapping allows rapid, cost-effective, accurate mapping of linear corridors such as power utility right-of-ways, gas pipelines, or highways. A major commercial market is mapping power line corridors to allow for proper modeling of conductor catenary curves, sag, ground clearance, encroachment and accurate determination of tower locations. For example the use of data acquired through airborne laser surveys can be combined with simultaneous measurements of air and conductor temperature and load currents to establish admissible increases in load-carrying capacity of power lines.

Flood Plain Mapping: Accurate and updated modeling of flood plains is critical both for disaster planning and insurance purposes. Airborne laser mapping offers a cost-effective method of acquiring the topographic data required as input for various flood plain modeling programs. As part of its Map Modernization Plan, the Federal Emergency Management Agency (FEMA) in the U.S. is currently performing an assessment of advanced technologies including laser altimetry for possible use in the preparation of National Flood Insurance Program (NFIP) maps and related products. FEMA has recently released guidelines which present specifications that to be used for the application of laser altimetry systems for gathering the data necessary to create digital elevation models (DEMs), digital terrain maps, and other NFIP products.

Urban Modeling: Accurate digital models of urban environments are required for a variety of applications including telecommunications, microclimate modeling, wireless communications, law enforcement and disaster planning. An active remote sensing system such as a laser offers the ability to accurately map urban environments without some of the disadvantages of other technologies.

Disaster Response and Damage Assessment: Major natural disasters such as hurricanes or earthquakes stress an emergency response organization's abilities to plan and respond. Airborne laser mapping allows timely, accurate survey data to be rapidly incorporated directly into on-going disaster management efforts and allows rapid post-disaster damage assessments. It is particularly useful in areas prone to major topographic changes during natural disasters; areas such as beaches, river estuaries or flood plains.

Wetlands and Other Restricted Access Areas: Many environmentally sensitive areas such as wetlands offer limited ground access and due to vegetation cover are difficult to assess with traditional photogrammetry. Airborne laser altimetry offers the capability to survey these areas. The technology can also be deployed to survey toxic waste sites or industrial waste dumps.

In addition to the commercial applications discussed above, various efforts are under way to investigate other application areas where airborne laser altimetry may offer significant advantages.

2.2. Commercial Instruments

The current generation of commercial airborne laser altimetry instruments use a combination of three mature technologies; rugged compact laser rangefinders (LIDAR), highly accurate inertial reference systems (INS) and the global positioning satellite system (GPS). By integrating these subsystems in to a single instrument, it is possible to rapidly produce accurate digital topographic maps of the terrain beneath the flight path of the aircraft. Similar to aerial cameras, the instruments can be installed in small single or twin-engine planes or helicopters. For commercial surveys, the absolute accuracy of the laser-derived elevation data is generally quoted as 15 cm; relative accuracy less than 5 cm. Absolute accuracy of the planimetric data is dependent on operating parameters such as flight altitude but is usually quoted at decimeter to meter levels. Accuracy tends to degrade with terrain slope, roughness and vegetation cover resulting in generally lower accuracy than quoted assuming a smooth, flat surface. To date there have been limited independent studies published that verify the accuracy claims of commercial operators (Huising and Gomes Pereira, 1998; Kraus and Pfeifer, 1998). However, there is a growing body of work by independent agencies such as the USGS, FEMA and similar agencies in Europe that indicates these levels of absolute accuracy are achievable, but only if commercial operators are rigorous in their attention to calibration of their instruments and implement appropriate QA/QC procedures on the laser data.

With current commercial instruments, elevation data is generated at 1000s of points per second, resulting in elevation point densities far greater than traditional ground survey methods. One hour of data collection can result in over 10,000,000 individually geo-referenced elevation points. With these high sampling rates, it is possible to rapidly complete a large topographic survey and still generate DTMs with a grid spacing of 1 m or less. With current commercial systems it is possible to survey one thousand square kilometers in less than 12 hours and have the geo-referenced DTM data available within 24 hours of the flight. A 500-kilometer linear corridor, such as a section of coastline or a transmission line corridor can be surveyed in the course of a morning, with results available the next day. Airborne laser mapping instruments are active sensor systems, as opposed to passive imagery such as cameras. Consequently, they offer advantages and unique commercial capabilities when compared to traditional photogrammetry. For example, airborne laser mapping systems can penetrate forest canopy to map the floor beneath the treetops, accurately map the sag of electrical power lines between transmission towers or provide accurate elevation data in areas of low relief and contrast such as beaches. Airborne laser mapping is a non-intrusive method of obtaining detailed and accurate elevation information. It can be used in situations where ground access is limited, prohibited or risky to field crews. Since the instruments are less sensitive to environmental conditions such as weather, sun angle or leaf on/off conditions, the envelope for survey operations is increased. In addition, airborne laser mapping can be conducted at night with no degradation in performance.

Commercial airborne laser instruments are now available from several instrument manufacturers while various survey companies have designed and built proprietary sensors. A number of service providers are operating these instruments around the world, either for dedicated survey needs or for hire on a project basis. (See www.airbornelasermapping.com for a complete directory.) Some organizations are starting to survey areas on speculation and then offering the laser-generated data sets for resale similar to the satellite data market. While the basic principles and design constraints of airborne laser altimetry are well-known (Wehr and Lohr, 1999; Baltsavias, 1999a), there is still significant variation in design from instrument to instrument, especially across custom-designed sensors. The general characteristics and specifications of the current generation of commercial systems are summarized in Table 1.

Specification	Typical Value
Wavelength [a]	1.064 μm
Pulse Repetition Rate	5 - 15 kHz (25 kHz max)
Pulse Energy	100s μJ
Pulse Width	10 ns
Beam Divergence	0.25 - 2 mrad
Scan Angle (full angle)	40° (75° max)
Scan Rate	25 - 40 Hz
Scan Pattern	Zig-zag, parallel, elliptical, sinusoidal
GPS Frequency	1 - 2
INS Frequency	50 (200 max)
Operating Altitude	500 - 1000 m (6000 m max)
Footprint	0.25 - 2 m (from 1000 m)
Multiple Elevation Capture	2 - 5
Grid Spacing	0.5 - 2 m
Accuracy (elevation)	15+ cm
Accuracy (planimetric)	10-100 cm
Post-Processing Software [b]	Proprietary
Price (standard)	$0,850k - $1,000k
Price (custom)	$1,000k - $2,000k
Delivery (standard)	20 - 26 weeks

[a] generally diode-pumped Nd:YAG, Nd:YLF and Nd:YVO_4 although there are some systems operating at 1.5 μm

[b] refers to geo-referencing of laser slant ranges to an established reference frame, normally WGS84

Table 1. Characteristics of Typical Commercial Systems

Intensity capture of the return pulse, either through waveform digitization or return pulse peak capture, is becoming increasingly common on commercial instruments and will become a standard feature within the next 12 - 18 months. Additional data analysis capabilities such as automatic feature extraction are also being developed. Improvements to the sensor designs, added capabilities such as fully integrated digital cameras and increased reliability/decreased operating costs are all under consideration by the commercial sector.

3. INSTALLED INSTRUMENT BASE

It is instructive to look at the recent growth of the installed instrument base to help predict future trends in the commercial deployment of laser altimetry.

3.1. Adoption Curve

While research and scientific laser altimetry systems have been deployed for many years by government and academic institutions, it is only recently that there has been a large growth in the number of commercial organizations operating such instruments on a "for profit" basis. As a new technology, the adoption curve - the rate at which airborne laser altimetry is being deployed and accepted as a standard operational tool in the commercial sector - is an important indicator to review. It provides insight into trends in the implied demand for services based on the technology. It can also be used as the basis for estimating the projected instrument base and the resulting competitive environment for survey companies using airborne laser altimetry. A review of the commercial sector since 1995 shows the number of installed instruments has been increasing rapidly over the past five years. A breakdown of the annual rate at which commercial firms have taken delivery of instruments, either OTS or proprietary designs, is presented in Table 2. The numbers clearly demonstrate significant year-over-year growth in the installed instrument base.

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Year	#instruments	%base
1995	3	8%
1996	6	16%
1997	2	5%
1998	9	24%
1999	18	47%
Total by Jan 1st 2000	38	100%

Table 2. Installed Instrument Base by Year

Since 1995, the number of laser altimeters deployed and operating in the commercial sector has increased from 3 to 38, with a significant percentage of this growth occurring since 1997. The 38 sensors listed in Table 2 represent a capital investment of ~$30M - $35M based on current pricing levels, allowing for reduced costs in proprietary instruments compared to OTS systems. Significantly, 47% of the systems currently operating in the field were delivered in 1999 with 70% of the installed instrument base having been deployed since January

1998. Table 3 expands on the historical data by providing a projection for deliveries in 2000 based on orders confirmed by the manufacturers for the first six months of the year and projected orders in the second six months.

Year	#instruments	%base
Jan 1st 2000	38	66%
2000 (Jan - June)	10	17%
2000 (July - December)	~10	17%
Total by Jan 1st 2001	~58	100%

Table 3. Projected Growth In Installed Instrument Base By 2001.

There is no evidence that the adoption of the technology by commercial survey companies is going to slow in the next 12 - 18 months. Unlike 1997, when a significant increase in installed systems the year earlier was followed by a drop in orders, 2000 looks set to follow-up on 1999's level of deliveries with continued gains. With 10 systems already confirmed for delivery within the first six months, the total order book for the first half of 2000 is ahead of the year-earlier pace. Initial projections indicate that annual deliveries will remain at or exceed the 1999 level.

It is also useful to look at the breakdown of installed instruments by manufacturer, with proprietary systems as a separate category. Table 4 presents this breakdown as of January 1, 2000.

Manufacturer	#instruments	%base
Azimuth	2	5%
Optech	17	45%
TopEye	7	18%
Proprietary [a]	12	32%
Total	38	100%

[a] Includes 3 instruments that are based on a proprietary design of Azimuth's OTS instrument.

Table 4. Installed Instrument Base by Manufacturer

Since 1995, the commercial off-the-shelf manufacturers have captured 68% of the instrument market. Optech has established itself as the market leader with 65% of the OTS market. If the proprietary sensors that are based either on Azimuth subsystems or proprietary designs of their standard sensor are included as OTS systems instead, then the commercial instrument manufacturers have 76% of the installed base. The subtotal reported in Table 4 for proprietary instruments includes a number of legacy instruments that were already built or in development prior to the widespread availability of commercial off-the-shelf systems. It is not clear if the organizations operating these proprietary sensors would replace their systems with OTS instruments or continue their own proprietary development if they need to expand their instrument base. Since January 1998, only 23% (6 of 26) of systems delivered to the field have been proprietary builds. Further evidence of a shift away from custom-built designs can be seen in the fact several owners of previously proprietary designs (Nortech, TerraPoint, TopoSys) have recently started to formally or informally offer their customized systems for sale or lease. This change in business strategy for companies previously focused exclusively on providing survey services through proprietary technology can be attributed in part to the successful emergence of dedicated instrument manufacturers. It is becoming harder for survey companies to leverage the capital investment required to develop a proprietary instrument into a corresponding increase in their share of the survey market. Access to OTS instruments with similar, or in some cases enhanced, functionality is readily available to their competition, reducing the competitive advantage for survey companies who design and build their own proprietary instruments. A proprietary development program also requires a survey organization to develop skills which are not synchronized with their survey business, while on-going support and maintenance for proprietary systems can divert staff and resources away from the core business. It can be anticipated that as more OTS instruments are deployed, there will be a further reduction in the percentage of custom-built systems operating in the market, although the actual number of proprietary instruments should continue to increase slightly. The fact there is still on-going development and deployment of proprietary systems with essentially the same functionality as OTS instruments is evidence that the capital costs of OTS instruments are still high enough to act as a barrier to entry for many survey companies. The capital investment to acquire a commercial OTS sensor still makes even the relatively large development costs of a proprietary sensor attractive to some companies. From this, it can be concluded that there must be some price-point flexibility on OTS instruments if the custom market is to be fully co-opted by the dedicated instrument manufacturers. Regardless of any future price reductions, custom-built systems will remain attractive for those organizations that can leverage existing laser/lidar expertise during their design process or for those organizations that require advanced functionality not yet offered by OTS systems.

The geographic distribution of currently installed instruments is presented in Table 5. The distribution is heavily weighted towards North America and Europe. However, it should be noted that many of the current commercial operators have international operations, through either subsidiaries or strategic partners. Consequently, airborne laser surveys are being undertaken in most regions of the globe. In can be speculated that part of the continued growth in the installed instrument base will address current inefficiencies in delivering laser altimetry services to a global market without a regionally balanced base of sensors. Based on the breakdown of booked orders, North America and Europe will continue to experience the largest growth in available instrument base over the next 12-18 months. However, several of the instruments in the queue are likely intended to address international operations of these firms and may be based outside Europe or North America.

Region	#instruments	%base
North America [a]	16	42%
Europe [b]	14	37%
Asia/Pacific [c]	6	16%
Africa	2	5%
Total	38	100%

[a] U.S.A. and Canada

[b] includes Russia

[c] includes Australia, New Zealand, Japan , Korea and China

Table 5. Installed Instrument Base By Geographic Region

It is important to distinguish between the demand for instruments based on the adoption rate for the technology, the actual production capacity and the actual booked sales of OTS instruments. Production capacity in this context is taken to be the sum total of all sensors that could be produced by OTS and proprietary instrument manufacturers given their current levels of staffing, capital infrastructure investment and related resources. The total existing production capacity is difficult to determine. Manufacturers are understandably reluctant to discuss details of their in-house capacity, while proprietary system owners are not willing to reveal their internal growth strategies. In addition, the potential for new entrants on the instrument side of the business can not be discounted since the majority of the engineering challenges and technical issues related to airborne laser altimetry have already been reduced to practice. The decision to enter the instrument side of the industry is essentially a business decision, not a technical challenge. The emergence of another instrument supplier would obviously increase the production capacity of OTS systems. The impact of the OTS manufacturers approach to the market also needs to be considered in estimating the production capacity as their strategy will play an important role in determining increases in the installed instrument base. Given the limited competition that currently exists on the OTS instrument side of the industry, it may not be in the manufacturers' best interest to ramp-up production to meet immediate demand, but rather to delay orders and deliveries to increase their backlog. There is limited financial risk for the manufacturers in such an approach since currently there are few alternatives for companies wanting to obtain laser altimetry capabilities but not in a position to fund a proprietary development program. Secondary evidence of this strategy can be seen in the fact that the overall sales effort of the OTS manufacturers across the entire industry is probably less than 15 full-time staff. Such a limited effort compared to the potential economic value of the instrument market probably acts to distort the sales of OTS instruments relative to demand. However, from extended delivery times for OTS instruments, order backlogs and anecdotal evidence, it can be estimated that the current production capacity of the industry is nearly saturated and it will be extremely challenging for the manufacturers to deliver 20 instruments to field in 2000, although actual demand may exceed this level.

3.2. Projected Growth 2000 - 2005

While it is difficult to analyze all the variables that will determine the increase in the installed instrument base over the next five years, it is instructive to project forward based on the average percentage growth in the instrument base from 1998-2000. The average annual increase in the instrument base from 1998-2000, including 10 firm deliveries by June 2000, was ~25%. If only the two year period 1999-2000 is considered, the average increase is ~35%. Table 6 presents a forward projection for the installed instrument base based on these growth rates.

Year	25% [a]		35% [b]	
	Year	Total	Year	Total
1998	9	29	9	29
1999	18	38	18	38
2000	20	58	20	58
2001	15	73	20	78
2002	18	91	27	105
2003	23	114	37	142
2004	29	143	50	192
2005	36	179	67	259

[a] 3 year average, 1998-2000

[b] 2 year average, 1999-2000

Table 6. Projected Installed Instrument Base

A recent strategic market report on the world market for remote sensing data (World Remote Sensing Data and GIS Software Markets, Frost and Sullivan, Consulting Report, 1999) indicates a 9.1% compound annual growth rate through 2005 for aerial imaging and data collection. The survey and mapping industry is itself experiencing significant growth due to the impact of GPS technology and the growth in GIS markets, both of which are billion dollar segments of the global economy. It can be assumed that a minimum annual growth of 10% in the installed base of laser altimetry instruments will be required just to address the growth in the downstream segments of the value chain. However, it is also reasonable to assume that the growth in the installed instrument base will eventually plateau as the adoption of the technology reaches saturation. To account for this, it is important to establish a limit on the projected increase. For the purposes of this paper, a comparison to the installed base of aerial cameras is used to constrain the growth curves.

3.3. Comparison to Installed Base of Aerial Cameras

While the adoption rate for airborne laser altimetry can be estimated based on the recent growth and breakdown of installed instruments, projections for the future growth of the installed base are more subjective and open to interpretation. In estimating the installed instrument base that may eventually be justified by demand for laser altimetry sensors, it is useful to make a comparison to a comparable base of instruments. The aerial camera market is an established sector of the remote sensing industry that offers one possible reference frame for estimating the final base of laser sensors. Aerial film cameras are a very mature technology that has been available as a commercial product for nearly 80 years. Industry estimates of the total number of aerial cameras built since 1920 for peaceful commercial purposes are ~ 7,000 with a current worldwide base of ~2000 (Fricker, 1999). Annual deliveries of new cameras are estimated at 25-35 each year. (Walker, 1999). There are many operational similarities that support this comparison between aerial photogrammetry firms and survey companies offering airborne laser services. Historically, many of the early adopters of commercial laser altimetry were, and continue to be, aerial survey companies looking to add elevation capture to their imaging services. The operational requirements for air photo and laser surveys - access to survey aircraft, trained and experienced aerial survey crews and ground crews, support infrastructure, business focus and skill sets are very comparable.

To date the barriers to entry for most commercial air survey firms have been the high capital costs of the laser sensors and limited experience and exposure to laser technology. If the barriers to entry for deploying laser altimetry within a survey business were completely removed or significantly reduced, it can be argued that 100% of aerial film camera operators would incorporate laser altimetry in to their operations. The addition of simultaneous elevation data capture to their normal imaging operations would significantly increase the value of their data end products in addition to opening new niche markets for their services. However, for the purposes of this paper, a more conservative estimate of 10% will be used to estimate the percentage of the aerial camera owners that may eventually acquire laser altimetry instruments. The 10% estimate is assumed to be conservative enough to allow for continued barriers to entry slowing adoption of the technology as well as for the potential introduction of competing technology that may reduce the operational advantages of laser altimetry. A 10% overlap between the aerial camera market and laser altimetry implies a total instrument base of ~200 sensor worldwide. This is significantly more than the currently installed base of ~40 instruments, even projecting through 2000 to an installed base of 60. A deficit of ~160 instruments represents a significant challenge to the industry given the estimated production capacity of 20 deliveries per year. Unless there is a significant increase in this capacity, it will take the commercial instrument manufacturers 7+ years to reach this level of an installed instrument base. This becomes a concern considering the dynamic nature of laser-based technology, which implies a more rapid obsolescence than in the mature camera market.

3.4. Review of Assumptions

It is important to review the assumptions made in projecting the total installed instrument base to identify possible biases and areas for further study.

Installed Instrument Base: The information used to determine the installed base of laser altimetry sensors, the year-over-year growth, the booked and projected orders for 2000 and the geographical distribution of instruments, was provided by various sources and hence is open to some interpretation and bias. In general, the total installed base does agree with a recently published review of airborne laser scanning systems that included bathymetric lidar systems. (Baltsavias, 1999b). Further review of the database complied for this study over the next 12 months will be useful to help revise these estimates. For reference, a detailed industry directory is maintained by the author at www.airbornelasermapping.com and updated versions of the tables presented above will be available throughout 2000. While there is some degree of uncertainty in the absolute numbers presented, there is general agreement from most sources that the current base of instruments is 35 - 40 with an additional 20+ instruments likely to be in the field by mid 2001.

Size of Aerial Camera Market: The data on the size and growth of the aerial film camera market are anecdotal best estimates. Variations of ±10% can easily be expected. More detailed research in to this market would help to refine these numbers and provide a better basis for the resulting estimates of laser altimetry instruments that may eventually be installed. In addition, regional breakdowns of aerial camera distributions would help to allow for regional projections of laser altimetry. A more comprehensive review of aerial survey company size and organizational resources would be instructive to help better define barriers and price points that may need to be addressed if this client-base for laser altimetry sensors is to be captured.

10% Penetration of Market: This critical figure is an educated assumption (i.e. a "guess") based on a conservative approach to estimating the total market for laser altimetry. A more detailed survey of aerial survey companies along with greater education of this community about the benefits of laser altimetry would help to better define the percentage of this client-base that may be targeted as primary adopters of laser altimetry. Interactions between price points and potential demand could also be investigated. It should also be noted that an estimate based on the established aerial camera market ignores any new entrants to the field who may create additional demand for instruments.

4. CONCLUSIONS

The development of a competitive commercial airborne laser altimetry sector within the remote sensing community will be dependent in part upon the availability of a mature, reliable instrument base. Maturing the technology and increasing its acceptance by the end-user community requires both a technology road map and effective forward planning on the part of the stakeholders in instrument design and development. A review of the commercial sector since 1995 shows a growing increase in the number of instruments installed worldwide with continued growth projected for at least the next 12 - 18 months. It is estimated that the currently installed base of ~40 systems will expand to ~60 by the end of 2000. The annual growth rate for the instrument base has been between 25% - 35% over the last three years with an increase in the percentage of commercial off-the-shelf instruments compared to proprietary systems. A preliminary estimate of the number of laser altimetry instruments that may eventually be installed worldwide has been made based on the aerial camera market. It is suggested that ~200 laser altimetry sensor may be required to fulfil the demand. At current growth rates, this base will not be fully installed until 2005.

Such analysis is an important factor for any forward-looking estimate of the impact of airborne laser altimetry on the commercial remote sensing industry. It provides a view of what the competitive sector will look like for survey companies offering laser altimetry services, especially if further reductions in the barriers to entry are considered. It can also provide a basis for future production capacity planning.

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6. REFERENCES

Ackermann, F., 1999. Airborne laser scanning - present status and future expectations. ISPRS Journal of Photogrammetry and Remote Sensing, 54(2/3), 64-67.

Baltsavias, E.P., 1999a. Airborne laser scanning: basic relations and formulas. ISPRS Journal of Photogrammetry and Remote Sensing, 54(2/3), 199-214.

Baltsavias, E.P., 1999b. Airborne laser scanning: existing systems and firms and other resources. ISPRS Journal of Photogrammetry and Remote Sensing, 54(2/3), 164-198.

Blair, J.B., Hofton, M.A., 1999. Modeling laser altimeter return waveforms over complex vegetation using high-resolution elevation data. Geophysical Research Letters, 26(16), pp. 2509-2512

Blair, J.B., Coyle, D.B., Bufton, J.L., Harding, D.J., 1994. Optimization of an airborne laser altimeter for remote sensing of vegetation and tree canopies. Porc. Int. Geosci. Remote Sens. Symp. II, pp. 938-941.

Bufton, J.L., Garvin, J.B., Cavanaugh, J.F., Ramos-Izquierdo, L., Clem, T.D., Krabill, 1991. Airborne lidar for profiling of surface topography. Opt. Eng. 30, 72-78.

Flood, M., 1999. Review of airborne laser technology. EARSel Newsletter, June 1999, pp. 20-23

Flood, M., Gutelius, B., 1997. Commercial Implications of Topographic Terrain Mapping Using Scanning Airborne Laser Radar. Photogrammetric Engineering and Remote Sensing, 63(4), pp. 327-329 and 363-366.

Fricker, P., 1999. Product Manager, LH-Systems. Personal correspondence.

Gutelius, B., 1998. Engineering applications of airborne scanning lasers; reports from the field. Photogrammetric Engineering and Remote Sensing, 64(4), pp. 246-253.

Huising, E.J., Gomes Pereira, L.M., 1998. Errors and accuracy estimates of laser data acquired by various laser scanning systems for topographic applications. ISPRS J. Photogramm. Remote sensing 53(5), pp. 245-261.

Krabill, W.B., Collins, J.G., Link, L.E., Swift, R.N., Butler, M.L., 1984. Airborne laser topographic mapping results. Photogrammetric Engineering and Remote Sensing, 50(6), pp. 685-694.

Kraus, K., Pfeifer, N., 1998. Determination of terrain models in wooded areas with airborne laser scanner data. ISPRS J. Photogramm. Remote Sensing 53(4), pp. 193-203.

Walker, S., 1999. Director of Marketing, LH-Systems. Personal correspondence.

Wehr, A., Lohr, U., 1999. Airborne laser scanning - an introduction and overview. ISPRS Journal of Photogrammetry and Remote Sensing, 54(2/3), 68-82.