The challenge of active optical sensing from extreme orbits

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ABSTRACT

A review of the history and current state of atmospheric sensing lidar from Earth orbit was conducted and it was found that space based earth remote sensing is still in its infancy with only one limited success extended duration autonomous mission to date. An analysis of the basic requirements for some candidate geo-synchronous lidar concepts was completed and it was concluded that significant basic work is required in all areas of lidar development.

Keywords: lidar, laser radar, laser remote sensing, geosynchronous orbit

1. INTRODUCTION

A geo-stationary orbit is attractive from a sensing perspective as unlike a lower altitude orbit it offers the capability to stare and dwell or revisit a target at an interval dictated by a science measurement. This contrast with a lower orbit where the satellite orbital velocity as it moves over the Earth's surface dictates the time that a target can be accessed. However from the perspective of an active instrument a geo-stationary orbit can be regarded as an extreme orbit in that the demands placed on the instrument are significantly more demanding than for the typical low earth orbit that is usually considered for an active instrument.

The Earth Science Technology Integrated Planning System database [1] contains a large number of different lidar measurement concepts that have been considered for their science benefit. In order to look at the application of lidar from a geo-stationery orbit we can break down the mission/instrument concepts contained in the database into three broad lidar categories:

1.1. Ranging/ backscatter profiling instruments

In this category we have altimeters and cloud/aerosol backscatter lidars. These are time of flight and signal intensity measurement devices that measure the round trip time to the target and the signal strength returned from the target. Requirements on the laser are relatively relaxed. These are the only type of lidar to have flown in space for earth remote sensing.

1.2. Doppler instruments

These instruments are intended for the measurement of wind velocity. They transmit a frequency stable, narrow linewidth beam through the atmosphere that is backscattered by either molecules or aerosols. The backscattered signal is Doppler frequency shifted by the line of sight component of the wind velocity. This Doppler shift is detected and used to determine the line of sight wind

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velocity. Doppler lidar instruments have been demonstrated from the ground and aircraft but have yet to be demonstrated from space.

1.3. Differential absorption instruments

These instruments target a specific atmospheric component and transmit two frequency stable, narrow linewidth beams that are precisely separated in wavelength. The atmosphere absorbs the two wavelengths differently such that the backscattered return signals collected at the lidar will have different intensities. The ratio of the returned signal intensities can be used to determine the concentration of the targeted atmospheric component. For each atmospheric component of interest a different pair of laser wavelengths is required. These instruments have been demonstrated from the ground and aircraft.

2. STATE OF THE ART FOR SPACE BASED LIDAR FOR EARTH SENSING

In 1977 NASA convened a working group of scientists to identify the major goals of a space-based lidar program for global surveillance of the atmosphere, propose a set of experiments that could be conducted from the Space Shuttle and provide an assessment of technology available for the program. A final report was released in 1979 [2]. Despite this start almost 30 years ago space-based lidar for Earth Remote Sensing is an immature technology. Illustrative of this is the fact that it was almost two decades from the release of the 1979 report to the flight of the Lidar In-Space Technology Experiment [3] became the first Earth remote sensing lidar. Active optical remote sensing has been used on a limited number of space based missions (Table 1) all of these have been ranging/ backscatter profiling instruments of which only a few have been backscatter profiling instruments.

Mission	**Year**	**Functionality**	**Target**	**Status**
Apollo 15	1971	Ranging	Moon	Success
Mars Orbiter Laser Altimeter 1	1992	Ranging	Mars	Spacecraft lost
Clementine	1994	Ranging	Moon	Success
Lidar In-space Technology Experiment	1994	Ranging/Backscatter profiling	Earth	Success
MIR/ Balkan	1995	Ranging/ Backscatter profiling	Earth	Success
MIR /ALISSA	1996	Ranging/ Backscatter profiling	Earth	Success
NEAR	1996	Ranging	Asteroid	Success
Shuttle Laser Altimeter 1	1996	Ranging/ Backscatter profiling	Earth	Success
Mars Orbiter Laser Altimeter 2	1996	Ranging	Mars	Success
Shuttle Laser Altimeter 2	1997	Ranging/ Backscatter profiling	Earth	Success
MPL/DS2	1999	Backscatter Profiling	Mars	Spacecraft lost
Icesat/GLAS	2003	Ranging / Backscatter profiling	Earth	Success, but shorter lifetime that expected
Messenger/Mercury Laser Altimeter	2004	Ranging	Mercury	En Route
CALIPSO/CALIOP	2005	Ranging/ Backscatter profiling	Earth	Launch soon
ALADIN/AEOLUS ADM	2007	Doppler	Earth	Under construction

Table 1 Space Based Lidars

The Lidar Inspace Technology Experiment flew as a short duration Shuttle payload bay experiment and was the first lidar to measure properties of the earth’s atmosphere by measuring backscatter from clouds and aerosols at three wavelengths. The Balkan [4] and ALISSA [5] lidars were flown on the MIR space station and are known to have returned data with Balkan primarily looking at returns from the ocean surface and ALISSA at returns from clouds. The GLAS instrument on Icesat [6,7] is primarily for ice topographic mapping but also contains channels for the detection of aerosol backscatter. The CALIOP instrument [8] to be launched in 2005 on the CALIPSO platform is an aerosol and cloud backscatter lidar that builds on knowledge gained from LITE. Of these few backscatter instruments only two (GLAS and CALIOP) have been designed and built for prolonged autonomous operation on-orbit. GLAS has had some issue on orbit that has limited the useful demonstration of "prolonged, autonomous operation" and CALIOP has yet to launch. The ALADIN instrument is intended to measure tropospheric winds and is the sole instrument on the European Space Agencies AEOLUS Atmospheric Dynamics Mission (ADM) and is currently under construction.

A number of these missions have not been without problems most noticeably in the reliability of the laser transmitter source. This is a recognized problem and is also one of the the limiting factors as to why a number of the more complex Doppler and differential absorption lidar techniques have yet to be flown on orbit. This immaturity of laser technology for space-based lidar was the subject of a report to the Associate Administrator for Earth Science [9] and a topic of a recent workshop [10].

3. SCIENCE FROM GEO-SYNCHRONOUS ORBIT

The GEO orbit offers the elimination of the limited temporal sampling that is provided by a lower Earth orbit and to date there have been two studies that looked at the potential science application from GEO. The first [11] took a preliminary look at measuring atmospheric winds and moisture from GEO and suggested that a GEO orbit had the potential to "Revolutionize our ability to monitor and predict severe atmospheric events on a routine basis including tropical cyclone tracks and intensity, tornado, hail and flooding, high winds including jet stream location/strength, severe event precursors (moisture convergence, tropospheric/stratospheric interactions and shear)". This study considered a direct detection Doppler lidar and a water vapor differential absorption lidar. The second study [12] looked at the prospect of GEO chemistry using differential absorption techniques. This second study identified tropospheric ozone as a potential measurement candidate from GEO. It should be noted that this second study reviewed the state of the art for differential techniques and found only the ozone measurement as routinely undertaken from aircraft. Common to both studies was the operation of the lidar in a number of modes starting from a global surveillance mode with a long repeat period (6-12 hours) with steps down to progressively more targeted regions with revisit periods of ~ 1hr and a horizontal sampling of 5 – 20 km and a vertical sampling of 0.5 –1 km. Recent studies [13] have shown the benefit of targeted observations on improving forecast accuracy. Geo-stationary lidars located over the Pacific and Atlantic oceans offer a potential method of being able to make many of these targeted observations without requiring aircraft and pilots to fly into hazardous situations.

4. MOVING TO GEO-SYNCHRONOUS ORBIT

The implications on the orbital parameters of interest for designing a lidar for a geo-synchronous orbit are compared with those for two low earth orbits (LEO) in table 2. Current LEO instruments have relied on the spacecraft motion to sweep a nadir view over the Earth's surface and have not attempted to scan the laser beam. While a number of different scanning mechanisms for space-based lidars have been proposed none have flown to date. For a lidar in a geo-synchronous orbit scanning is a basic necessity in order to obtain coverage. For a system capable of varying the off-nadir look angle Table 2 gives the maximum angle required to look at the limb of the earth. As the off-nadir angle increases the slant path through the atmosphere also increases and this leads to increasing attenuation of the lidar beam. Figure 1 shows the atmospheric extinction as a function of off-nadir angle from a GEO orbit and the two LEO orbits referenced in Table 2. For the purposes of calculating Figure 1, an off-nadir angle of 45 deg was used for both of the LEO orbits and the atmospheric data is that defined for use in Doppler lidar concept studies [14].

	LEO-1	**LEO-2**	**GEO**
Orbit Height, (km)	300	800	36000
Maximum off-nadir angle (deg)	72.8	62.7	8.7
Round Trip time at nadir (s)	0.002	0.005	0.24
1/Range^2 (m^{-2})	1.1E-11	1.6E-12	7.7E-16
Sub-satellite point velocity over the surface at the equator (m/s)	6922	6163	0
Swath width at LEO for a 45 deg off nadir look angle (km)	615	1720	

Table 2 A comparison of some of the orbital parameters of interest for designing a lidar

The 355 nm plot is representative of a lidar operating in the ultra-violet while the 2.06 µm plot is representative of a lidar operating in the infrared. In both cases it is noticeable that atmospheric transmission increases significantly for a GEO lidar with a nadir angle above 7 degrees while for angles less than 6 degrees the atmospheric attenuation is less than for the LEO orbits. Another consequence of increasing the off-nadir angle is that the range from the lidar to the earth's surface, R increases and the signal to noise ratio (SNR), which is proportional to $1/R^2$ decreases. Figure 2 shows the impact of increasing the nadir angle on the range to the ground and the relative signal to noise ratio (SNR) when the effects of atmospheric extinction is also included. The SNR assumes that the noise is independent of nadir angle and has been normalized to a direct nadir view. If we apply this same normalization to the lidars at LEO their relative SNR varies between 330-880 for an 800 km orbit and 3270 – 6060 for a 300 km orbit. This means that scaling a typical LEO lidar design to GEO will require increasing the signal to noise by a factor of 300 – 6000 depending on the initial altitude of the LEO design. Practically this means increasing the pulse energy from the laser or increasing the telescope aperture. It seems clear from Figure 2 that a geo-synchronous lidar operating at short wavelengths is penalized severely by atmospheric attenuation at large off-nadir angles and any practical design would probably be limited to nadir angles up to 6-7 degrees. This would mean that there would be no coverage at the poles. For a geo-synchronous lidar operating in

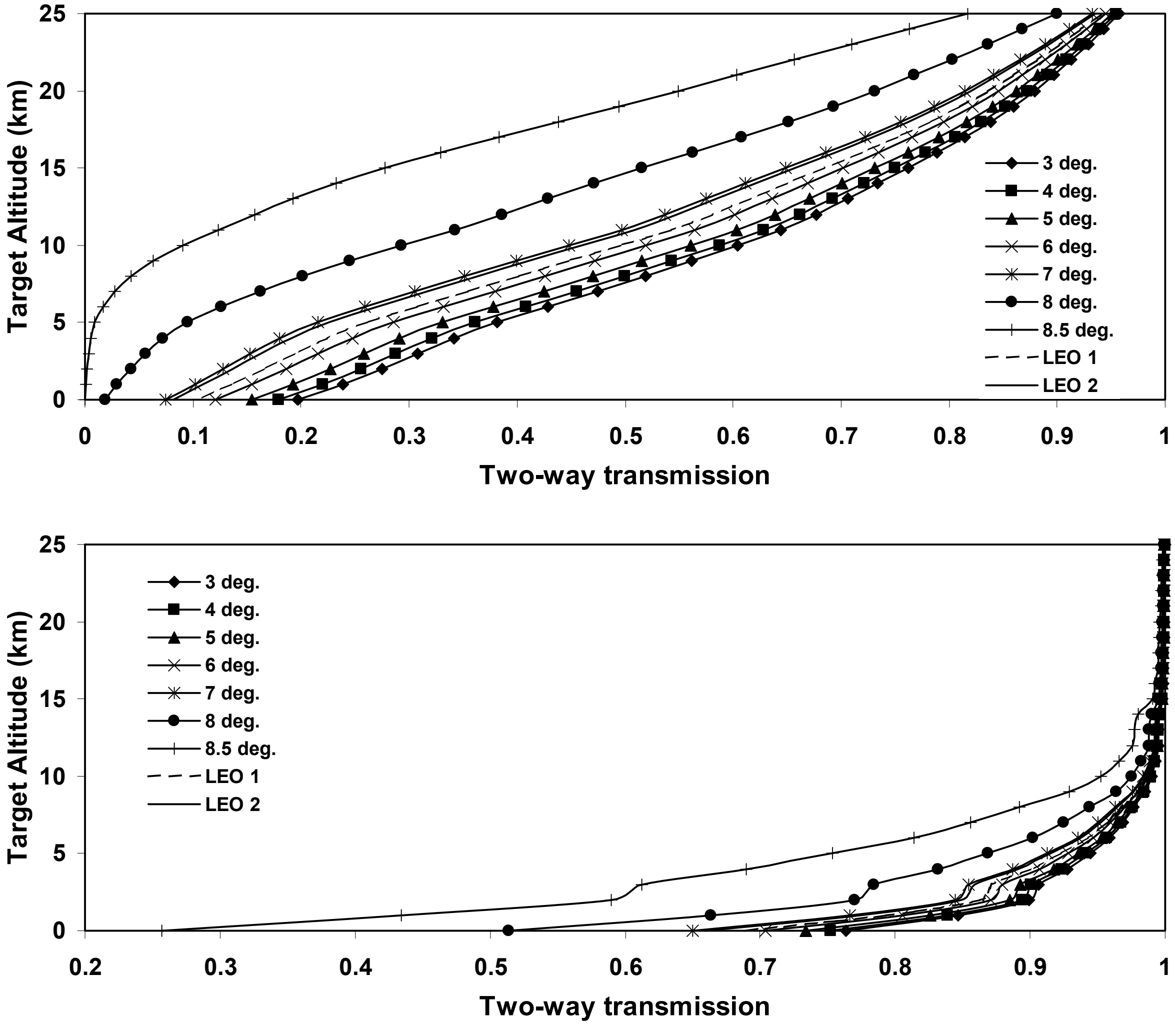

Figure 1 Atmospheric transmission from GEO and two LEO orbits as a function of nadir angle for a lidar operating at 355 nm (top) and 2.06 µm (bottom).

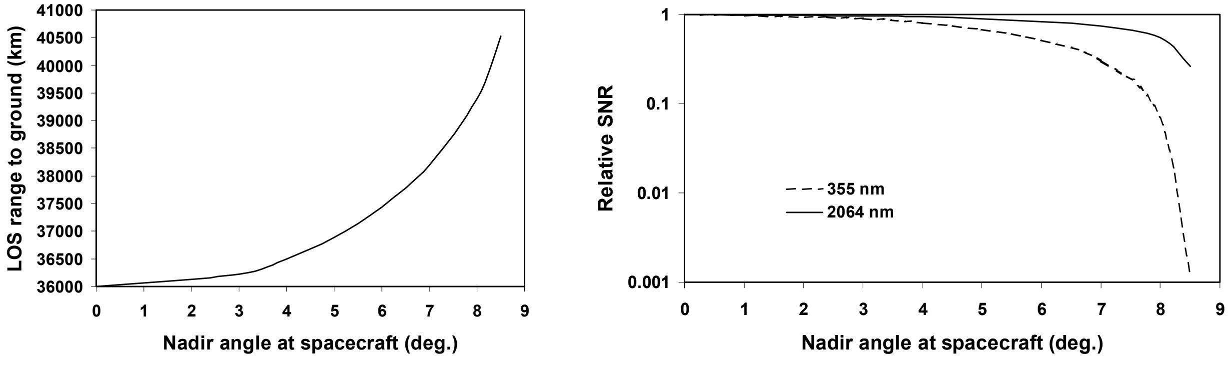

Figure 2 Dependence of the line of sight range and signal to noise ratio on the off-nadir look angle

the infra-red there is less of an impact at large off-nadir angles and 'pole to pole' coverage is feasible from a signal to ratio perspective.

5. SCALING UP LOW EARTH ORBIT DESIGNS

The current state of the art is embodied in the non-scanning GLAS and CALIOP ranging/backscatter instruments. A summary of some of the key parameters of these instruments is given in table 3. It is instructive to look at scaling this type of instrument for use at GEO. These instruments are both nadir looking and scaling them up to GEO will require a factor of ~2644 (CALIOP) or 3600 (GLAS). Table 4 lists some combinations of laser pulse energy and telescope aperture that can achieve this scaling. Such large increases in telescope aperture and/or laser performance are unlikely to become available in the near term. Over the last few years NASA has invested significantly in a laser risk reduction program [15] that is significantly less ambitious than the laser pulse energies required for the more modest apertures listed in table 4.

	GLAS	**CALIOP**
Orbit height (km)	600	705
Wavelength (nm)	532,1064	532,1064
Pulse energy @1064 nm (mJ)	70	110
PRF (Hz)	40	20.2
Telescope diameter (m)	1	1

Table 3 Parameters of the CALIOP and GLAS instruments

Telescope Diameter (m)	**Energy (J) to scale CALIOP**	**Energy (J) to scale GLAS**
1	252	287
10	2.5	2.9
30	0.28	0.32
50	0.10	0.11
100	0.025	0.029

Table 4 Scaling GLAS and CALIOPE to GEO

Once scaled to a common orbit the GLAS and CALIOPE aperture/energy combinations are essentially identical as might be expected. Table 4 fails to take advantage of one significant benefit of GEO and that is the ability to stare at a target and accumulate data over multiple laser shots – this can reduce the required laser pulse energy significantly and practically this is the approach that the prior design studies from GEO have taken however even with this approach the telescope apertures and laser pulse energies required (Table 5) are well beyond the current state of the art.

	Doppler Wind Lidar	**Water Vapor DIAL**	**Ozone DIAL**
Study Author	Emmitt [11]	Emmitt [11]	Ismail [12]
Wavelength (nm)	355	813/818	308/320
Pulse Energy (J)	1.5	1	1J
PRF (Hz)	100	30	20
Dwell time (s)	5	5	600
Telescope Diam (m)	100	100	35
Vert. Res. (km)	1	1	0.5
Av. Power @1.064 µm (W)	450		80

Table 5 GEO Lidar concepts

A number of the wavelengths required are generated by conversion from a 1.064 µm fundamental wavelength and that the conversion process typically requires a factor of ~3 greater pulse energy at the fundamental wavelength. While there has been some work on telescopes in the few m class diameter there has not been significant work for 35 – 100 m class apertures. Some of the issues that must be addressed include maintaining the secondary/primary spacing/alignment and physically getting the telescope in place on orbit.

It should be noted that the operational environment at GEO is significantly different than at LEO and there has been little consideration for the implications of this within the lidar community to date.

6. POINTING ISSUES

All of the geo-synchronous lidar concepts require a scanning mechanism in order to provide the global coverage desired but this has yet to be addressed and demonstrated for LEO lidars. Unlike large space telescopes that are slewed to a new target and then held on that target for some considerable time the lidar is constantly retargeted in order to provide the coverage required by the science measurement. A simple look at the mass and angular momentum of 35 m and 100 m class mirrors (Figure 3) shows the impracticality of moving these mirrors around dynamically and some other scanning mechanism will be required.

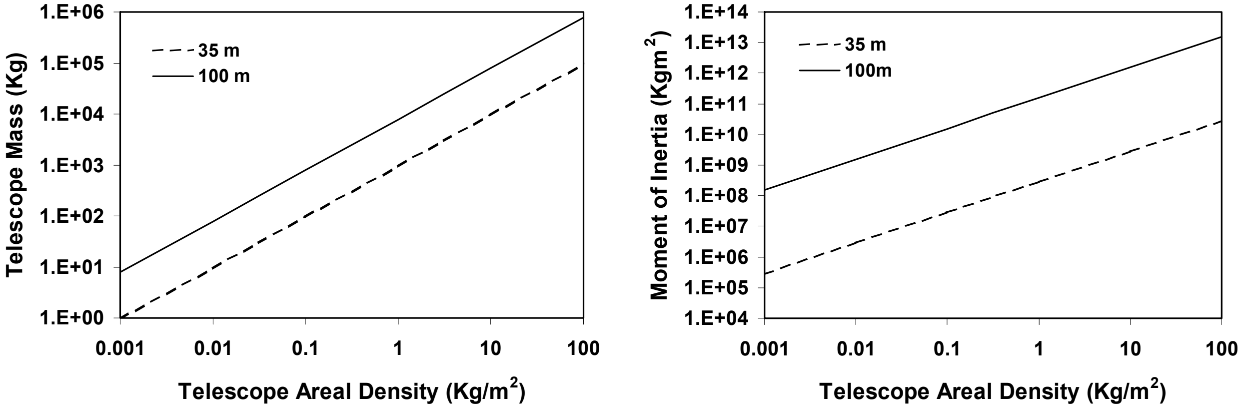

Figure 3 Telescope mass and moment of inertia as a function of areal mass

The current science studies have identified targets at various scales and, for example, the Ismail study identifies the benefit of targeting small scale (~5km) urban features for pollution monitoring. A 5km target subtends an ~100 microradian angle and if we assume we want to maintain the beam on target to within 10% of the target size this gives a pointing control requirement of ~ 10 microradians over 10 minutes. A similar argument can be made for the desired vertical sampling of 500m which implies a pointing control of ~ 1-2 microradians over the data accumulation time.

These basic requirements neglect the impact of atmospheric refraction that will 'steer' the beam as it passes through the atmosphere. At small (3 deg) off-nadir angles atmospheric variability can contribute an uncertainty of ~10 microradians to the line of sight pointing while at larger angles (8.5 deg) it contributes up to 100 microradians uncertainty. In any practical implementation knowledge of atmospheric parameters obtained from other sources can be used to narrow the uncertainty over that stated here.

Finally the round trip time of flight to the target is ~0.24s and during this time the transmit/receive boresight must remain aligned such that the signal can be adequately captured without significant loss. If we assume the 5 km target size discussed previously and assume that we want the transmit/receive overlap to be better than 10% of the target size then this implies a pointing drift control of ~10 microradians over 0.24 s.

All of the pointing control/knowledge requirements outlined here are challenging and require significant investment in platform pointing and control especially when the requirement to scan the lidar field of view over the large areas in relatively short periods of time is considered.

7. CONCLUSION

The science benefit of lidar from geo-synchronous orbit is still being evaluated but there appear to be some clear benefits for certain applications however the lidar technology is currently immature. Given the development history and current state of the art of lidar for low earth orbit the cost and time to develop lidar for geo-synchronous orbit will be significant.

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