# A Contamination-Free Ultrahigh Precision Formation Flying Method for Micro-, Nano-, and Pico-Satellites with Nanometer Accuracy

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**Abstract.** Formation flying of clusters of micro-, nano- and pico-satellites has been recognized to be more affordable, robust and versatile than building a large monolithic satellite in implementing next generation space missions requiring large apertures or large sample collection areas and sophisticated earth imaging/monitoring. We propose a propellant free, thus contamination free, method that enables ultrahigh precision satellite formation flying with intersatellite distance accuracy of nm ($10^{-9}$ m) at maximum estimated distances in the order of tens of km. The method is based on ultrahigh precision CW intracavity photon thrusters and tethers. The pushing-out force of the intracavity photon thruster and the pulling-in force of the tether tension between satellites form the basic force structure to stabilize crystalline-like structures of satellites and/or spacecrafts with a relative distance accuracy better than nm. The thrust of the photons can be amplified by up to tens of thousand times by bouncing them between two mirrors located separately on pairing satellites. For example, a 10 W photon thruster, suitable for micro-satellite applications, is theoretically capable of providing thrusts up to mN, and its weight and power consumption are estimated to be several kgs and tens of W, respectively. The dual usage of photon thruster as a precision laser source for the interferometric ranging system further simplifies the system architecture and minimizes the weight and power consumption. The present method does not require propellant, thus provides significant propulsion system mass savings, and is free from propellant exhaust contamination, ideal for missions that require large apertures composed of highly sensitive sensors. The system can be readily scaled down for the nano- and pico-satellite applications.

**Keywords:** formation flying, photon thruster, intracavity, satellite, spacecraft, interferometer, interferometric ranging, propellantless, tether, SPECS, MAXIM, TPF, ST-3, contamination free, micro, nano, pico.
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## INTRODUCTION

In recent years, microsatellites and nanosatellites provide an opportunity to insert sophisticated sensors and processing technologies into orbits of interest at low costs (Leitner, 2004). Building a cluster of small satellites has been recognized to be more affordable, robust and versatile than building a large monolithic satellite. Specifically, the grouped satellite cluster is crucial for enabling orders-of-magnitude improvements in resolution and coverage achievable from advanced remote sensing platforms. Size limitations on launch vehicle fairings leave formation flying as the only option to assimilate coherent large apertures or large sample collection areas in space (Leitner, 2004). For example, for NASA applications, the ultrahigh precision satellite clusters can be used for interferometry and distributed large aperture sensors, especially at optical (TPF, and SPECS) and x-ray wavelengths (MAXIM) (Leisawitz, 2004, Cash, 2002). For non-NASA applications, the proposed system can be used for advanced geophysical monitoring where GPS and standard laser range finders are currently inadequate to measure and monitor small changes in the movement of earthquake plates, and gravity wave detection. Other commercial and military applications include distributed large aperture optical and infrared sensors for ultrahigh resolution monitoring and imaging at low-cost.

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Such a technology critically depends on the formation flying method that enables precision spacecraft formation keeping from coarse requirements (relative position control of any two spacecraft to less than 1 cm, and relative bearing of 1 arcmin over target range of separations from a few meters to tens of kilometers) to fine requirements (nanometer relative position control). For example, one of the most challenging applications for formation flying thus so far is that of the proposed x-ray interferometry for space imaging applications, MAXIM (Cash, 2000). The concept has evolved to include a pathfinder mission, consisting of a single x-ray interferometer and a trailing imaging satellite, and the full MAXIM, consisting of a fleet of 33 x-ray mirror satellites, a trailing collector satellite, and an imaging or detector spacecraft. Summary of the requirement of the baseline accuracy tolerance of several exemplary missions compared with the capability of the present formation flying method is shown in Fig. 1.

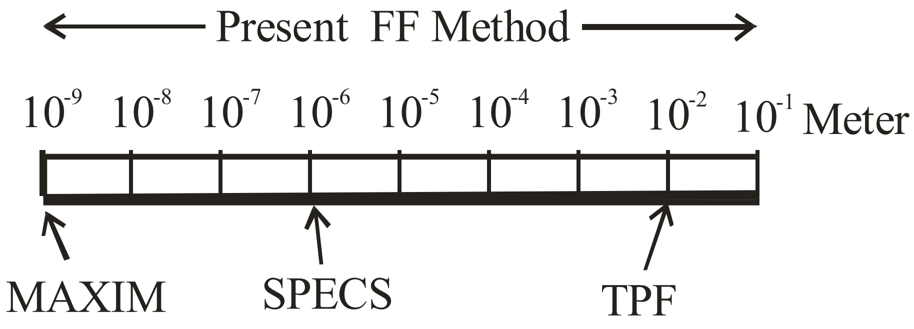

**FIGURE 1.** Required Base Line Accuracy of Several Exemplary Missions and the Capability of the Present FF Method.

In MAXIM, the relative distance between the hub satellite and collector satellites should be precisely maintained with the tolerance of a few nm ($10^{-9}$m) at the distance of 200 m, and the precision requirement in maintaining the distance, thus, is 10 parts per trillion, one of the most stringent accuracy requirement seen in any scientific fields. In addition, potential contamination of neighboring spacecraft by propellant exhaust plumes and the possibility of pulsed electromagnetic interference with low power inter-satellite communications remain a real concern for grouped satellite clusters. These requirements essentially rule out the usage of the most of the conventional propellant based propulsion systems, such as gas hydrazine thrusters, pulsed plasma thrusters, hall thrusters, electrostatic ion engines, and field emission electron propulsion systems.

To alleviate these concerns, several propellant-free formation flying methods have been proposed. The propulsive conducting tethers and spin-stabilized tether systems have been proposed in place of on-board propulsion systems to form and maintain satellite formations (Johnson, 1998, Quinn, 2000). While such concepts offer intriguing possibilities for small arrays consisting of only a few spacecraft, implementing a system for dozens of satellites quickly becomes extremely problematic. Several other new concepts have been proposed. They are: 1) the microwave scattering concept (LaPointe, 2001), 2) Coulomb force concept (King, 2002), 3) magnetic dipole interaction concept (Miller, 2003). In the microwave scattering formation flight method (LaPointe, 2001), radiation forces on the order of $10^{-9}$ N/W may be generated using electromagnetic gradient forces or scattering forces; microwave beam powers of 10-kW can thus produce restoring forces of approximately 10-μN, which are sufficient to correct a number of orbital perturbations. It requires very high power consumption, and focusing of the microwave requires larger antenna arrays, and the scattered microwaves may electronically interfere with other neighboring satellites. The Coulomb control system (King, 2002) is limited to close formation flying in plasma environments characterized by Debye lengths greater than inter-vehicle separation. Even for such formations, however, the Coulomb control forces become negligible for separations greater than 50 m. It is apparent that more traditional thrusters would be necessary for formation keeping over larger distances. Generating usable Coulomb control forces requires charging spacecraft to high voltages, thus great care must be taken in vehicle design to prevent differential charging and instrument damage due to electrostatic discharge. In the magnetic dipole concept (Miller, 2003), two technical challenges should be overcome: 1) it may not work at the distances greater than tens of meters, thus cannot be used for MAXIM, 2) the system can be extremely bulky and heavy (tons). Therefore, searches continue for the concept that does not require propellant nor extreme high voltages, and is power efficient and light. Very recently, a new form of propellant-free thrust has been investigated and reported to be observed by

Woodward (2004) and Woodward and Vandeventer (2006). The usage of such a mechanism for ultrahigh precision formation flying is very interesting, and remains to be investigated.

Even if an efficient propellant-free thrust is developed, for ultrahigh precision formation flying, the issue of thrust pointing, the method of controlling thrust to the desired accuracy, the precision ranging metrology and the overall system architecture should be addressed. The proposed concept in this paper, we believe, satisfies all of these criteria, because:

- The proposed photon thruster system is capable of generating propellant-free continuously for tens of years,
- In combination of a tether system, the proposed photon thruster is capable of controlling and maintaining continuously the intersatellite distance with an accuracy better than nanometer,
- The dual usage of the photon thruster as a laser source for the ultrahigh precision interferometric ranging system simplifies the system architecture and control, and minimizes the system weight and power consumption,
- The thrust vector can be defined with ultrahigh precision due to the nature of the laser cavity.

## THE PROPOESED ULTRAHIGH PRECISION FORAMTION FLYING METHOD

The proposed method enables ultrahigh precision satellite formation flying with intersatellite distance accuracy of nm ($10^{-9}$ m) at maximum estimated distances in the order of tens of km. Thus, the present method can be used for most of next generation formation flying missions envisioned so far, including ST-3, TPF, SPECS, and MAXIM. The method is based on innovative ultrahigh precision laser intracavity thrusters able to provide continuously adjustable precision CW thrust between microsatellites and tethers. In slowly spinning systems, as in SPECS, centrifugal force can provide a precise repulsive force, allowing a low-mass tether to provide precise control of distance. There is a problem how quickly that force can be adjusted without risk of inducing undesired resonances, and to solve the problem, the agile control loop can use adjustable laser power rather than mechanical tether length control as the primary control mechanism. In non-spinning systems centrifugal force is not available, and a laser will provide the major repulsive force. In both spinning and non-spinning cases, the fast feedback possible can be used not just to control position, but to reduce the required agility of the tether control, and hence the problems induced by undesired tether resonances.

The schematic diagram of the proposed concept is shown in Fig. 2. Specifically, the proposed formation flying method is based on pulling-in force provided by tether tension and the pushing-apart CW thrust of the intracavity photon thruster. Although the thrust produced by single bounces of photons is typically negligibly small, the intracavity geometry allows photons to bounce between two mirrors as many times as tens of thousands, resulting in several orders of magnitude amplification of the thrust with a given laser power. With this proposed method, we estimate the distance between the satellite pairs in the constellation structure can be adjusted and maintained rapidly to the accuracy of nanometer. The photon thrust and tension of tethers form the backbone linear force structure of the crystalline-like structured formation flying, and can rapidly damp the perturbation from the space environmental sources, such as solar pressure, drag-force, and temperature fluctuation, applied from any direction. Several exemplary structures are illustrated in Fig. 2. For example, the tetrahedral structural can be used for SPECS applications. For MAXIM applications, an elongated polygon bipyramidal structure similar to the 10 satellites constellation can be used, except instead of 8 satellites 32 collector spacecrafts will be used in the plane. The apex will be occupied by the hub and converger crafts. The approximate distance between the collector and hub crafts is about 100 m, and that between the collector and the converger crafts is about 10 km. This is slightly modified structure from the original one (Cash, 2000). These numbers will be used to estimate the necessary operation parameters in the later sections. For one to two dimensional structures, such as in ST-3, multiple photon thrusters and tethers are necessary for a pair of satellites to stabilize the angular disturbance.

More specifically, for SPECS applications, the proposed concept here has two important advantages. First, the usage of tethers will obviate the need for a massive amount of thruster propellant and high-quality imaging interferometry with a 1 km maximum baseline. "High quality imaging" implies the need for dense coverage of the "u-v" plane (i.e., moving the light collecting telescopes to fill the area subtended by the synthetic aperture). To produce images at a reasonable rate, the light collectors will have to be moved around a lot. Although even the most efficient thrusters available can't perform such a task, the tension in a tether can do nearly all the work. Second, to operate with the required sensitivity at far-IR wavelengths, SPECS will have cryogenic optics maintained at 4 K. Therefore, contamination of the optical surfaces is a big concern. The proposed system can be used as an alternative version for the originally proposed for SPECS to overcome these concerns.

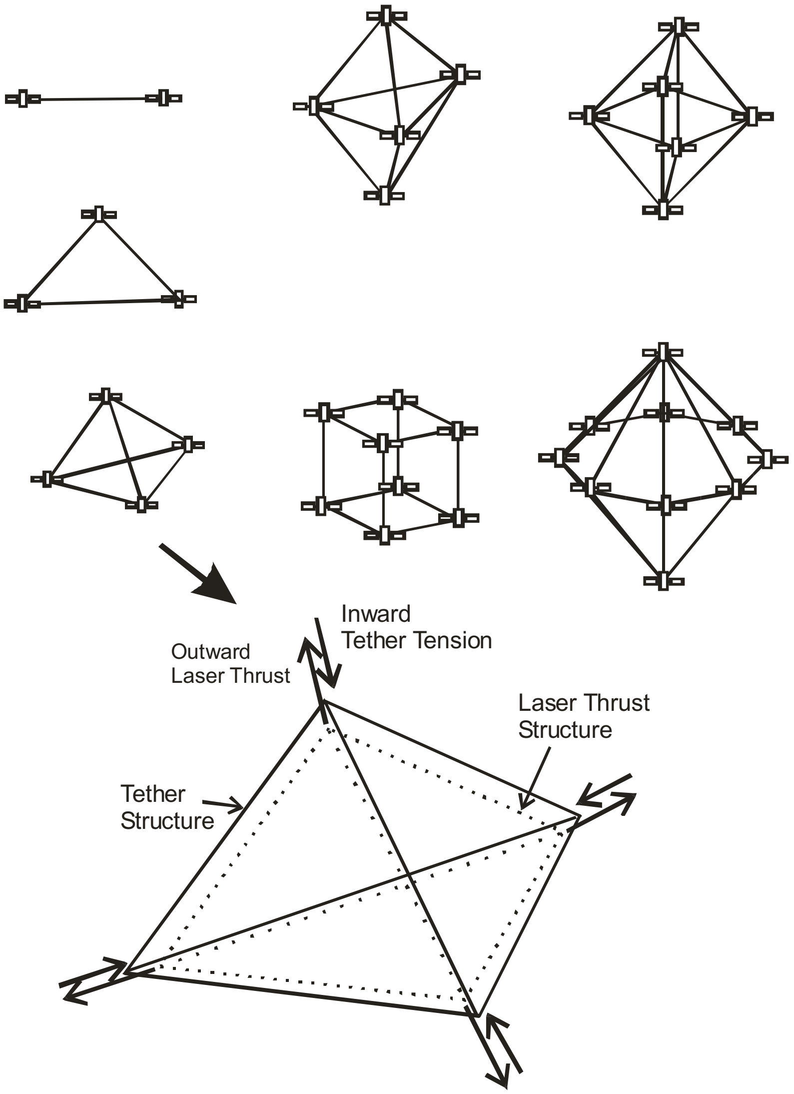

**FIGURE 2.** Schematic Diagrams of the Exemplary Satellite Mission Configurations with the Proposed Ultrahigh Precision Formation Flying Method.

The more detailed schematic diagram of the system architecture of the proposed system is shown in Fig. 3. The system has three major sub-systems: 1) the photon thruster system, 2) the interferometric ranging system, and 3) the tether system. The proposed ultrahigh precision photon thruster will provide the thrust that will push the satellites apart resulting in Hook's law type extension proportional to the laser thrust. The opposite force is balanced by the tether tension and the length of the tether is proposed to be adjusted by linear translators composed of piezoelectric translators and stepper motors to the accuracy better than 1 nm. The ultrafine balance of the pulling-in and pushing-apart is maintained by the above two mechanisms and controlled by a computer in real time, forming crystal structure-like satellite cluster. The vibration perturbation or resonance induced by the actuation and motion of the systems and satellites in tether can be rapidly (almost in real time) damped by the photon thruster.

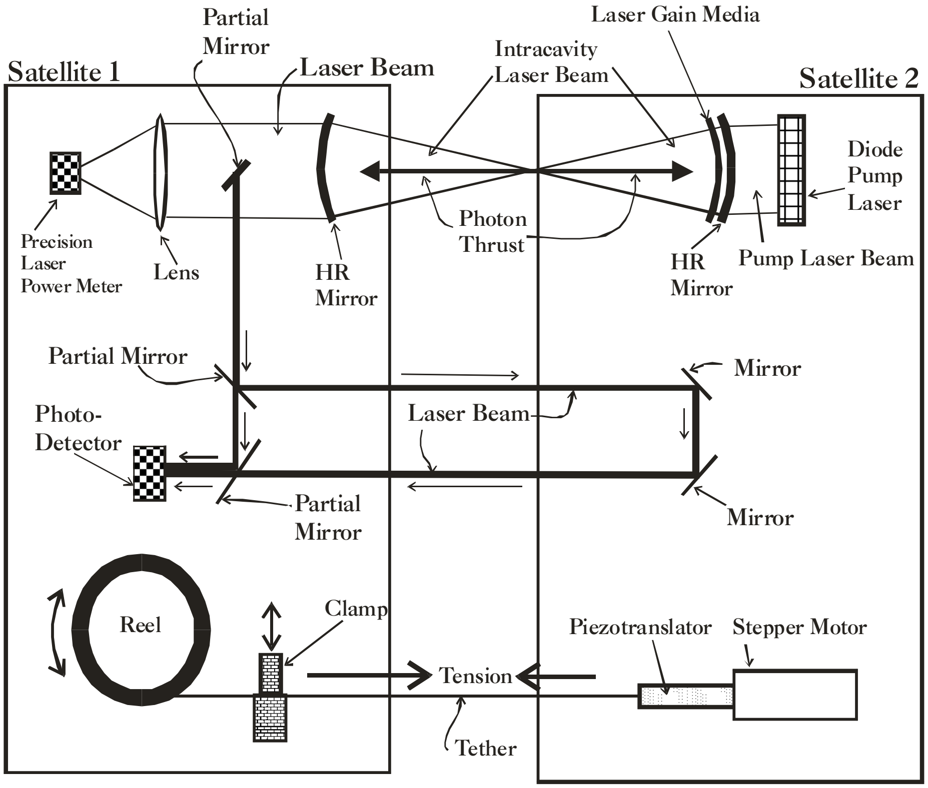

**FIGURE 3.** Schematic Diagram of the Proposed System Architecture for Pairs of Satellites in Ultrahigh Precision Formation Flying.

For example, diode pumped solid state laser systems, such as a diode pumped YAG laser intracavity laser system, can be used for the proposed formation flying method. In this case, we estimate that the extracavity laser power in the order of 10 W capable of providing photon thrust up to mN is suitable for the weight of each satellite in the order of 100 kg. The power consumption and weight of such a laser system are estimated to be about 30 W and several kg, respectively. The intracavity laser beam is formed between two high reflectance (HR) mirrors located in two separate satellites. The matching tether diameter in this case, for example, is in the order of 0.1 mm with quartz fibers. The power of the laser and the inverse of the cross sectional area of the tether is linearly proportional to the weight of the satellite. For example, the formation of 10 kg and 1 kg satellite constellations, the required laser powers are in the order of 1 W and 0.1 W respectively. The weight of the laser system decreases rapidly as the laser power decreases, thus the technology can be easily adapted to much smaller and lighter satellite platforms.

In the following sections, the details of the subsystems of the proposed formation flying method are given.

## The Intracavity Photon Thruster System

In this section the technical details of the intracavity photon thruster system shown in Fig. 3 are presented. The intracavity laser thruster system is proposed to be used to provide ultrahigh precision repulsive force between satellites against the tether contraction force. If the laser cavity is formed by two mirrors located separately in two satellites, the thrust, $F_T$, produced by a laser beam on each mirror is given by:

$$F_T = \frac{WRS}{c}, \tag{1}$$

where W the is laser power, c the light velocity, 3 x $10^8$ m/s, R the reflectance, and S is the total power enhancement factor that is the ratio of the intracavity laser power to the extracavity laser power. Here, the preferred laser cavity is a confocal resonator that consists of two identical concave spherical mirrors separated by a distance equal to the radius of curvature of the mirrors. The usage of the confocal resonator is much more advantageous than that of a flat mirror resonator. The typical cavity with flat mirrors requires an angular alignment adjustment accuracy of the order of one arc second. However, the confocal resonator has a self-aligning property, thus the alignment requirement requires only about a quarter of a degree, two orders of magnitude less stringent than that with two plane mirrors. Furthermore, the former has much less diffraction loss than the latter (Fowles, 1975).

The total laser power in the intracavity is a function of the reflectance of the HR mirror and other complicated parameters, such as the saturation power of the laser media. Here we consider first the effect of the HR mirror reflectance. Because laser photons are virtually trapped in the intracavity laser formed between two mirrors, the average laser power in the intracavity will be amplified. If there is no saturation of the gain media and no thermal management limitations, the ideal total power enhancement factor, S, of the intracavity is given by:

$$S = \frac{T(1+R)}{(1-R)^2}, \tag{2}$$

where R is the reflectance of the mirror, T is the transmittance through the mirror given by 1 – R –A, and A is the absorption of the mirror coating during reflection. For high quality mirrors, A ~ $10^{-6}$, thus, for the R < 0.99999, T ~ 1 – R, and the Equation (1) becomes:

$$F_T \approx \frac{2W}{(1-R)c}. \tag{3}$$

The parameters that determine the maximum attainable intracavity laser power are:

- The power saturation of the gain media
- The thermal management capacity of the gain media
- The HR mirror manufacturing consistency

For estimating the theoretical limit maximum intracavity laser power and the corresponding thrust, the other parameters are neglected, and results of the maximum theoretical thrusts as a function of the reflectance of the mirrors at the extracavity laser power of 10 W are summarized in Table 1.

**TABLE 1.** The Maximum Theoretical Thrusts of the Photon Thruster as a Function of the Mirror Reflectance at the Extracavity Laser Power of 10 W.

| Maximum Operation Laser Power (extracavity) | HR Mirror Reflectance | Maximum Theoretical Thrust |
|---|---|---|
| 10 W | 0.90 - 0.99 (commonly used in laser cavities) | 0.67 - 6.7 μN |
| 10 W | 0.999 (used in laser cavities) | 67 μN |
| 10 W | 0.9999 (research grade) | 0.67 mN |
| 10 W | 0.99995 (typically used super mirror) | 1.34 mN |

The optimum design of the proposed intracavity photon thruster is different from that of the typical laser cavities. The cavity design of the typical lasers is tailored to maximize the laser output power in the extracavity. Depending on the characteristics of the gain media, the reflectance of the output mirror (output coupler) is chosen 0.9 – 0.99 for the conventional laser cavities. In some cases the HR mirror with the reflectance of 0.999 has been used (Lee, 2005). To minimize the absorption loss in the gain media, the proposed photon thruster should be designed to maximize the intracavity power, thus the gain media should be very thin to minimize the absorption loss in the gain media, similar to the one used in the state of the art solid state disk lasers used for intracavity second harmonic generation, except without the need of the frequency doubling crystal (Schielen, 2004). In this case, the thermal management of the gain media becomes an important issue.

In this analysis, we have only considered the reflectivity and absorption loss of the mirrors, however, several other factors including thermal limitation and optical absorption and saturation of the laser gain media have to be considered. In reality, because of the limitation in the laser gain medium and other thermal effect, the total thrust presented in Table 1 should be considered as upper bounds. The current off-the-shelf technological limit of the system reported to date is obtained with super mirrors used for the cavity ring down spectroscopy (Romanini, 1997) (currently available in the advanced research grade only) with the reflectance of 0.99995.

The maximum thrust of the proposed photon thruster as a function of the mirror reflectance, R, is shown in Fig. 4. Note that the x-axis represents 1/(1-R), which is approximately proportional to the number of reflections between two mirrors of the photon thruster. The photon thrust shown here is calculated for a 10 W laser system, and the higher laser power will reduce the required value for 1/(1-R) proportionally. The approximate perturbation forces applied to the satellite pair of several exemplary formation flying structures due to solar radiation pressure or gravitational perturbation are shown in Fig. 4.

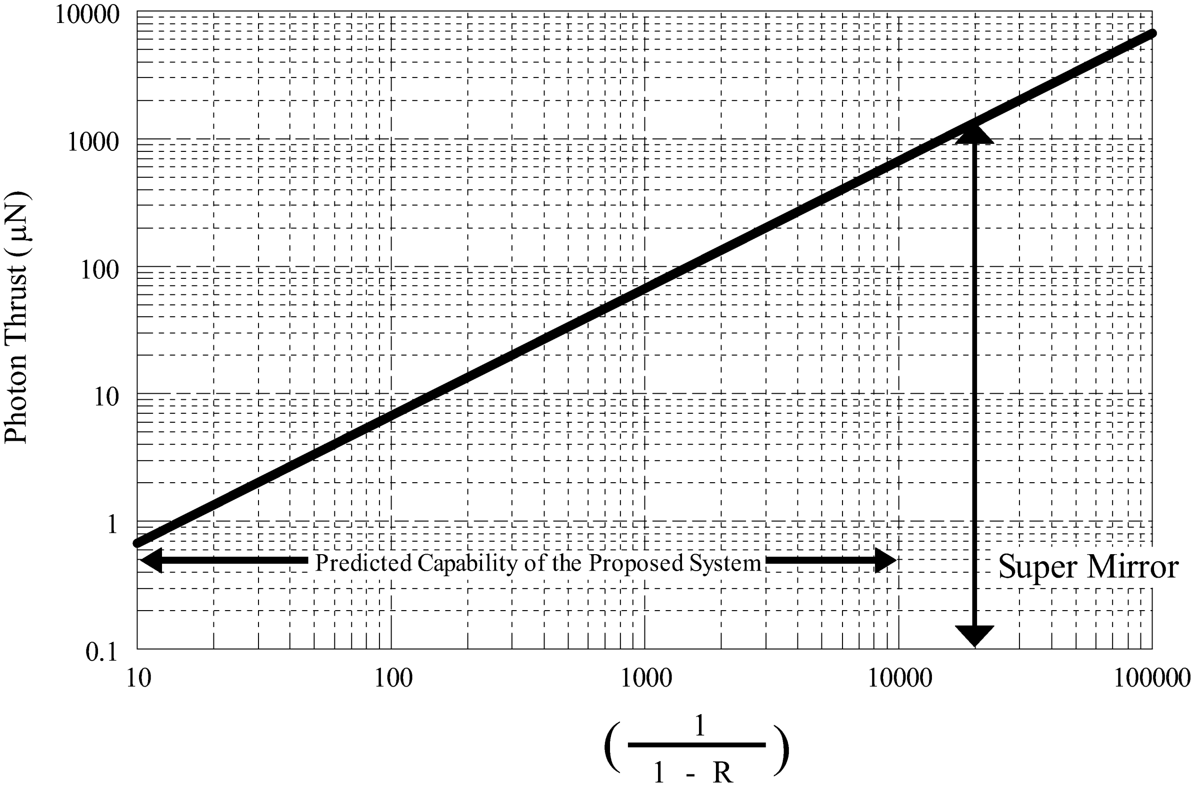

**FIGURE 4.** The Maximum Thrust of the Proposed Photon Thruster of 10 W as a Function of the Mirror Reflectance, R.

Based on the currently available laser technology, by making the gain media thin enough, the photon thruster with 0.999 -0.9999 is predicted to be readily possible with the laser design optimized for maximizing the intracavity power in the near future. With this, 10 W photon thrusters are predicted to be able to deliver up to 670 μN, which is large enough to compensate various perturbations in the space environment for most of missions envisioned as shown in Fig. 4. We note that the achievement of such high photon thrust will require highly sophisticated gain medium and pumping design and engineering, which is predicted to be within reach in the near future.

## Dual Usage of the Photon Thruster for the Interferometric Ranging System

The next generation formation flying will require a highly sophisticated ranging system for monitoring the intersatellite distance. One of the best candidates for the ranging system for the proposed ultrahigh precision formation flying method is the laser interferometric ranging system (Jeganathan, 2000, Bender, 2003). We propose here the dual usage of the photon thruster as a laser source of the interferometric ranging system. Fig. 3 illustrates the schematic diagram of the proposed subsystem in which a portion of the extracavity laser beam is reflected by a partially reflecting mirror (or a fully reflecting mirror) to be used for interferometric ranging. The schematic diagram represents one of many possible designs, and the selection of the most suitable system may depend on the specific mission requirement. The interference of the primary laser beam in the primary satellite and the laser beam reflected by the mirrors in the secondary satellite is used for assessing the relative distance change between the satellites. This dual usage will significantly simplify the system design and reduce the system weight and power consumption.

## Lifetime of the Proposed Intracavity Laser System

When the interferometer in the satellite cluster operates, the intracavity laser should operate continuously to dynamically adjust the relative distances and bearings between the satellites. The lifetime of the formation system is thus limited by the lifetime of the laser system. Currently, the lifetime of the diode pumped solid state lasers at full operation power is limited by that of pump diodes to about 10,000 hours (1 year) continuous operation. At the reduced power operation the lifetime of the pump diodes is expected to be longer. The overall lifetime of the system can be further extended by simply replacing the pump diodes with new ones. The alignment of the pump diodes does not have to be precise; a design with carousels of pump diodes can be easily made. With a ten unit carousel, for example, the lifetime of the system is extended to tens of years. With the rapidly developing diode laser technology, the lifetime is expected to increase significantly over the next decade.

## The Tether System

The proposed intracavity laser system will be combined with a tether system that will provide pulling-in force between a satellite pair through tension. For the gross length adjustments of the tether, in one of the pair satellite is proposed to have a reel mechanism and inchworm actuator that can be clamped to or released from the tether to allow low-noise fine adjustments (Fig. 3). The tether will be extended with the use of laser thrust that will be counterbalanced by the tether tension. The other satellite in the pair is proposed to have a piezoelectric translator with sub nm accuracy. Currently, off-the-shelf piezoelectric translator can deliver the accuracy resolution of 0.02 nm. Because the accuracy in the distance maintenance relies on that of the piezoelectric translator, the proposed system will be able to deliver the sub nm accuracy. The variation in length $\Delta l_F$ with the tension F, which is counterbalanced by laser thrust, is given by:

$$\Delta l_F = \frac{1}{Y}\frac{F}{A}l, \tag{4}$$

where Y is the Young's modulus, A is the cross sectional area of the tether, and *l* is the length of the tether.

Many exemplary mission systems can use the proposed formation flying method. As an example, we will consider a system that consists of satellites with an intersatellite distance of 200 m and the distance accuracy in the order of 1 nm. The system has intracavity photon thrusters with 10 W capacity with the mirror reflectance, R=0.999, capable of producing the intersatellite thrusts up to 67 μN. The tethers are made of quartz, and have a diameter of 100 μm. We assume the maximum perturbation force on each satellite is 10 μN, thus the maximum perturbation force on a satellite pair is 20 μN as shown in Fig. 4. In this system, to maintain the intersatellite distance in the accuracy of 1 nm at a distance of 200 m with a quartz tether with a diameter of 100 μm ($A = 7.85\text{x}10^{-9}$ m$^2$) and $Y = 5.4\ \text{x}10^{10}$ Pa, the system should be able to provide the thrust accuracy in the order of 2 nN ($2\text{x}10^{-9}$ N). One way to maintain such an accuracy is that the tether is stretched by the constant photon thrust of 30 μN in average (in length of 15 μm), and the perturbative force is counter balanced by changing the photon thrust or the tether tension by moving the piezoelectric translators. In this case, because the piezoelectric translators have the resolution much better than 1 nm, the limiting step is the photon thruster power accuracy, and to obtain 1-nm accuracy, the photon thrusters should have the noise to main power ratio in the order of $10^{-5}$. In the currently available CW laser systems, such noise to main power ratio can be achieved. Theoretically, either the photon thruster power or the piezoelectric translator can be continuously controlled in real time by the feedback distance signal from the laser interferometers that measure and monitor the intersatellite distance continuously. Therefore the proposed intracavity thruster system, in principle, can provide the distance adjustment better than nanometer accuracy.

In another example, a system considered has an intersatellite distance of 1 km and the distance accuracy in the order of 1 μm. The system has intracavity photon thrusters with 10 W capacity with the mirror reflectance, R= 0.9995, capable of producing the intersatellite thrust up to 134 μN. The similar thrust can be achieved by the system with R=0.999 and 20 W photon thruster power. We assume the maximum perturbation force on each satellite is 50 μN, thus the maximum perturbation force on a satellite pair is 100 μN. See Fig. 4. In this system, to maintain the intersatellite distance in the accuracy of 1 μm at a distance of 1,000 m with a quartz tether with a diameter of 100 μm ($A = 7.85\text{x}10^{-9}\ \text{m}^2$) and $Y = 5.4\ \text{x}10^{10}$ Pa, the system should be able to provide the thrust accuracy in the order of 4.2 μN. One way to maintain such an accuracy is that the tether is stretched by the constant photon thrust of 100 μN (23.8 μm in length) in average, and the perturbative force is counter balanced by changing the photon thrust or the tether tension by moving the piezoelectric translators. The accuracy requirement is only 0.042, thus readily achievable with the present proposed system. The ultimate intersatellite distance accuracy achievable with the current system by assuming the laser power noise in the order of $10^{-5}$, is 0.24 nm.

## Thermal Contraction/Expansion of the Tether System

One of important problems that the tether based system will encounter is thermal expansion/contraction of the tethers due to exposure or non-exposure of sunlight. In fact, this thermal expansion/contraction is the key factor that limits the usage of any formation methods relying on solid monolithic structured beds, in which the engineering of the real-time response system to the thermal effect is daunting. However, the proposed system with tethers and photon thrusters has a built-in capability of responding to such thermal perturbation. In the proposed tether system, the length change $\Delta l_t$ resulted from the temperature change $\Delta t$ is given by:

$$\Delta l_t = \beta l \Delta t\,. \tag{5}$$

For example, at $l$ = 200 m an environmental temperature change, Δt =10 C, will result in the tether length change as much as 1.1 mm. This temperature fluctuation will be readily compensated by a piezoelectric linear translator coupled to the tether in the similar fashion to the force perturbation. The interferometer monitors the change and provides the feedback signal that controls the piezoelectric translator for compensation. If the temperature change results in the tether length changes greater than the dynamic range of the piezoelectric translator, a reel and/or stepper motor system will kick in to provide much larger dynamic range.

## Maximum Range of Operation, Deployment and u-v Plane Activity Related Issues

The maximum range of the operation of the proposed system depends on the diameter of mirrors. The theoretical limit of the intracavity length, L, for a confocal cavity resonator is given by (Yariv, 1975):

$$L = \frac{r_1 r_2}{\lambda}, \tag{6}$$

where $r_1$ and $r_2$ are the radii of the laser beam projected on the mirrors, and λ is the wavelength of the laser. For example, for MAXIM applications with L=200 m, the required minimum diameter of mirror is 3 cm. The required minimum diameter of mirrors for the photon thrusters as a function of the operation distance is given in Table 2. The deployment process of the proposed system can be achieved by firing the photon thruster at programmed thrust until the satellites establish a desired initial intersatellite distance, while the pointing/alignment of the laser is actively controlled by the mirror controlling system and the tether is gradually released. In the most of the envisioned missions, the need for dense coverage of the u-v plane requires continuously variable operation distance. In addition, in some missions, repeatable satellite segmentation/desegmentation may be necessary.

**TABLE 2.** The Distance of Operation and the Required Diameter of Mirrors for the Photon Thruster Operation.

| Distance of Operation | Required Minimum Diameter of Mirrors |
|---|---|
| 200 m* | 3 cm |
| 1 km | 6.4 cm |
| 10 km** | 20.2 cm |

*Maximum distance between the collector and hub crafts in MAXIM.
** The distance between the hub (or collector) and converger crafts in MAXIM.

So far, we have considered the design and performance of the proposed system at the maximum intersatellite operation distance. Because the curvature and radius of the mirrors of the proposed formation flying method are designed for the maximum baseline distance, during deployment process and u-v plan activities at shorter distances, the laser beam in the cavity will be defocused. In this case, the characteristics of the laser cavity will be in between that of the confocal cavity and that of the flat mirror cavity. The fractional power loss per transit of the laser beam in the intracavity is a function of the Fresnel number, N given by (Fowles, 1975):

$$N = \frac{r_1 r_2}{\lambda L}, \tag{7}$$

where L is the length of the laser cavity, $r_1$ and $r_2$ are the radii of the laser beam projected on the mirrors, and $\lambda$ is the wavelength of the laser. In the proposed system, $r_1$, $r_2$ and $\lambda$ are constant, thus N is inversely proportional to L. The fractional power loss per transit is a function of N, and for the confocal cavity, it is a rapidly exponentially decreasing function of N, while for the flat mirror cavity, it is a slowly exponentially decreasing function of N (Fowles, 1975). At shorter operation distances, as N increases, the curve of the fractional power loss per transit shift from that of the confocal cavity to that of the flat cavity. At very short operation distances, particularly during the initial deployment, the laser cavity is close to that formed by flat mirrors. These effects of increased N and the shift of curves on the fractional power loss per transit in the laser cavity are expected to compensate each other; however, the degree of compensation is not known currently. If the effect of the increased N on the fractional power loss per transit under-compensates that of the curve shift, the increase of the mirror diameter is necessary. The details of the optical analysis of these issues are currently underway.

## CONCLUSION

We have presented general engineering requirements, design concepts, possible implementation approaches, and technology requirements for a novel propellant free, thus contamination free, method that enables ultrahigh precision satellite formation flying with intersatellite distance accuracy of nm ($10^{-9}$ m) at maximum estimated distances in the order of tens of km. In particular, the proposed method takes advantage of the dual usage of the photon thruster as a laser source for the laser interferometric ranging system for monitoring intersatellite distances in greatly reducing the complexity of the system design, weight, and power consumption. The proposed formation flying method is expected to expedite the realization of many new space missions and sophisticated earth imaging/monitoring, and to open a new class of space missions based on groups of micro-, nano, and pico satellites. We have also shown that the proposed formation flying method is within the currently available technology, and that with the laser technology specifically optimized for the proposed method will improve its efficiency by orders of magnitude in the near future. The detailed mission-specific technical analyses and supporting engineering studies on the outstanding technical issues are currently underway.

## NOMENCLATURE

A = cross sectional area of tethers ($m^2$)
$\beta$ = thermal expansion coefficient ($K^{-1}$)
c = vacuum speed of light (m/s)
$l$, $l_F$, $l_t$ = tether length (m)
F = force (N)

$F_T$ = thrust (N)
L = length of the laser cavity (m)
$\lambda$ = wavelength of the laser photon (m)
$r_1$, $r_2$ = radii of the laser beam projected on the mirrors (m)
R = mirror reflectance
S = total laser power enhancement factor in the laser cavity
*t* = temperature (K)
T = transmittance through the mirror
W = laser power (W)
Y = Young's modulus ($N/m^2$)

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