

## The Role of Small Satellites in Aeronomy

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**Abstract:** The scientific community and NASA are continually evaluating and setting the direction of future Aeronomy missions, including those targeted at space weather. Missions, and the required supporting technologies, have historically been outlined within strategic plans developed for NASA by the science community. Many of the proposed future missions will require constellations that act as single missions, making coordinated observations as a single virtual instrument. The science return occurs from the multi-point or spatially distributed observations and not from a collocation of a complex suite of instruments, as does the current model. The only conceivable way many of these missions can be achieved is through the use of small, low-cost satellites. Thus, future science objectives will very likely push the development of small satellites for constellation missions. Within this paper we show the trend of Aeronomy science missions towards multiple spacecraft and outline some of the missions proposed by the science community requiring small satellites.

### 1 INTRODUCTION

Aeronomy is the branch of science concerned with the upper atmosphere of the Earth and other planets, with specific attention to their physical properties, relative motion, and chemical composition. It is akin to meteorology, which is the study of the weather within the lower atmosphere, including the troposphere and lower stratosphere. There are two distinct components of the upper atmosphere. The first is the neutral gasses which are a continuance of the Earth's atmosphere to higher altitudes where they become ever thinner and hotter. This is called the Thermosphere. The second is the electrically active plasma component created from the thin neutral gasses by solar radiation. This is called the ionosphere and is several orders of magnitude less dense than the thermosphere. Aeronomy, for the purposes of this paper, includes the study of the ionosphere, thermosphere and magnetosphere which is the region of space dominated by the magnetic field of the Earth.

The term "space science" is sometimes used synonymously with aeronomy, but it also includes interplanetary space, where the upper atmosphere trails off into regions dominated by the sun. The upper atmosphere can be divided into a region that is accessible for direct study by satellites, above 200 km in altitude, as well as one that is too low for satellites due to atmospheric drag. This 50 to 200 km region can only be directly probed during the brief passage of a rocket in flight, since it is too high for balloons and aircraft.

The field of aeronomy has rapidly grown along with the space age as the upper atmosphere has become more accessible to scientists and as the space environment has become more important for engineering. Within this paper we present a review of the science rationale and missions that require, or are enabled by, the development of compact, low-cost spacecraft and associated launch systems. These are multi satellite missions that can be divided into those that will require "clusters" of spacecraft (in the range of 2-6 spacecraft) and constellations missions (30-36 or more spacecraft).

#### 1.1 *The Dynamic Upper Atmosphere*

The upper atmosphere does not exist in isolation. It is created and largely shaped by absorbed photon radiation from the sun in the UV through gamma ray wavelengths. The other major energy inputs are the particles streaming off the sun in the form of the solar wind and the Earth's lower atmosphere. Large variations in the density and velocity of the solar wind change the pressure on the Earth's magnetosphere, resulting in geomagnetic storming and the dissipation of large amounts of energy in the polar regions due to aurora processes. Atmospheric tides and waves propagating up from the lower atmosphere also influence the upper atmosphere.

The upper atmosphere has been shown to display both a background state (climatology) and a disturbed state (weather). Progress has been made on the climatology of the upper atmosphere through some suc-

cessful modeling, but weather has been much more difficult to understand. This is because the ionosphere (and perhaps thermosphere) can vary significantly on an hour-by-hour basis.<sup>1</sup> Unfortunately, ionospheric weather can have detrimental effects on several human activities and systems, including high-frequency communications, over-the-horizon radars, and survey and navigation systems using Global Positioning System (GPS) satellites. It is also a challenging engineering environment for spacecraft orbiting within it, due to surface charging, the radiation environment, chemical erosion of surfaces, and variable spacecraft drag.<sup>2,3</sup>

## 1.2 Space Weather

The initial progress in the field of aeronomy has been made with the aid of a large combination of observational techniques, including in-situ rocket and satellite measurements and remote observations using satellites and ground-based radio, radar, and optical probes. Recently highly sophisticated computer based empirical and theoretical models have been developed for the study and specification of the upper atmosphere climatology and weather. These are largely funded in an effort to mitigate the adverse effects of the space environment on military and civilian operations and to further develop the field of aeronomy.

The effort is focused on developing specifications and forecast models that use state-of-the-art data assimilation techniques, in which physics based models are driven with observational data of the upper atmosphere. This approach has been shown to be an effective method when dealing with a medium, such as the ocean or lower atmosphere, which has a complex and perhaps nonlinear response to both internal and external driving forces. A similar approach is being taken with the upper atmosphere. Kalman filtering and other assimilation techniques are being applied to physics models of the ionosphere or thermosphere, where it is also not possible to accurately specify all of the drivers or the initial conditions of the medium. Physics-based models alone cannot provide reliable specifications and forecasts. The accuracy of these assimilation models is dependant on the quality and quantity of observations with which they are driven.

An example of this type of effort is the USU Global Assimilation of Ionospheric Measurements (GAIM) program in which both satellite and ground based observations are used to drive a physics model of the ionosphere that incorporates thermosphere climatology. The USU GAIM model has been implemented at the Air Force Weather Agency for operational

use.<sup>1</sup> The next step is to apply assimilative methods to a model, such as the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM).<sup>4,5</sup> The TIEGCM is a self-consistent, three-dimensional, time-dependent model of the Earth's upper atmosphere, which predicts winds, temperature, major and minor composition of the thermosphere, and electrodynamic quantities, such as currents and density of the ionosphere, for the entire globe. The coupling of these types of models with sufficient observation to drive them will make space weather forecasting possible. This is the ultimate goal of the United States National Space Weather Program, which is a multi-agency Federal research program seeking to mitigate the adverse effects of space weather.<sup>6,7</sup>

## 2 EXPERIMENTAL AERONOMY

Advance in aeronomy, like in all sciences, requires observations, theory, and subsequent testing of theory. For aeronomy this testing is typically achieved through more, focused observations or experiments. At present, one of the major obstacles for a better understanding of the upper atmosphere and for the detailed testing and improvement of global models is the limitation on our understanding of transport processes. The field needs better observational data to make progress in understanding the motions or winds within the upper atmosphere. This need can be divided into knowing the motions of the ionosphere, and the motions, or winds, in the thermosphere. Winds are critical to understanding the changing conditions in the ionosphere, which lead to phenomena as diverse as equatorial plasma bubbles, and the effects of geomagnetic storming on the whole upper atmosphere. Planetary scales observations are needed to study and understand these transport processes. Improvements in the observational and experimental components of the scientific method are currently required for dramatic progress in Aeronomy.

### 2.1 Observation Objectives and Techniques

Observational techniques exist that can determine a number of parameters of the upper atmosphere, ranging from the density of ionized and neutral species to electric fields and drift velocities. The techniques can be broadly categorized among the classes such as in-situ, space-based remote sensing, and ground-based remote sensing. The understanding of transport in the upper atmosphere will ultimately be accomplished in a number of different ways. The most direct process would be to measure the drifts of the upper atmosphere with sufficient spatial and altitudinal resolution for direct comparison with global models. Such data

could also be used to drive assimilative models for space weather prediction. An example of in-situ instrumentation for this type of direct measurement is that employed by the Coupled Ion Neutral Dynamic Investigation (CINDI) to be flown on the Air Force's Communications / Navigation Outage Forecast System (C/NOFS) satellite. A direct remote sensing example would be the instruments from the NASA UARS spacecraft, WINDII (Wind Imaging Interferometer) and HRDI (High Resolution Doppler Interferometer), which gave the first global views of the tides in the lower thermosphere.<sup>8</sup> A different approach to observing transport would be to measure composition, density, or another parameter and use it as a tracer of motion in the upper atmosphere.

Remote and in-situ techniques each offer different advantages and disadvantages for measuring transport in the upper atmosphere. For instance, remote sensing approaches have given us the first global views of parts of the upper atmosphere and present the prospect of being able to monitor large regions of the upper atmosphere from a single point, such as with a UV imager on a satellite in a geostationary orbit. The disadvantage is that remote sensing techniques typically measure integrated quantities; along the lines of sight and high spatial resolution it is difficult to obtain. The in-situ techniques generally offer more precision and spatial specificity, but do not provide the global view. Without the global, multi-point observations, it is impossible to understand transport in the upper atmosphere.

Local in-situ measurements on a single spacecraft suffer in two ways. First, it is difficult to separate the time varying phenomena in the data from the results of flying through spatial variations. The only way to resolve this well know temporal-spatial ambiguity is to compare a first set of measurements with a second identical set made a short period of time later. A short period for understanding the upper atmosphere transport is much less than the 90 minute orbital period of a spacecraft in LEO. The second way in which in-situ measurements suffer is that the data returned is a relatively sparse sampling of the upper atmosphere and it is impossible to compare what is happening at one location with what is occurring at another. The way to overcome the shortcomings of both remote and in-situ techniques is through multipoint measurements.

## **2.2 The Need for Clusters and Constellations**

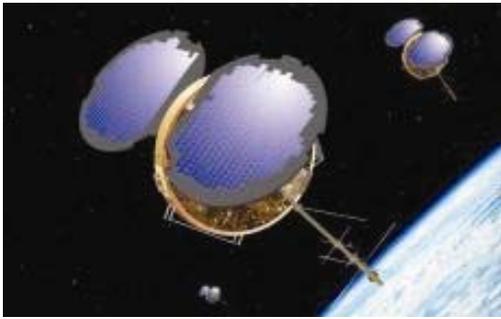
Multipoint measurements in the upper atmosphere imply the use of multiple spacecraft from which observations are made. The instrumentation on these

spacecraft needs to be identical, so that modern signal processing techniques can be used to maximize the understanding of the observations. For example, a remote sensing technique can be improved through multipoint observations by the application of stereo imaging or tomography techniques. If one has multiple observations of a volume of space, each along a different integration path, the combined information can be used to reduce the integrated nature of individual measurements and provide better spatial resolution of the quantity being observed. The additional benefit is that integrated quantities are reduced to basic quantities, such as average densities over a volume, instead of integrated quantities along the line of site. An example would be multiple instruments observing the airglow signature from different vantage points in the upper atmosphere. Any single instrument's data would be the integrated signal from along the view path. All combined, one could determine the airglow coming from small volumes of space and, depending on the physics behind the airglow signature, the average velocity or density of those regions of the upper atmosphere.

In a similar way, multipoint in-situ measurements of the upper atmosphere can be combined to provide much more information about transport in the upper atmosphere than a measurement from a single spacecraft. Satellites in the same orbit, but distributed in different locations, like a string of pearls, can easily be used to separate the temporal-spatial ambiguity as they sequentially pass through the same region of space. Observations made from multiple satellites distributed in different orbits can provide the global view of the upper atmosphere that cannot be achieved with a single spacecraft. The benefits of multi-point, in-situ measurements to aeronomy are expected to be similar to the benefits seen by the fields of oceanography and meteorology from their arrays of instruments deployed on buoys or distributed over the surface of the Earth.

## **2.3 Current and Proposed Clusters and Constellations**

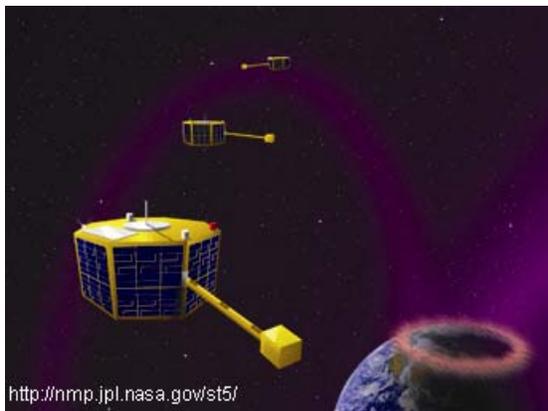
The need for multiple satellites to conduct observations is compelling across the field of Aeronomy and has been for more than a decade. There are indications of this by the recent multi-satellite programs launched, planned, and being discussed within the space science community. An example of two multi spacecraft programs that have been launched within the last few years have been the joint Taiwan/U.S. COSMIC/FORMOSAT-3 program and the NASA ST5 program. A third program, THEMIS is nearing launch.



**Figure 1 Cosmic/Formosat-3**

COSMIC/FORMOSAT-3 is the Constellation Observing System for Meteorology, Ionosphere and Climate and Taiwan's third satellite mission. The cluster of six satellites, depicted in Figure 1, was launched aboard Orbital's Minotaur space launch vehicle on April 14, 2006. The scientific instrumentation for COSMIC/FORMOSAT-3 is composed of the GPS radio occultation (limb sounding) technique and EUV observations of ionospheric density. These satellites will be used to collect atmospheric data for weather prediction and for ionosphere, climate, and gravity research. Data from the satellites will be made available to the international scientific community in near real-time.<sup>9,10</sup>

The ST5 Project is part of the New Millennium Program which is to identify, develop, build, and test innovative technologies and concepts for infusion into future missions. It is a three satellite cluster, as illustrated in Figure 2, which was launched April 26, 2006.

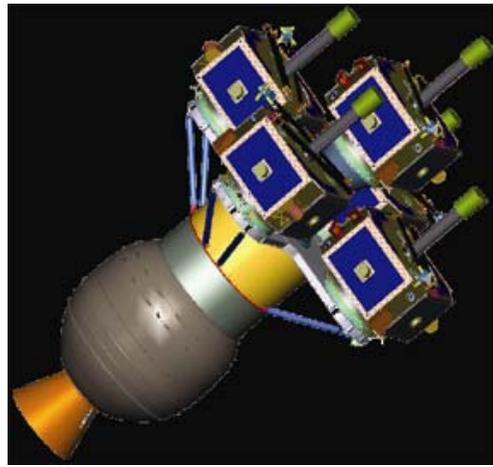


**Figure 2 NASA New Millennium ST5 Program**

The satellites, although working as a technology pathfinder, include a science class magnetometer and will provide limited data of use to the science community.<sup>11</sup> The proposed Magnetospheric Constellation would make use of some 50-100 ST5 like satel-

lites. Such a mission would provide global coverage of the magnetosphere as it reacts to major events caused by the Sun during geomagnetic storms.

The THEMIS mission, depicted in Figure 3, is to be launched in late 2006. It is a cluster of five spacecraft with a mission of answering questions regarding the magnetospheric substorm instability, a dominant mechanism of transport and explosive release of solar wind energy within geospace. The spacecraft are identical and carry in-situ instruments for observing energetic particles and electric and magnetic fields.<sup>12</sup>



**Figure 3 THEMIS Mission of Five Small Satellites**

In addition to these programs, there are a variety of other science investigations that are being discussed within the Aeronomy community and are in various stages. These include a cluster of four spacecraft carrying in-situ instrumentation to provide mapping for the Earth's radiation belt. A cluster of four spacecraft has also been proposed to monitor the Earth's ionosphere by looking for transport and coupling between different altitudes. These missions have been discussed within the NASA Living with a Star Program and have emerged as the Radiation Belt Storm Probes and the Ionosphere Thermosphere Storm Probes, paired down to only two spacecraft for each mission. This is partly out of the perceived cost risk to NASA of conducting a mission with multiple spacecraft. Similar concerns have paired down the proposed Global Electrodynamics Connections mission of 4-Satellites to a mission that now consists of only two. Two other constellations have been proposed as part of the NASA Solar Terrestrial Probes Line, including Draco, a constellation of 50-100 satellites, and the Magnetospheric Multiscale mission of five satellites, but both have been substantially delayed due to the NASA man space Exploration Initiative. The science community is actively discussing other programs,

such as a set of spacecraft to perform radio imaging of the magnetosphere. This would require a small constellation of about ten satellites. Another example would be a small cluster of spacecraft for studying ionosphere/thermosphere coupling, which would consist of about five satellites. Ultimately, a functional space weather capability will require a dedicated constellation of 50-500 satellites in various orbits in the upper atmosphere, returning data in real time.

### 3 CONCLUSIONS

The role of small satellites in Aeronomy is in providing constellations and clusters of spacecraft to advance our understanding of transport processes and to push the field towards developing a predictive space weather capability. The small satellites that will fulfill this role represent both a technology and a programmatic advancement over what is now generally achieved. The small satellites must be capable, low-cost, and produced in quantities. To achieve these goals greater emphasis needs to be placed on standardization and manufacturability for small satellite systems and their associated launch systems. Effort will be needed in developing ground and space support systems to retrieve data in near real time from these space clusters and constellations. The fusion of such data with assimilative computer models is ultimately what is required to advance the field of Aeronomy.

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