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THE ION-F FORMATION-FLYING EXPERIMENTS

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The Ionospheric Observation Nanosatellite Formation (ION-F) comprises three small spacecraft that will cooperate to make measurements of the ionosphere's electron density and its effects on GPS signal propagation. A novel feature of the mission is the planned suite of formation flying experiments involving the three satellites. The uniqueness of these experiments is enhanced by the dissimilar nature of the sensors and actuators used by the three spacecraft, including micro-pulsed plasma thrusters, a hydroxylammonium nitrate (HAN) monopropellant thruster, and differential drag control. In this paper, we describe the ION-F mission, the designs of the three satellites, and the proposed suite of formation flying experiments.

INTRODUCTION

The ION-F mission is part of the Air Force Research Laboratory/DARPA University Nanosatellite Program, which provides technology demonstration for the TechSat21 Program. The University Nanosatellite Program involves 10 universities building nanosatellites for one or two 2002 launches on the space shuttle. The ION-F mission involves three of these universities: University of Washington, Utah State University, and Virginia Tech. The three satellites are being designed and built by students at the three universities, with close coordination to ensure compatibility for launch, deployment, and both the ionospheric observation and formation flying missions.

The three satellites, University of Washington's *DawgStar*, Utah State's *USUSat*, and Virginia Tech's *HokieSat*, are all similar in size, with each massing between 10 and 15 kg and having a hexagonal shape of 18" in diameter. The three nanosats also have common designs for some subsystems. However, the three spacecraft have several distinct features, especially the mode of orbit control. In this paper, we describe in some detail the science mission and the individual satellite configurations. Then we describe the formation flying mission.

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IONOSPHERIC SCINTILLATION NANOSATELLITE FORMATION MISSION

The objective is the understanding of ionospheric density structures that can impose large amplitude and phase fluctuations on radio waves passing through the ionosphere. The formation provides a unique opportunity to answer questions about ionospheric disturbances that cannot be addressed any other way. A single satellite can only provide limited information on the dimensions and evolutionary time scales of the ionospheric disturbances it flies through because a full orbit (90 minutes) must occur between adjacent observations. In general the situation is even worse because only zero-inclination equatorial satellites have a good possibility of measuring the same region twice due to the co-rotation of the ionosphere with the Earth. This science investigation contributes to the TechSat 21 basic research mission of investigating global ionospheric effects that affect the performance of space-based radars. It also addresses broader Air Force interests in ionospheric effects on navigation and communication links.

The ION-F mission will make the first global multi-satellite electron density measurements in the ionosphere. It will also make the first global multi-baseline RF-scintillation measurements of the ionosphere. The scintillation of GPS signals using receivers on each spacecraft will provide information about the scale sizes of disturbances between the nanosatellite constellation and the GPS transmitter.

The Earth's ionosphere frequently shows density disturbances and fluctuations over a very large range of scale sizes (from hundreds of kilometers to centimeters) at all latitudes and longitudes, and nearly all altitudes. Ionospheric plasma density irregularities are associated with two-dimensional turbulent processes driven by both low latitude tidal neutral winds and high latitude current systems. We seek to determine the global distribution of plasma structure in both the quiet and disturbed ionosphere. The proposed measurements would provide essential information for the understanding of ionospheric effects on communications, navigation, and GPS systems and for the development and validation of realistic predictive global ionospheric models. These observations are related to the priority measurements set up the by the National Space Weather Program.

The electron saturation current probe is based on the DC response of a plasma to an applied potential on a probe. These probes were pioneered in the early 1920s by I. Langmuir and consequently are also known as Langmuir probes. The plasma frequency probe technique is based on the AC response of the probe. Early work in this technique can be traced back to diagnostics on V2 rockets shortly after World War II. These types of probes have been called impedance probes, RF-probes, and capacitance probes.

A Langmuir probe consists of a small conducting electrode immersed in a plasma. This electrode is connected to a power supply that can be biased at various potentials with respect to some appropriate "ground", typically the spacecraft structure. The method then consists of interpreting the current collected by the probe as a function of the applied voltage. Langmuir probes are simple devices, but the theory underlying their response is, unfortunately, extremely complicated in general. The primary virtue of a Langmuir probe is that the instrumentation is simple. The primary disadvantage of Langmuir probe techniques is that experimenter must accurately account for the varying parametric influences of the probe surface conditions and overcome such experimental difficulties as ground reference variations, contamination, and probe geometry effects. Thus claims of absolute calibrated (as opposed to relative) density measurements with any degree of real accuracy must be viewed with skepticism.

An impedance probe consists of short antenna immersed in a plasma. This antenna is driven with a voltage oscillator operating at RF frequencies. The magnitude and phase of the current flowing to the antenna is sensed from which the impedance of the antenna can be determined. The impedance of such short antenna in a plasma has been extensively studied theoretically and laboratory experiments have shown excellent agreement with theory. The impedance of an antenna immersed in a plasma peaks as the antenna resonates with the characteristic frequencies of the plasma. For instance the impedance near the plasma's upper hybrid frequency electrically behaves like a parallel inductor, capacitor, tuned circuit. At the electron cyclotron frequency the antenna also exhibits a strong resonance that is electrically similar to a series inductor, capacitor, tuned circuit. The primary advantage of impedance techniques is that an absolute electron density can be confidently calculated from the data to within 1% accuracy. The measurement is independent of electron temperature, ground potential, probe surface contamination, and orientation to the geomagnetic field. Relative variations as small as 0.05% of the total density are routinely achieved in space plasmas by this technique.

The scintillation measurements will be extracted from the GPS receivers that are part of the orbit determination system on the nanosats. The 1575 MHz signals from the GPS satellites originate at 20,000 km over the Earth and must travel through the ionosphere, line of sight, to the location of the nanosats at ~380 km altitude. The signal will encounter regions of disturbed ionospheric plasma that will slightly increase or decrease the signal strength at the receivers. The size of these disturbed regions can be estimated by comparing signals measured over closely related propagation paths, such as between two nanosats.

DESCRIPTION OF THE ION-F NANOSATS

All three satellites will be 18" diameter hexagonal structures, each massing from 10 to 15 kg. All three will have GPS receivers and crosslink communications systems for relative position determination and for coordinating science and formation flying activities. The three satellites will be deployed with other nanosats from a Shuttle Hitchhiker Experiment Launch System (SHELS) and then deployed individually from an AFRL-designed "mother ship." The formation flying experiments will occur early in the ION-F mission, as the lifetime of the satellites is expected to be less than six months, and the propulsion capabilities of the satellites are not sufficient to recover quickly from large separation distances.

UW DawgStar

The University of Washington satellite, DawgStar, will include micro pulsed plasma thrusters (μPPTs) developed by Primex Aerospace Corporation. These μPPTs will provide minimum impulse bit of as low as 70 μN-s for fine control of both position and attitude. The thrusters will also be used to raise the orbit and extend the life of the mission. Figure 1 illustrates the various subsystems of DawgStar.

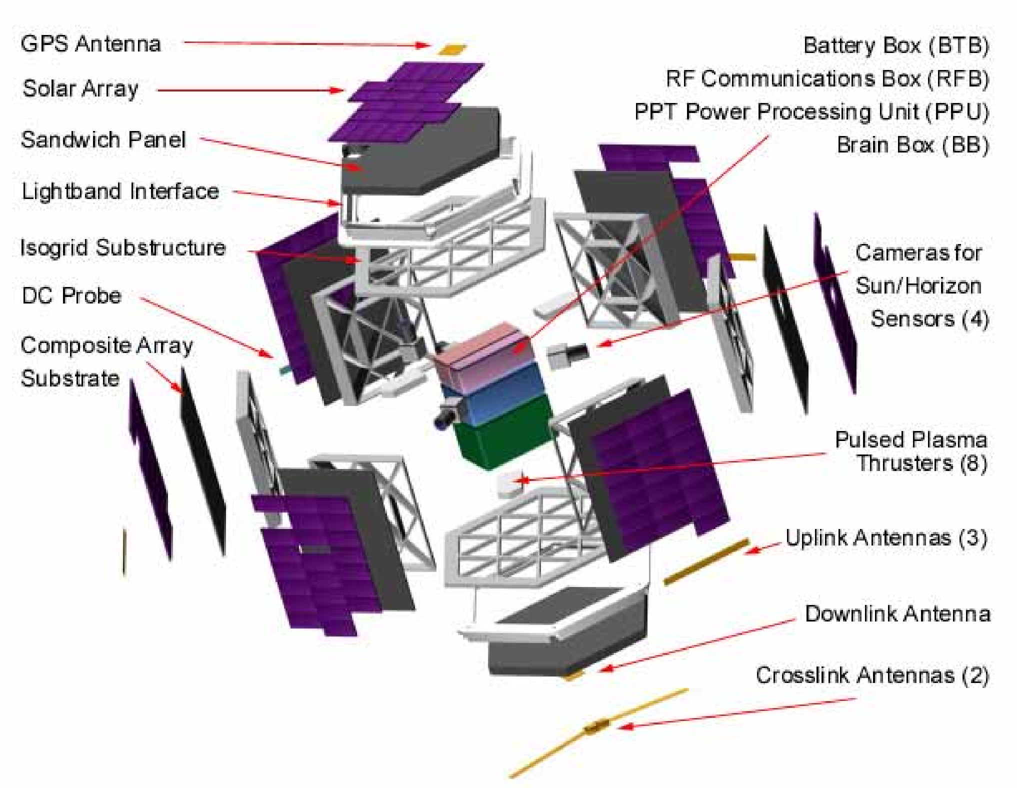

Figure 1: Breakout of the UW DawgStar Satellite

USUSat

The Utah State University satellite, USUSat, will not include any propulsion capability, but will be able to effect orbit control by controlling the drag force acting on the spacecraft. Using permanent magnets to control the attitude, the spacecraft's ballistic coefficient $[m/(C_D A)]$ will be controllable in a range of 20-60 kg/m^2. The resulting change in aerodynamic force will be used to control the orbital motion of the spacecraft. Of course, this control will lead to an overall decrease in altitude during the mission, effectively limiting the lifetime of the USUSat mission and the ION-F formation flying experiments.

VT HokieSat Subsystems and Hardware

The VT HokieSat structure is a hexagonal prism, 12.625”. high, 9” on each side, and 18” across at its largest diameter. The structure consists of two hexagonal base plates and six side plates. The primary load-bearing structure of each plate is isogrid of Aluminum 6061-T651. Attitude determination will be accomplished using a combination of a three-axis magnetometer, sun sensors, a three-axis gyro, and four digital CMOS cameras for horizon and sun sensing. The cameras are experimental in nature, and are to be used as the back-up system. Power is supplied by strings of 11 high efficiency solar cells to give a 22 V bus, and NiCd batteries. DC-DC converters are used for those components operating at other voltages. The L3 Communications T-400 transmitter is used for the downlink. This S-band frequency agile transmitter has been used for tactical video and telemetry applications, and meets IRIG standards. The L3 Communications CAR-915A receiver is used for the uplink receiver. This L-band receiver has crystal frequency control. The communication downlink uses one patch antenna, while the crosslink and uplink receiver antennas are monopole tape designs. Although only USU and VT will have ground station/satellite communications, an internet based operations center will enable each university to control its satellite (and constellation) from its own remote location. The flight computer is a Sharp LH77790 ARM processor, using the VxWorks operating system. HokieSat will also include a hydroxylammonium nitrate (HAN)-based monopropellant system developed by Primex Aerospace Corporation. These HAN-based thrusters will provide minimum impulse bit of as low as 2 mN-s and will primarily be used for orbit control during the formation-flying mission and for orbit-raising to extend the life of the overall mission.

FORMATION FLYING

Formation-flying is defined in Ref. 5 as follows: A constellation is two or more spacecraft in similar orbits with no active control by either to maintain a relative position. Formation flying is two or more spacecraft that use an active control scheme to maintain the relative positions of the spacecraft. When all satellites have the same altitude, velocity vector, and radial separation, there is a separation in time only, and this is termed a leader-follower formation. Control is only required for minimizing disturbances (differential drag, etc.). When the inclinations are different, but all satellites have the same altitude and velocity magnitude, this is called a side-by-side formation. This formation creates an appearance of the chaser satellite moving to the left and right of the leader satellite. Control is needed to maintain the relative distance between satellites. When all satellites have different altitudes, inclinations, and velocity vector magnitudes and directions, but pass over the same ground track, this is called a same ground track formation. This formation is termed “ideal” by Goddard, and creates the same ground track, but at a different times. This formation requires control/propulsion throughout.

The Applied Physics Lab (APL) at Johns Hopkins University is currently developing an integrated GPS/cross-link system for ION-F through a grant by NASA Goddard Space Flight Center (GSFC). Preliminary specifications of this system include 450 MHz frequency, 200 mW transmit power, 2 kbps data rate, monopole tape antenna, and mass of 500 g. The system allows multiple receive frequencies, thus allowing the multiple satellites to communicate at the same time. The GPS receiver is integrated into the system, and adds an additional 200 g and 1.85 W. Orbit determination software will allow the accuracy of the relative satellite distances to be determined with accuracy on the order of 10 m.

The UW DawgStar thrusters are miniature versions of an experimental PPT thruster, to be flown on the EO-1 mission 1. They are being designed in collaboration with Primex Aerospace Company, through a grant with the Washington Technology Center. The work attempts to reduce the mass and power of the propulsion system by 1) using ceramic capacitors, instead of oil filled capacitors, 2) using high voltage switches (~500V) to charge only the intended capacitor, and 3) to move, reduce, or remove the igniter, which selects and activates the correct thruster. A prototype of one thruster is shown in Figure 3, while a summary of the characteristics of the thruster system are given in Table 1. These specifications have since been verified experimentally during tests in October 1999; for more information on the DawgStar propulsion system, see Ref. 8.

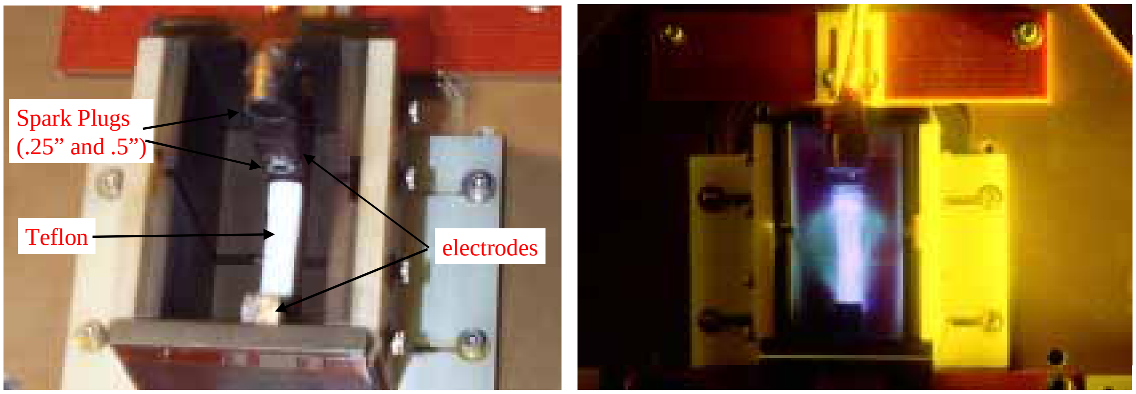

Figure 3: Prototype set-up of one PPT (left), and its firing in October 1999 (right)

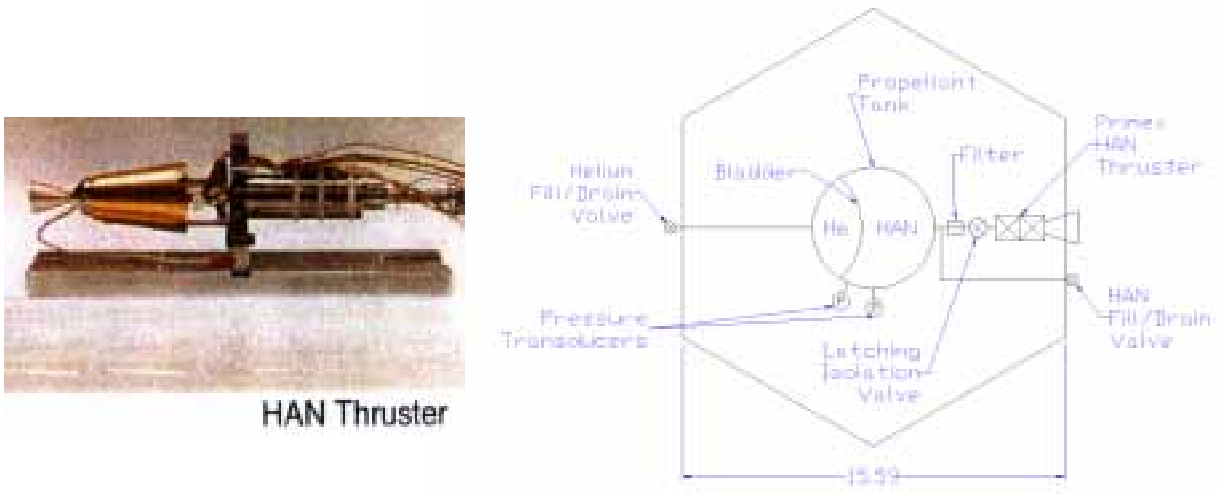

Figure 2: HAN thruster and propulsion system configuration

Table 1: Summary for the PPT and μ-PPT

	PPT	μPPT
Satellite Mass (kg)	100 – 5,000	5 – 100
Impulse Bit – IBIT (μNs)	700	65
Specific Impulse – ISP (sec)	1150	400
Energy – E (J)	50	5
Mass – m (kg)	4	1
Thrust – T (mN)	0.7	0.065

The UW DawgStar will utilize only eight thrusters for five-axis control in order to save mass. All six degrees of freedom are controllable, however, through coupling in the orbital dynamics. The system will contain four clusters of two thrusters each, with one capacitor per pair. One power-processing unit with high voltage switches will power the system.

Figure 4 shows the locations of the thruster pairs. Through the use of a 45°angle in the fuel bar/electrode plane, five degrees of freedom can be controlled directly. Referring to the numbering in Figure 4, direct control of five degrees of freedom is as follows:

- X: 2,3 and 6,7
- Y: 1,8 and 4,5
- θ_X : 1,4 and 5,8
- θ_Y : 2,7 and 3,6
- θ_Z : 1,3,5,7 and 2,4,6,8

Note that four thrust combinations require two thrusters to fire at once. Given two thrusters firing at 1 Hz, 13 W of power is required, which is the maximum power allotted to the propulsion subsystem.

The Virginia Tech satellite, HokieSat, will include a hydroxylammonium nitrate (HAN)-based monopropellant system developed by Primex Aerospace Corporation. These HAN-based thrusters will provide minimum impulse bit of as low as 15 mN-s and will primarily be used for orbit control during the formation-flying mission and for orbit-raising to extend the life of the overall mission. If safety issues prevent the use of HAN-based thrusters, HokieSat will use a two thruster version of UW's μPPT system.

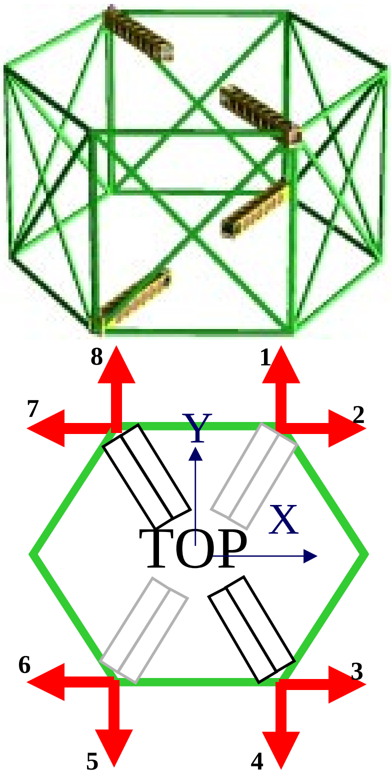

Figure 4: Locations of the eight thrusters for DawgStar

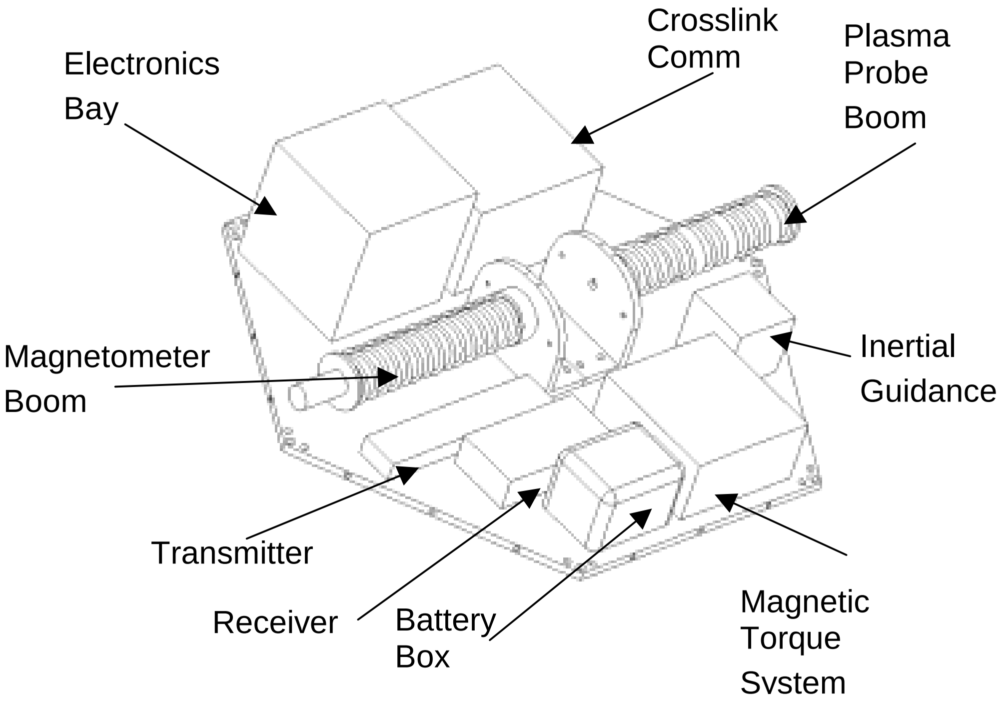

Figure 5. Utah State University USUSat

The Utah State University satellite, USUSat, will not include any propulsion capability, but will be able to effect orbit control by controlling the drag force acting on the spacecraft. Using permanent magnets to control the attitude, the spacecraft's ballistic coefficient [$m/(C_D A)$] will be controllable in a range of 20–60 kg/m^2. The resulting change in aerodynamic force will be used to control the orbital motion of the spacecraft. Of course, this control will lead to an overall decrease in altitude during the mission, effectively limiting the lifetime of the USUSat mission and the ION-F formation flying experiments.

The USUSat program intends to investigate the use of aerodynamic forces to maneuver within the Ion-F formation. The magnitude and perhaps the direction of the aerodynamic forces acting on USUSat are controlled in turn by orienting different surface areas of the spacecraft into the ram direction. By properly modulating this force, USUSat can maneuver with respect to the remainder of the propulsive driven formation.

The aerodynamic forces acting on an object within a free molecular flow can be approximated as[8]

$$\vec{f} = \rho_a V_R^2 \oiint\limits_{\substack{spacecraft\\surface}} H(\cos\alpha)\cos\alpha \left\{ \left[\left(2 - \sigma_n - \sigma_t\right)\cos\alpha + \sigma_n \left({V_b}/{V_R} \right) \right] \hat{n}_A + \sigma_t \hat{V}_R \right\} dA$$

where

$\vec{f}$	is the aerodynamic force vector acting on a surface
α	is the angle between the velocity vector and a surface inward unit normal vector
$H(\cos\alpha)$	$= 1$ for $\cos\alpha > 0$ and $= 0$ for $\cos\alpha \leq 0$
ρ_a	is the atmospheric density
V_R	is the relative free stream velocity of the flow
V_b	is the mean free molecular velocity
σ_n, σ_t	are the average normal and tangential accomodation coefficients
$\hat{n}_A$	is the inward unit surface normal vector
$\hat{V}_R$	is the relative free stream unit velocity vector
dA	is the incremental surface area

Note that this equation predicts that not only is a drag force generated (the $\hat{V}_R$ component), but that a surface normal force is also be present (the $\hat{n}_A$ component). This opens up the possibility of generating forces perpendicular to the orbital velocity vector.

The principal unknown in the above equation is the atmospheric density, which varies according to the solar cycle, altitude, day/night variation, and other space weather effects. Table 1 presents estimates[15] of the variation in this value over the altitude range where USUSat is expected to fly.

The measure of the ability of a formation to remain relatively close together in a drag environment is the relative decelerations acting on each spacecraft, described approximately by each spacecraft's Ballistic Coefficient:

$$B.C. = m / C_D A$$

where m is the spacecraft mass, C_D is the drag coefficient, and A is the cross-sectional spacecraft area. All three spacecraft in the ION-F stack are designed with a hexagonal cross-section approximately 0.46 m in diameter. However, The USUSat is only 0.16 m thick, whereas the UW and VT nanosats are 0.31 m across. Based on current mass estimates, the ballistic coefficients of the three ION-F spacecraft are shown in Table 2.

Table 2. Ballistic Coefficients

	University of Washington[4]	Virginia Tech.	USUSat (min drag orientation)	USUSat (max drag orientation)
Ballistic Coefficient (kg/m^2)	46	48	34.1	96.8

Autonomous formation flying using inter-satellite cross-links has never been accomplished previously. There are many cases of rendezvous in the past, and soon EO-1 will formation fly with Landsat. However, the latter case will be accomplished through satellite-ground communication links, rather than autonomously through the satellite cross-links. Therefore, the formation flying mission objectives are qualitative rather than quantitative:

Primary Objectives:

- Demonstrate inter-satellite communications
- Demonstrate autonomous formation keeping
- Demonstrate autonomous formation maneuvering

Secondary Objectives:

- Demonstrate more than one formation
- Demonstrate three satellite formation maneuvering

With these objectives, the formations to be attempted within the ION-F mission for formation keeping and maneuvering will be very simple. The primary focus will be on the leader follower formation. The leader-follower formation is exactly as the name

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[4] UW and VT satellites are assumed to have a drag coefficient of 2.4, a mass of 14 kg. and to be flying in a minimum drag orientation.

implies: same orbital parameters, but at different times. Once the three satellites deploy and check out (for instance, the thrusters and cross-link, attitude control), the satellites will be drifting apart because of the separation velocity and differences in drag. This separation will be primarily in the radial path. The ION-F satellites will then perform a series of experiments using the formation's control capability. These are described subsequently.

The same ground track formation, termed "ideal" by NASA Goddard 5, is one in which two or more satellites have identical ground tracks. Examining the same ground track formation more closely, consider Figure 6. Shown are two satellites as they cross the equator at slightly different times (1,2,3). In the upper left, the first satellite crosses the equator (1) and then moves on (2,3). In the lower right, the second satellite is lagging behind (1), but within a small amount of time, it too crosses the equator (3). The Earth, meanwhile, is rotating (center, between the satellites). For the same ground track formation, given the small amount of time it takes the second satellite to cross the equator, the Earth exactly rotates such that the two satellites fly over the same point on the surface of the Earth.

The Same Ground Track formation can be simplified to a change in time (ΔT) between when the satellites pass over the same point on the Earth. Using the geometry of Figure 6, we see that the relative separations are

$$\Delta X = -V_x \Delta t + \omega_E R \Delta t \cos\theta_I$$
$$\Delta Y = \omega_E R \Delta t \sin\theta_I \cos(\omega_E t)$$

where all parameters are known, and the initial condition for $t = 0$ is defined at the equator.

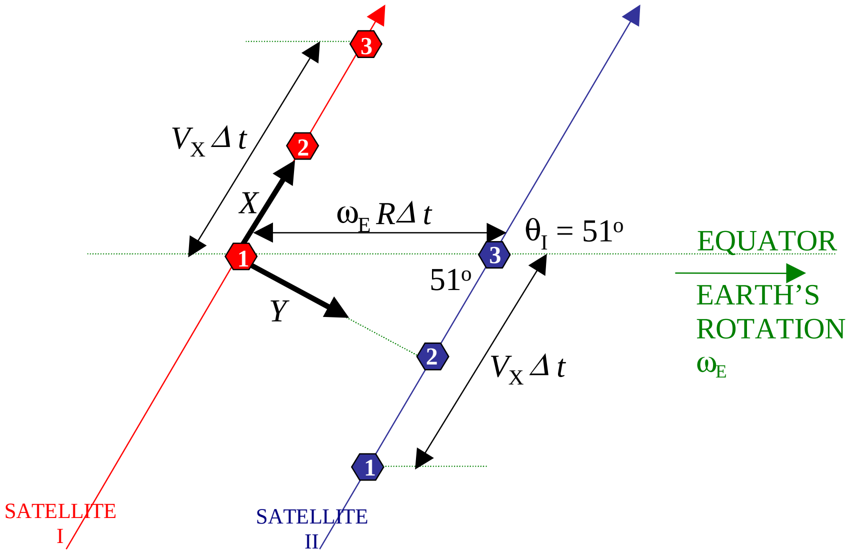


Figure 6: Same ground track formation as satellites pass over the equator

Considering the objectives, two-month minimum lifetime, and two simple formations described above, the following is an outline of the nominal formation-flying mission:

Table 3: ION-F Mission Timeline.

Duration	Activity
5 days	Deploy as an ION-F stack from AFRL mother ship Checkout of GPS, attitude determination, thrusters, communications Downlink health data and debug
4 days	Deploy as individual nanosats from ION-F stack Checkout of attitude control, thrusters, inter-sat communications Downlink health data and debug
7 days	Maintain leader follower formation in 2-3 km separation range Both UW and USU fly relative to VT Debug as necessary, attempting to keep nanosats within 2-3 km separation
21 days	Attempt various formation maneuvering and keeping algorithms (UW, GSFC, USU, VT, others) Maneuver formation to a leader follower separation from 2-3 km separation to 10 km separation and back Formation keep at various points
7 days	Maneuver formation to same ground track formation using UW's PPTs and VT's HAN-based system Formation keep to a separation of approximately 2-3 km Maneuver back to leader follower formation.
3 days	Maneuver or drift out to an inter-satellite separation of approximately 20 km
7 days	Attempt three satellite formation maneuvers
7 days	Attempt formation keeping and pointing
as long as possible	Orbit raising and mission life extension

MISSION TIMELINE

MISSION SUCCESS

The nominal formation-flying mission is four months, while the minimum formation-flying mission is two months, based on the objectives listed above. However, with the uncertainty in the orbital parameters, the minimum numbers are used in simulations and calculations. For instance, based on a drag model for the DawgStar satellite in Jan-Apr 2002, the lifetime of the satellite is approximately three months. If DawgStar is to make its four-month lifetime requirement, it must make-up drag at least by the end of the second month, which is approximately when the absolute drag of the satellite counteracts the maximum thrust (based on two thrusters).

Using this result, DawgStar will have a two-phased mission sequence: Phase I for formation flying and ionospheric science, and Phase II for drag make-up and ionospheric science. Table 4 shows a summary of the total ΔV required for the DawgStar satellite. The attitude control calculations are based on CP-CG = 2 cm, and the full drag model for 2002. Formation keeping is based on USU-UW differential drag, and formation maneuvering is based on full 1 Hz thrust (min time). Orbit maintenance is based on full drag make-up, which is equivalent to the thrust from two PPTs firing at 1 Hz.

Table 4: Total ΔV required for DawgStar

	Phase I		Phase II	
	ΔV (m/s)	% T	ΔV (m/s)	% T
Attitude Control	3.4	100	6.5	100
Formation Keeping	13.8	90	n/a	n/a
Formation Maneuvering	4.8	10	n/a	n/a
Orbit Maintenance	n/a	n/a	38.5	0
Total	22.0		45.0	

Figure 7 shows a preliminary block diagram for autonomous formation flying for DawgStar. Trajectories are generated on the satellite or on the ground, using approaches such as linear programming (min time/fuel) or other simpler trajectories. The control logic is based on the thrust asked for, and the minimum thrust of the PPTs. If the controller asks for more than the given thrust of the PPTs, they fire. Figure 8 shows a simulation of a 1 km leader-follower maneuver, followed by formation keeping at a 1 km relative separation. This is a simulation of only the UW and USU nanosats, which are quite different in terms of drag capability. Note that the UW DawgStar thrusts at its maximum (1 Hz) during the maneuver, while it only partially thrusts during formation keeping. This is because the drag difference is much smaller than the thrust capability of the PPTs. A full set of simulations and details on the control logic can be found of Ref. 1.

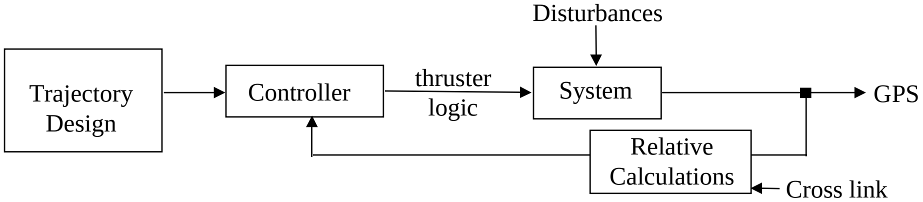
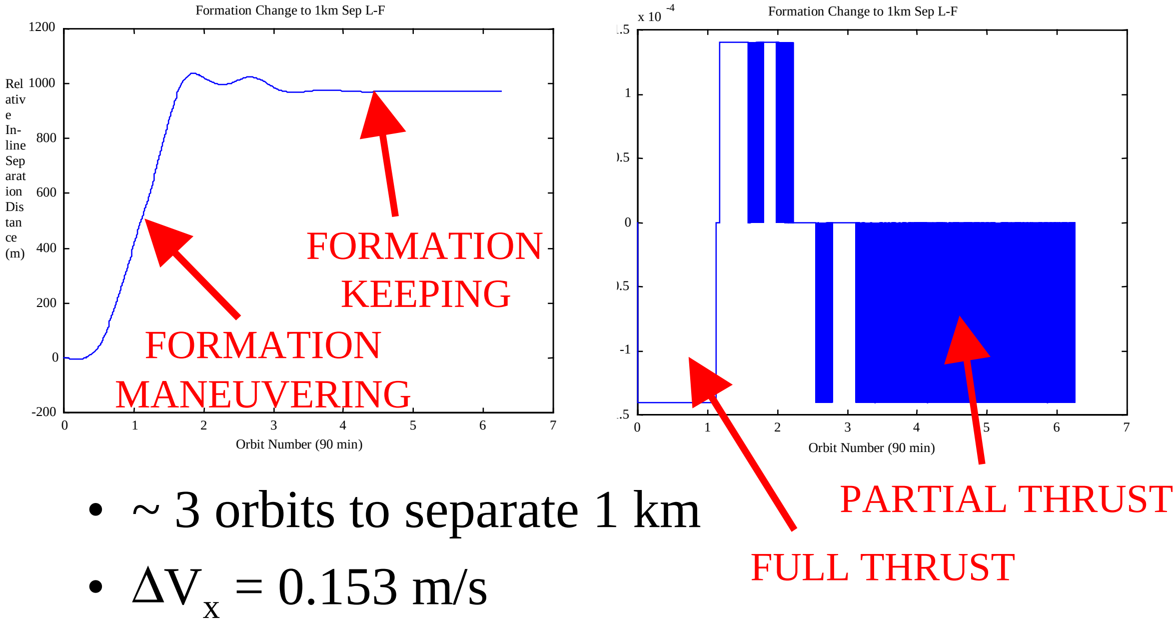


Figure 7: Block diagram of the autonomous formation flying control system.



- ~ 3 orbits to separate 1 km
- $\Delta V_x = 0.153$ m/s

Figure 8: Simulation of the along track separation and PPT thrust profile for UW DawgStar nanosat and a leader-follower maneuver from 0 to 1 km relative separation.

CONCLUSIONS

The Ionospheric Observation Nanosatellite Formation will demonstrate several novel technologies, as well as demonstrate autonomous formation-flying of closely separated nanosatellites. The novel technologies include μPPTs, HAN-based monopropellant thruster, and differential drag for orbit control. ION-F will be deployed from the space shuttle along with another "stack" of university-built nanosatellites. Furthermore, the formation will obtain novel scientific measurements that will help to characterize the ionosphere.

REFERENCES

1. T. L. Beach, *Global Positioning Sytem Studies of Equatorial Scintillations*, Ph.D. Thesis, Cornell University, Ithaca, New York, 1998
2. M. Campbell and T. Schetter, "Formation Flying Mission for the UW DawgStar Satellite," IEEE Aerospace Conference, Big Sky MT, March 2000
3. M. Campbell *et al.*, "UW DawgStar: One-Third of ION-F," 1999 *USU/AIAA Small Satellite Conference*, August 1999, Paper No. SSC9-III-4
4. N. Davis, J. DeLaRee, C. D. Hall, W. L. Stutzman, and W. A. Scales, "Virginia Tech Ionospheric Scintillation Measurement Mission," AIAA/Utah State University Conference on Small Satellites, Logan, UT, Aug 31- Sep 3, 1999, Paper SSC99-III-3

5. D. C. Folta, L. K. Newman, and T. Gardner, “Foundations of Formation Flying for Mission to Planet Earth and New Millennium,” AIAA-96-3645-CP, NASA Goddard Space Center, 1996
6. G.W. Hill, “Researches in the Lunar Theory,” *American Journal of Mathematics*, Vol. 1, No. 1; pp. 5–26; 1978
7. W. A. Hoskins, M. J. Wilson, M. J. Willey, N. J. Meckel, M. Campbell and S. Chung, “PPT Development Efforts at Primex Aerospace Company,” 35th *AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Los Angeles CA, June 1999, AIAA 99-2291
8. P. C. Hughes, *Spacecraft Attitude Dynamics*, John Wiley & Sons, 1986
9. W. J. Larson and J. R. Wertz, ed., *Space Mission Analysis and Design*, 2nd edition, Microcosm, Torrance, CA, 1992
10. D. Meinhardt, G. Brewster, S. Christofferson, and E. J. Wucherer, “Development and Testing of New, HAN-Based Monopropellants in Small Rocket Thrusters,” in *Proceedings of the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Cleveland, OH, July 13–15, 1998, AIAA 98-4006
11. C. Rayburn, M. Campbell, A. Hoskins, and J. Cassady, “The Micro-Pulsed Plasma Thruster for Small Satellites,” submitted to the *AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, July 2000
12. A. Robertson, G. Inalhan, and J. How; “Spacecraft Formation Flying Control Design for the Orion Mission,” AIAA Conference on Guidance, Navigation and Control, Portland, OR; pp. 1562-1575, 1999