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THE GOES IN-SITU GEOMAGNETISM EXPERIMENT REIMAGINED

Bereket Abraham,[1] Donald Chu,[2] Gustave J. Comeyne,[3] Marco Concha,[4] David W. Fellows,[5] Matthew G. Heacock,[6] Sivakumara K. Tadikonda[7]

The Geostationary Operational Environmental Satellites (GOES) carry several instruments each with its own requirements. Because accommodating all of them is difficult, there is interest in putting some on their own smaller platforms. The simplest instruments are the magnetometers. These are small and have low communication, attitude control and cleanliness requirements. Getting on-station and operating in close proximity with another satellite, however, requires significant propulsion capabilities. This paper describes a CubeSat mission that goes from geo-transfer to geostationary orbit and operates next to a GOES spacecraft. Requirements, a notional design and performance predictions are provided.

INTRODUCTION

NASA's Geostationary Operational Environmental Satellite (GOES) program has placed geostationary satellites in orbit since 1976 with the primary purpose of observing storms. The GOES satellite system provides additional observational platforms, including solar observing instruments, particle sensors, and magnetometers. These instruments each have individual needs and requirements, most commonly including sensitivity to contamination and magnetic fields. In an attempt to simply accommodation and operations, it may be advantageous to host some of these instruments on separate platforms.

NASA is again considering a distributed architecture for the next generation of GOES satellites to be launched in 2030. A similar approach was considered for the recently-launched GOES-R series.[1] Perhaps the greatest increase in flexibility is acquired via re-hosting the magnetometer to a satellite separate from the larger GOES satellites. Implementing such a formation would allow for simpler requirements on the larger GOES formation, particularly due to the high degree of magnetic cleanliness required for proper operation of the magnetometer. Furthermore, removing the magnetometer from the larger GOES formation obviates the need for an onboard boom used to distance the magnetometer from the

[1] Author, Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA, 15213.
[2] Corresponding author, donald.chu-1@nasa.gov, Chesapeake Aerospace LLC, NASA/GSFC, Greenbelt MD, 20771.
[3] Author, 1335 East-West Highway, SSMC1, 8th Floor, NOAA/NESDIS, Silver Spring, MD, 20910.
[4] Author, Relative Dynamics Inc., 7852 Walker Dr., Suite 402, Greenbelt, MD 20770.
[5] Author, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 02139.
[6] Author, The Johns Hopkins University – Whiting School of Engineering, Baltimore, MD, 21218.
[7] Author, 180 Admiral Cochrane Dr, #230, Constellation Software Engineering, Annapolis, MD, 21401.

magnetically noisy environment present on the GOES satellites. Finally, distributing the GOES instrumentation among several smaller, independent satellites provides launch scheduling flexibility.

While distributing the GOES instruments among smaller, separate platforms improves scheduling flexibility, it presents the new challenge of placing these platforms in geostationary orbit (GEO). Delivering these satellites to GEO is cost-prohibitive due to the relative dearth of direct-to-GEO flights. Consequently, these CubeSats will require significant chemical propulsion systems to boost them from geostationary transfer orbit (GTO), to which launch opportunities are more common, to GEO, along with the traditional electric propulsion systems for station keeping maneuvers.

Furthermore, the GOES formation flight will require significant station keeping maneuvers performed in parallel among all of its constituents to ensure the entire formation is co-located and remains within its longitudinal dead bands. Although this initial investigation only consists of two satellites – “GINGER”, which will consist of the magnetometer, and GOES which will consist of the remaining instrumentation – the significant differences in area-to-mass ratio between these satellites will require both satellites perform significantly different station keeping maneuvers.

ASSUMPTIONS

In solving the orbit control issues which arise around co-locating GOES and GINGER, several assumptions are made in order to simplify the problem. First we assume that orbital positions are known to within 100 m per axis, and propulsive maneuvers are commanded on a fixed cadence, with resulting delta-vs considered accurate to within 5% of the nominal value provided through numerical simulation.

Second, assumptions are made on the attributes and parameters of the large-scale GOES satellite to be considered within the orbital simulation. Specifically, the scalar eccentricity of the GOES orbit is limited to 0.0005, and the effective area-to-mass ratio of this satellite is assumed to be 0.015 m^2/kg.

Third, the force model used only includes gravitational perturbations present from higher order geopotentials and the solar radiation pressure. A full environmental model would consider the Sun and Moon, but these perturbations act solely to change satellite inclination which is not considered here. These perturbations are so small that the inclination changes by less than 0.5° within a year.[2]

GINGER PROPULSIVE SYSTEM DESIGN

GINGER faces a relatively unique problem in CubeSat propulsive system design. In general, CubeSat propulsion consists solely of electric propulsion systems, featuring low thrust yet high specific impulse. Consequently, these propulsive systems work well for station keeping maneuvers in which low delta-v are required. However, GINGER will require an orbit raising maneuver to GEO as a consequence of being dropped off within GTO.

In order to perform an orbit transfer from GTO to GEO, GINGER must raise its perigee from several hundred kilometers altitude to an altitude of 35,786 km. Such a maneuver will require a delta-v of at least 1500 m/s. For typical electric thrusters to acquire such a high delta-v, burn times will be on the order of a year, a period of time which would ensure mission failure as the radiation belts will damage the spacecraft electronics.

As a result, GINGER requires both traditional electric thrusters seen on CubeSats, as well as a dedicated chemical propulsion system to raise perigee. Assuming a specific impulse of 250 s^{-1} typical of chemical thrusters and the required delta-v of 1500 m/s, a dry mass of 25 kg would require an additional ~25 kg of fuel. Recent advances in chemical propulsion have now allowed for the advent of “green” propulsion systems, in which the propellant is non-toxic, which can achieve these metrics. This is quite important, as CubeSat regulations require that all propulsion systems utilize non-toxic propellants.

One prime example is the Busek Corporation Green Monopropellant Thruster, which provides a specific impulse of 250 s^{-1} within a compact, 1.5U volume. Furthermore, this system features the use of AF-315 as the propellant, which is a recently synthesized compound which provides a density increase over hydrazine, the traditional monopropellant used in similar small-scale chemical propulsion systems, whilst also classifying as non-toxic.

As mentioned previously, to execute station keeping maneuvers, a traditional electric thruster is adequate[2]. Accion System's TILE-1uses ion electrospray propulsion, a relatively new type of electric propulsion system which provides high specific impulse while requiring relatively little electric power. The TILE-1 provides 1.5 mN of thrust with a specific impulse of 1800 s. It requires only 1U of volume, and provides better performance than traditional electric propulsion systems such as Hall thrusters, resistojets, and pulsed plasma systems.

PROXIMITY OPERATIONS STRATEGIES

Various strategies to co-locate satellites exist. The rendezvous problem that precedes co-location has been analyzed in connection with proposed geostationary servicing missions.[3] This paper investigates several different strategies and comments on the advantages and disadvantages of each strategy depending on metrics relevant to the positioning of GINGER to GOES. These include minimum distance between the satellites, time to achieve a level of positioning stability, and resources to achieve such positioning stability.

In analyzing these co-location strategies, two orbit maintenance concepts must be defined. These are a separation method and a station keeping strategy. Here, the separation method is defined as the construction of orbits for GOES and GINGER such that the two satellites are adequately separated and the possibility of a collision is low. Additionally, the orbits should not diverge rapidly.

The station keeping strategy is defined as the implementation of some law which determines the use of propulsive maneuvers to ensure that each satellite remains suitably close to its defined orbit constructed via the previously defined separation method. The implementation of a station keeping strategy and a separation method are intertwined. The more robust and accurate the station keeping control law is, the freer the separation method is to define orbits in which GOES and GINGER can more closely co-located. In general, both concepts are formulated together, as the control law implemented informs which station keeping strategies are most realizable and vice versa.

Traditional Station Keeping Strategies

Various separation methods exist, but most are derivations of six basic modes.[4] These six modes consist of complete longitude separation, longitude separation during drift cycle, longitude separation during eccentricity libration, in-plane eccentricity separation, combined eccentricity and inclination separation, and general eccentricity and inclination separation. This paper focuses on longitude separation during eccentricity libration, and the application of a Proportional-Integral-Derivative (PID) control law for this purpose.

Complete longitude separation is not so much a co-location method as it is simply ensuring that two satellites keep themselves within a defined orbit. To ensure this mode is upheld, the following requirement be met

$$\delta\lambda_0 > 2(e_1 + e_2) + (|D_1| + |D_2|)\left[\max_s |s - s_0|\right]$$

in which *D* is the longitude drift rate, and can be calculated from semi-major axis:

$$D = \frac{-1.5(a - A)}{A}$$

where A is the geostationary semi-major axis of 42164.2 km.

Though simple, this mode of separation requires relatively large differences in longitude. The third mode, longitudinal separation during eccentricity libration, improves upon the central idea of dead band splitting. In particular, it splits longitude dead bands into smaller zones but allows these zones to overlap. The zones are occupied by both satellites but at times of the day. In this separation mode, it is required that:

$$\delta\lambda_0 > 0;\ \delta D = 0;\ \delta\vec{e} = 0$$

The two satellites can be separated by any longitudinal distance --assuming that the control law can ensure minimal differences in satellite drift rates and eccentricity vectors.

PID Controller

To build a control law which is robust and easily adjustable, station keeping methods were simulated employing a controller to determine the delta-v maneuvers needed to maintain the longitude separation during eccentricity libration separation. To this end, a PID controller was created utilizing the known error in longitude. By determining the required change in longitude, daily propulsive maneuvers were then calculated to correct longitude. This PID controller drives the eccentricity to zero, thus ensuring that GOES and GINGER remain close to geostationary orbit. It also implements daily burns to minimize longitudinal drift.

Understanding the context of the model, it is then worthwhile to simulate the controller in the context of GINGER attempting to co-locate with GOES given initial conditions along with desired final conditions which the controller will use to perform station keeping maneuvers. These conditions are provided as synchronous elements, *i.e.*longitude, drift rate, and the eccentricity and inclination vectors. These simulations also require a set of PID controller coefficients be provided for both GINGER and GOES.

As an initial case to analyze the viability of a station keeping control law, a simulation was run for 80 days, utilizing MATLAB's ODE45 integrator. The PID parameters for GOES were set to [0.1 32 0.6] and those for GINGER were [0.1 64 0.5]. The initial GOES conditions were [-75.01 0 0 0 0 0], and the initial GINGER conditions were [-75 0 0 0 0 0]. GINGER's area-to-mass ratio, σ, was set to be .04 kg/m^2. The target longitudes for GOES and GINGER were -75° and -75.01° respectively.

With these conditions, as shown in Figure 1, the controller provides the following change in distance between GOES and GINGER, compared to the natural change in distance over time without station keeping.

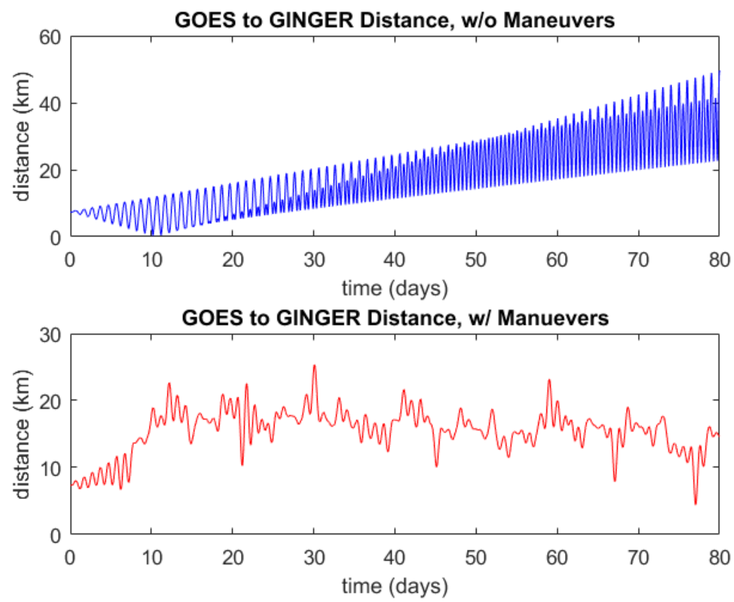

Figure 1.GOES to GINGER Distance, Case 1

The PID controller manages to keep GINGER within 30 km of GOES, and also maintains a weak convergence of approximately 15 km. By contrast the natural orbit separation rapidly oscillates and diverges. The maneuvers are relatively minimal, requiring a total delta-v of 2.06 m/s for GINGER and 2.04 m/s for GOES over the first 80 days. The distribution of these delta-vs are presented in Figure 2 below:

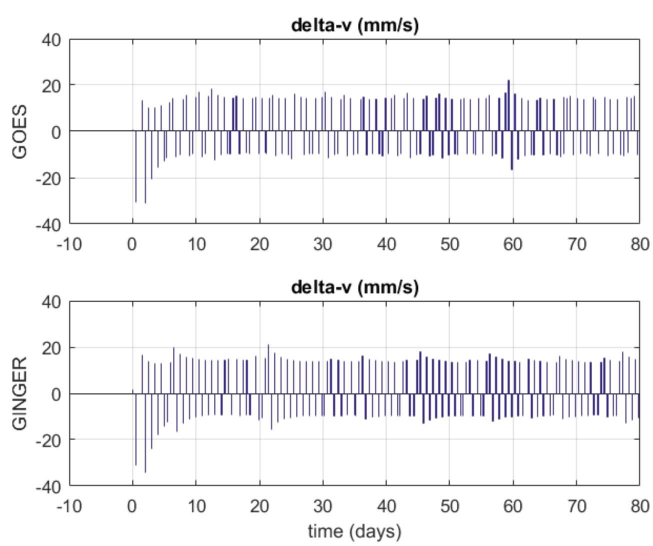

Figure 2. Delta-v Distribution, Case 1

Finally, Figure 3 shows the longitude and eccentricity of the GOES and GINGER orbits over time. Without maneuvers, both GOES and GINGER drift toward the geopotential minimum at 105^{o}W longitude. The solar radiation pressure also increases both the GOES and GINGER eccentricities. The PID controller stabilizes GOES and GINGER around their target longitudes after a period of 40 days and also limits GOES and GINGER eccentricity to an average of 0.00005 which is nearly an order of magnitude below the required level .

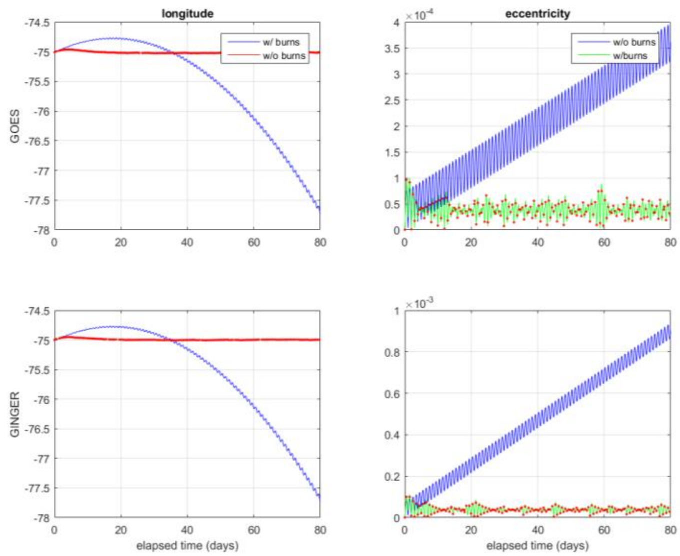

Figure 3.Longitude and Eccentricity Evolution of GOES and GINGER, Case 1

Of primary interest is how this station keeping control law holds up with an uncertainty surrounding the GINGER area-to-mass ratio. As the exact dimensions and mass and GINGER are not currently known, the control law must work with different values of σ. Thus, a case similar to case 1 was analyzed, but with twice the area-to-mass ratio for GINGER, *i.e.* 0.08 kg/m^2. Figure 4 shows the resulting GOES-GINGER separation.

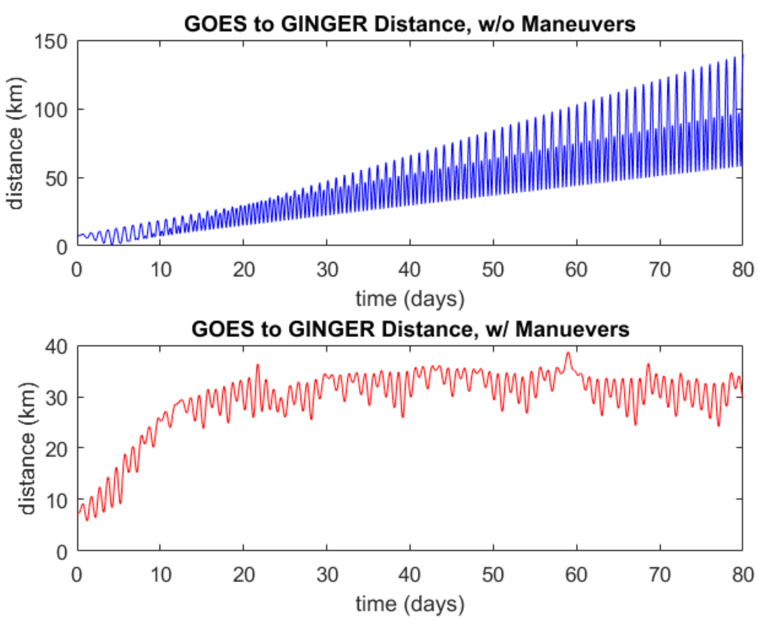

Figure 4. GOES-GINGER Separation, Case 2

Keeping all control parameters the same, the oscillations present in distance between GOES and GINGER actually decrease, but at the expense of a larger average distance between the two satellites. In an attempt to decrease this average distance, we retuned the controller gains. As shown in Figure 5, retuning such that the GINGER controller parameters were [0.1 64 1] helped alleviate the issues seen in the previous case, as average distance during the converged phase slightly decreases, and the time to convergence also slightly decreases.

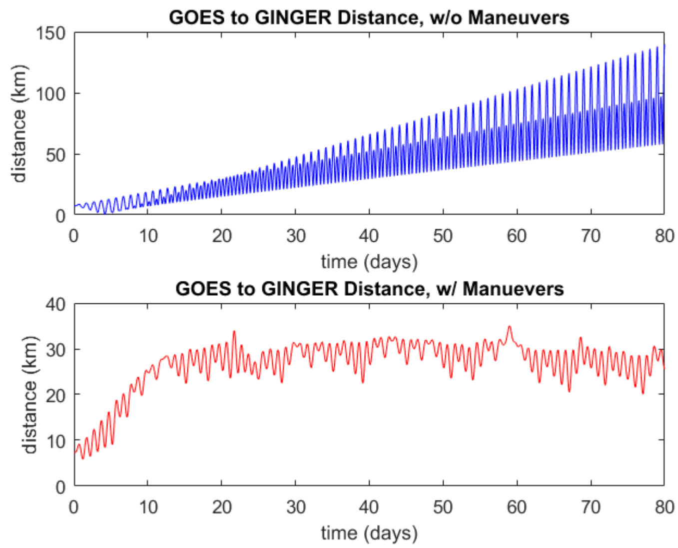

Figure 5. GOES to GINGER Distance, Case 3

Total delta-v required of GOES and GINGER became 2.04 m/s and 2.74 m/s, respectively. This was expected due to the fact that GINGER now requires more maneuvers to deal with the increased solar radiation pressure. The distribution of these delta-vs is shown in Figure 6.

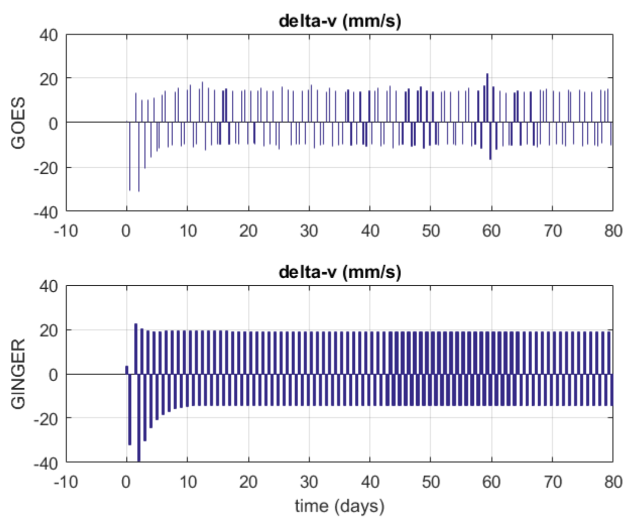

Figure 6. Delta-v Distribution, Case 3

Finally, the longitudinal changes seen by GINGER and of GOES is shown in Figure 7.

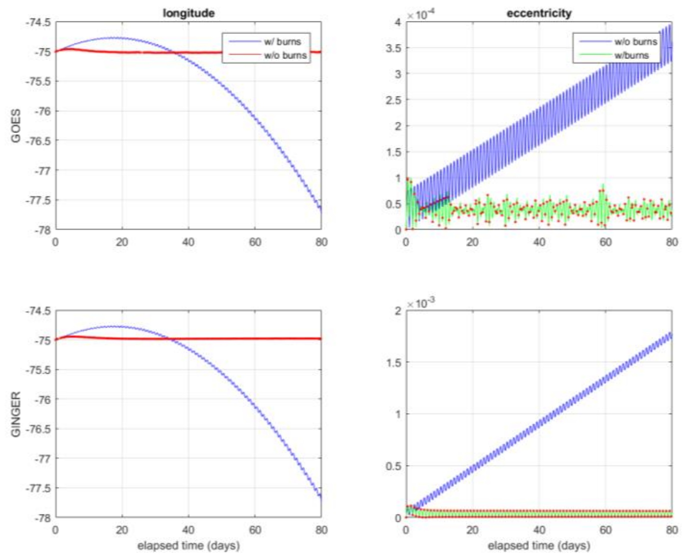

Figure 7. Longitude and Eccentricity Evolution of GOES and GINGER, Case 3

Even with the increased solar radiation pressure, the GOES and GINGER longitudes converge within a time frame similar to that in case 1, and the eccentricity is again kept suitably low.

CONCLUSION

We find that due to the scarcity of rides direct to geostationary orbit, the GINGER CubeSat will require a chemical propulsion system for orbit raising as well as traditional electric thruster for general station keeping activities. Due to recent advances in chemical and electric propulsion, commercial systems produced by Busek Corporation and Accion Systems provide the propulsive capabilities for this unconventional setup to be viable.

Further, to co-locate GOES and GINGER, a suitable separation strategy is "longitude separation during eccentricity libration" in which drift rates are minimized and eccentricities are matched. This theoretically allows for any nonzero longitude separation. A companion station keeping strategy is to use a PID controller to minimize eccentricity differences and maintain longitude separation. The controller is robust and allows for relatively stable distances to be maintained between satellites, regardless of the area-to-mass ratios.

Future work to improve station keeping could include using inclination to ensure separation and more rigorous probabilistic analysis to assess the likelihood of collision due to position knowledge and thruster error.[5]

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