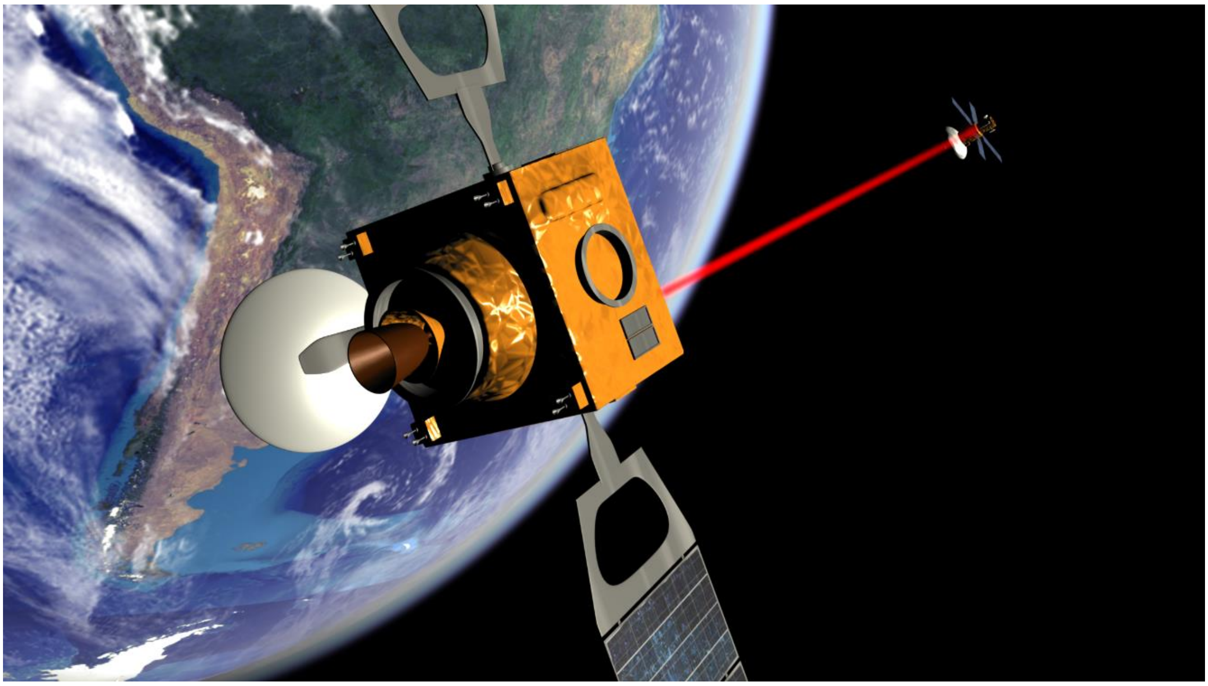
1 EXECUTIVE SUMMARY REPORT

Optical phase beam steering enables motionless pointing of light. The lack of mechanical moving parts not only reduces overall Mass, Volume, and Power (MVP) to a fraction of conventional solutions, but also reduces the associated risk due to friction fatigue. The applications of this technology both on Earth and in Space are only beginning to be fully understood and realised. In the context of telecommunications, the need for steerable beams has become the latest commercial frontier for market advantage allowing for communications channels to be differentiated in space as well as time/frequency. In the context of LiDAR, leading public, military, and private organizations have shown interest in reduced MVP LiDAR for Space, automotive and airborne applications. Technologies proposed include solid-state optical phased arrays, piezoelectric mirrors, diffractive optics, and liquid crystal spatial light modulators (SLM). MDA, in partnership with The University of Oxford (UoO), are proposing to develop a novel liquid crystal technology tailored specifically to SLMs for Space applications. Researchers from The Department of Engineering Science at Oxford University are pioneering new beam-steering technology based on the development of novel fast-switching liquid crystal modes that target frame rates which exceed 1 kHz whilst maintaining analogue control of the optical phase. This technology has the potential to enable a range of applications including Space telecommunications, situational awareness, and exploration.



2 OVERALL PROJECT OBJECTIVES

The key objective of the UltraFast Optical beamSteering (UFOS) project was to raise the technology readiness level (TRL) of a new liquid crystal (LC) phase modulator that could provide fast analogue switching ($\geq$ 1 kHz) coupled with full 2π phase modulation. When integrated into a spatial light modulator (SLM), this phase modulator configuration would be of benefit for a range of potential Space applications including optical communications as well as landing, docking, rendezvous, and docking. The idea is to enable a follow-on Phase-B activity of a full spaceflight program.

This work was divided into 2 main objectives split between MDA UK (MDA) and The University of Oxford (UoO).

- The technical challenge or raising the TRL of the LC was to be addressed by UoO under 4 work packages representing 75% of the UFOS programme budget and effort.
- The task of requirements analysis based on addressable space market and follow-on activity planning was to be addressed by MDA under 3 work packages representing 25% of the UFOS programme budget and effort.

The outputs of the MDA work would be used to determine the most critical technical requirements to aim for LC optimisation under UoO responsibility.

<u>MDA Work Package Summary</u>

Throughout the UFOS programme, MDAs objective was to frame the development of the Ultrafast Liquid Crystal medium in the context of Space from a market perspective. The idea was to answer the question "How do we prioritize technical development of SLM components in order to maximize the potential for SLM-based technologies to participate in Space markets?". MDA would answer this question by concentrating on 2 types of SLM-based technologies, LIDAR and Free Space Optical Communication (FSOC) terminals, and delivering a prioritized set of requirements derived from these markets to the component (SLM) level.

Table 3-1 is has been extracted from MDA results.

<u>UoO Work Packages</u>

The UoO team has been able to demonstrate the proof-of-concept of ultrafast switching in a novel LC technology. In order to breadboard critical functions of motionless optical beam-steering geared for Space applications, several technical challenges need to be addressed. The UoO objective was to raise the TRL of the underlying LC by:

• Optimising operating temperature and drive voltage

• Developing new strategies for low-loss and polarisation independent liquid crystal technology (UoO)

• Enhancing mechanical ruggedness for space deployment

This work was divided into 4 work packages performing underlying component and mixture selection, mixture ruggedization, and optimisation for manufacturability.

3 PROJECT CONCLUSIONS ON REQUIREMENTS ANALYSIS FOR TARGET EARTH AND SPACE MARKETS

The top level requirements and their verification status at the end of the UFOS programme are enumerated in Table 3-1. Requirements analysis under WP2 resulted in the following conclusions:

In terms of Lidar, the highest addressable markets in the near to long-term future are space applications related to science and exploration including altimetry, landing, and rendezvous and docking. Clean space, deorbiting and satellite servicing are other important applications in terms of addressable market.

In terms of laser comms, the challenge to address the market is mainly that of range. Assuming a coarse steering mechanism, the SLM field of view should not require expanding optics.

To enable this, high priority was given to SLM rate of operation, field-of-view, and range.

Table 3-1

Text	Rationale	V
SLM shall steer an incident light beam into at least 1 output beam with 2 DOF	This replaces 2 scanning mirrors Target market: ALL	**2DOF** Experimental evidence that mixture FE-016 exhibits full 2π phase modulation required for hologram generation
SLM shall operate in reflection mode	MDA UK LIDAR and communication terminal designs operate on reflection Target market: ALL	**Reflection** Experimental evidence that mixture exhibits full 2π phase modulation in reflection.
SLM shall generate a new output for all pixels at a rate of >1kHz **Target**: > 10kHz – 100kHz	This is the minimum possible speed that would maintain relevance in the LIDAR market (currently limited only by laser PRF) Target market: - 1kHz – 10kHz: FSOC, rover navigation - >10kHz: rdv and docking, cleanspace, autonomous landing (>10kHz)	**≈ 1kHz** Experimental evidence that mixture FE-016 exhibits a response to a 1 kHz generation rate (Section 4.3).
SLM shall be compatible with a minimum range of 1km. **Target intersatellite:** > 100km **Target earth to LEO:** > 600km **Target earth to MEO: >** 8000 km	This is sufficient for most LIDAR applications. Higher target required for intersatellite communications intersatellite and interorbital communications Target market: - < 1k: rover navigation - 1k - 5k: rdv and docking, autonomous landing, cleanspace - >100km: FSOC	**>1 km** Experimental evidence that existing SLMs have been characterized with propagation distances of at least 1 km in optical communications

Target interorbital: > 36000km		
SLM shall have a scattering loss <25% **Target: <**5%	This would be comparable to the scattering loss using steering mirrors. Important to achieve target range - Related to range, target 5% to be comparable with mirrors, which would then mean we do not need more powerful laser. High scattering loss would mean only low range applications are possible (rover navigation)	**<25%** Experimental evidence that mixture exhibits a scattering loss that is less than 20%

4 PROJECT CONCLUSIONS ON DESIGN AND TESTING OF OPTIMISED LIQUID CRYSTAL FORMULATIONS

Prior to the UFOS project, initial proof-of-concept demonstrations had to be carried out at very high temperatures (108°C) over a very narrow operating temperature range (e.g., 5°C). The workpackages (WP) of the UFOS project were therefore carefully designed to address some of the limitations that had been identified in the preliminary proof-of-concept demonstrations. Specifically, the broad aims of the project were to develop chiral nematic LC mixtures that could be operated at temperatures below 100°C (ideally <50°C) and that still exhibited strong flexoelectric coupling (i.e., they can still result in a tilt of the optic axis of 45°). This relatively large tilt of the optic axis is a mandatory requirement to ensure that a full 2π phase modulation is observed when the LC layer is sandwiched between two quarter waveplates as per the UFOS modulator configuration. In accordance with WP2 conclusions, later mixtures were tailored for speed over temperature requirements.

The project targeted the following performance metrics:

(i) lower operational temperature (<100°C);

(ii) reduced transmission losses (<25%);

(iii) achieve a more uniform alignment;

(iv) lower drive voltage (<50V);

(v) ensure mechanical stability and recovery of the alignment.

The key achievement was the development of a state-of-the-art mixture that meets the following requirements:

(i) Operational temperatures from 30°C - 45°C;

(ii) Reduced transmission losses to <15% using new alignment process;

(iii) Achieved a more uniform alignment using appropriate electric field conditions;

(iv) State-of-the-art mixture exhibits voltages >50V due to presence of polymer, non-polymer mixtures exhibit lower voltages;

(v) Recovery of the alignment and stability to laser powers of 2W

This mixture combines speed with lower temperature operation and full 2π phase. It can be polymerized to make the device rugged, withstands thermal cycling and exposure to UV light. Tests with the non-polymerizable mixture demonstrated resilience to high laser powers and exhibits <15% transmission losses (8% of which come from Fresnel reflection losses from the glass substrates). This could be reduced further using a reflective device geometry combined with anti-reflection coatings. For the state-of-the-art mixture, the drive voltages have exceeded the 50 V targeted, which is due to the presence of the polymer network.