Acta Astronautica 96 (2014) 97–105

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

An advanced optical system for laser ablation propulsion in space ☆

Grant Bergstue *, Richard Fork, Patrick Reardon

The University of Alabama in Huntsville, United States of America

A R T I C L E I N F O

Article history:
Received 5 March 2013
Received in revised form
18 September 2013
Accepted 16 November 2013
Available online 3 December 2013

Keywords:
Ablation
Propulsion
Optics
Ultrashort
Pulse
Space

A B S T R A C T

We propose a novel space-based ablation driven propulsion engine concept utilizing transmitted energy in the form of a series of ultra-short optical pulses. Key differences are generating the pulses at the transmitting spacecraft and the safe delivery of that energy to the receiving spacecraft for propulsion. By expanding the beam diameter during transmission in space, the energy can propagate at relatively low intensity and then be refocused and redistributed to create an array of ablation sites at the receiver. The ablation array strategy allows greater control over flight dynamics and eases thermal management. Research efforts for this transmission and reception of ultra-short optical pulses include: (1) optical system design; (2) electrical system requirements; (3) thermal management; (4) structured energy transmission safety. Research has also been focused on developing an optical switch concept for the multiplexing of the ultra-short pulses. This optical switch strategy implements multiple reflectors polished into a rotating momentum wheel device to combine the pulses from different laser sources. The optical system design must minimize the thermal load on any one optical element. Initial specifications and modeling for the optical system are being produced using geometrical ray-tracing software to give a better understanding of the optical requirements. In regards to safety, we have advanced the retro-reflective beam locking strategy to include look-ahead capabilities for long propagation distances. Additional applications and missions utilizing multiplexed pulse transmission are also presented. Because the research is in early development, it provides an opportunity for new and valuable advances in the area of transmitted energy for propulsion as well as encourages joint international efforts. Researchers from different countries can cooperate in order to find constructive and safe uses of ordered pulse transmission for propulsion in future space-based missions.

1. Introduction

1.1. Multiplexed ultra-short pulses for space

A growing area of research relevant to new missions in space is that of energy transmission, especially in regards to providing thrust. Transmitting energy between spacecrafts offers a remote power source. This strategy can reduce the mass, complexity and cost of a satellite or spacecraft receiving the transmitted energy.

The quantum process of stimulated emission enables configuration of optical energy in forms relevant to generation of propulsive thrust in space. Energetic ultrashort optical pulses generated as lowest order Gaussian modes can be both propagated over long distances in the vacuum of space and then simply and efficiently be transformed into propulsive thrust. The energetic pulses of interest, however, cannot typically be used in the atmosphere of Earth. Such pulses tend to collapse and self-focus if propagated over significant distance in Earth's atmosphere.

A further constraint is that the quantum process that enables generation of these energetic ultrashort optical

☆ This paper was presented during the 63rd IAC in Naples.

* Corresponding author. Tel.: 256 466 5647.
E-mail addresses: bergstg@uah.edu (G. Bergstue), forkr@uah.edu (R. Fork), reardonp@uah.edu (P. Reardon).

0094-5765/$ - see front matter © 2013 IAA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actaastro.2013.11.021

pulses requires specifically designed optical resonator and amplifier systems. These systems are typically limited to generating average power from a given mode-locked laser system on the order of a kilowatt [1,2]. This amount of average power from an individual mode-locked laser system can probably be improved to some degree, but also will probably not be improved to a degree that will enable a single mode-locked laser system to provide the levels of average power typically required for many applications in space.

As a means of accessing the higher average power required for many applications of interest in space, we are exploring multiplexing of mode-locked, ultra-short pulse lasers to advance propulsion capabilities for use in space. We currently see two types of such multiplexing. One approach is analogous to the time domain multiplexing used in terrestrial information oriented optical networks, but designed instead for applications delivering levels of power useful for propulsive thrust in space over relatively long distances. We describe some of that work in this current paper. We are also exploring a second type of multiplexing analogous to space division multiplexing in terrestrial optical networks. This latter strategy appears more relevant to shorter distance transmission of large average levels of power in space. An application of current interest is deflecting near Earth objects that may be discovered on collision course with Earth. We describe this latter work in a recent paper [3].

In this current paper we discuss primarily the time division multiplexing strategy for long distance transmission of ultrashort optical pulses to be used for propulsion. A recent focus in the space industry has been on developing new space-based propulsion engine designs. For example, strong emphasis has been placed on micro-propulsion for future NASA missions. The “NASA Space Technology Roadmaps and Priorities” gives micro-propulsion a high priority score as a potential solution to meet current technological challenges [4]. On the topic of micro-propulsion, the “NASA Space Technology Roadmaps and Priorities” report says, “The benefits of developing micro-propulsion concepts are not confined to small satellites, to NASA, or to the aerospace industry. For instance, micro-propulsion could be used by larger satellites for missions requiring accurate thrust delivery to counteract orbital perturbations … . They could also be used for precise formation flying of spacecraft clusters or as modular distributed propulsion for the control of large space structures” [4]. We propose a means of creating this modular distributed propulsion through beamed energy in the form of multiplexed ultra-short optical pulses in space (MUOPS).

In order to implement this strategy using MUOPS, a key piece of technology that is needed is the multiplexing optical switch. Below it is shown that a rotating off-axis parabolic reflector (OAP) can be used to collect pulses from different laser sources and multiplex them together given the correct positioning. There are limiting issues with this design however, and a more practical and rugged device must be used. It is proposed that a modified momentum wheel with multiple reflectors polished into it can serve as the multiplexing optical switch.

1.1.1. *Multiplexing concept review*

The authors previously proposed a multiplexing strategy to produce the needed amounts of energy for effective ablative thrust in space [4]. In brief summary, this concept described a strategy for reaching these high average power levels by utilizing an array of laser sources multiplexed together rather than a single, large laser source. Cooperation and safety were not only stressed but necessary for the effective transfer of the energy to be used for thrust generation. The pulses, once multiplexed, are expanded in time and space as they propagate as to not have sufficient intensity to cause ablation. Only at the cooperating spacecraft ready to receive the energy with the correct optical system to focus the pulses can ablative thrust be created. The strategy also included distributing the ablation events over an array at the receiver as to give more control to the thrust applied to the spacecraft [5].

While these methods were shown as possible options for the safe and effective transmission of ultra-short pulses in near-Earth space, specific optical system designs were left for future research. Proposed in authors' current work are new methods for achieving the multiplexing of the ultra-short optical pulses for transmission to a cooperating spacecraft.

2. New concepts for an ultra-short pulse multiplexing transmission system for propulsion in space

2.1. *Multiplexing optical switch*

One of the most important elements needed for this multiplexing strategy is a modulating switch to combine the laser sources into useful amounts of energy. An example of the importance of a multiplexing switch can be seen in terrestrial fiber communication networks. Just as a higher modulation of light increases the amount of data that can be transmitted, a higher modulation of the ultra-short pulses increases the total average power sent between spacecrafts.

The modulation of these energetic ultrashort pulses is significantly more difficult as the pulses have a much higher energy. The multiplexing device for the proposed system must combine and direct the pulses from an array of laser sources. One way of accomplishing this is by rotating an OAP about its local axis. If a point source is placed at the effective focal length of a parabolic reflector, collimated light of good quality will be produced. By moving the reflector off the optical axis, the source can be placed on axis while the collimated light propagates unblocked by the source. To verify this concept, a ray-trace simulation of a rotating OAP was done with Code V (Fig. 1).

This shows that a point source placed at any point along the circular pattern traced out by the OAP will produce well collimated light. However this is only true if the OAP is in the correct angular and rotational position to reflect the light.

There are other limiting issues with this particular optical switch design. The largest problem lies with the rotation of the OAP due to its size and asymmetric weight distribution. In order to transmit ultra-short pulse energy