16

The NanoSAIL-D2 NASA Mission

This chapter describes thoroughly the second sailcraft flown as sails transition from theory to reality. Once again, NASA made an historical step in the modern history of Astronautics, this time with the flight of NanoSail-D2.

THE GROUNDWORK

In 2011, NASA's NanoSail-D2 was the first sail to orbit the Earth. Measuring 10 m^2 and deployed from a 3U cubesat, NanoSail-D2 was also NASA's first cubesat deployed from another orbital spacecraft. Never intended to be a complete sailcraft, NanoSail-D2 was instead a sail deployment demonstration that could one day lead to an atmospheric drag system for removing decommissioned satellites from orbit at the end of their operational life. Built without an active guidance, navigation and control system, this demo-sailcraft re-entered the Earth's atmosphere on September 17, 2011, after spending 240 days in space.

Its flight twin, the NanoSail-D1, never had a chance to fly in space when its launch vehicle failed. And NanoSail-D2 was thought to be a failure when its planned ejection from its host spacecraft didn't happen has planned; the sailcraft instead remained stuck in the host spacecraft for several months and then spontaneously ejected—only then beginning what has become a resoundingly successful demonstration of a very small sailcraft in LEO.

The project began after the cancellation of NASA's Solar Sail Technology Project in 2007. Under that project, NASA developed two very large solar sail propulsion systems—400 m^2 each—and tested them under thermal vacuum conditions at NASA's Plumbrook Station in Sandusky, Ohio (Chap. 12). When the project was canceled, the hardware was returned to NASA MSFC and a small amount of money remained in the Project's account. The NASA MSFC team decided to capitalize on the investments made in the sail project thus far and leverage the considerable advances in cubesat technology to develop and fly a much smaller (than 400 m^2) solar sail for possible use on cubesats and other small spacecraft. Partnering with NASA's Ames Research Center, where NASA was at the time focusing its research and development of cubesats, the NanoSail-D missions were born.

G. Vulpetti et al., *Solar Sails,* Springer Praxis Books,
DOI 10.1007/978-1-4939-0941-4_16

16.1 The coiled TRAC booms used on the NanoSail-D2 were developed by the US Air Force Research Laboratory (Courtesy of the US Air Force)

For the collaboration, NASA Ames provided the cubesat spacecraft bus and NASA Marshall the sail. A launch opportunity aboard a test flight of the SpaceX Falcon-1 was identified and the team had less than a year to develop both the spacecraft bus and the sail. To meet this aggressive schedule, the sail material was cut from one quadrant of the large sail tested at Plumbrook. The spacecraft was manufactured from spare hardware from the GeneSat mission and the two were integrated into a single spacecraft for launch aboard the Falcon. In what was soon to be validated as a very smart project decision, a flight spare of the NanoSail-D was manufactured and the two spacecraft were named NanoSail-D1 and NanoSail-D2.

The engineers at NASA MSFC worked with Nexolve Corporation (Huntsville, AL) to develop the sail, with Nexolve providing the booms derived from the US Air Force Research Laboratory's Triangular Rollable And Collapsible (TRAC) boom. The TRAC booms were inherently stiff and self-deploying, requiring no active deployment mechanism or control (Fig. 16.1).

The sailcraft were completed and delivered in August 2008 to SpaceX. Figure 16.2 shows the scale of the deployed NanoSail in one of the ground tests performed prior to launch.

The NanoSail-D1 was launched aboard the third test flight of the SpaceX Falcon-1 rocket from the Kwajalein Atoll. The launch failed and NanoSail-D1 never had the chance to deploy in space; instead, it and the second stage of the Falcon-1 fell into the Pacific Ocean.

16.2 The NASA NanoSail D team celebrated the successful deployment of the sail prior to packaging for launch. The cubesat from which the sail deployed can be seen in the very center of the sail (Courtesy of NASA)

THE FLIGHT

The NanoSail-D2 spacecraft was then placed in storage, awaiting a launch opportunity. That opportunity came about a year later when NASA MSFC began developing the Fast Affordable Science and Technology Satellite (FASTSAT). The FASTSAT, containing NanoSail-D2, was prepared for flight and shipped to Kodiak, Alaska for integration into the Minotaur rocket that would ultimately carry it into space on November 19, 2010. The flight plan called for the FASTSAT spacecraft to deploy into a 650 km altitude orbit and be checked out for 2 weeks prior to the command being given for the NanoSail-D to eject from the FASTSAT's onboard deployment system and begin its mission. There was no command uplink to initiate the deployment; the NanoSail-D2 was to deploy from FASTSAT based on a command from an onboard timer.

The time for the NanoSail-D2 to deploy from the FASTSAT came and went, with the flight team originally believing that the spacecraft had deployed as planned. Had the deployment occurred, an onboard timer would have turned on the spacecraft's radio transmitter, announcing its presence in Earth orbit. No signal from the spacecraft reached the ground. Radar data later confirmed that NanoSail-D2 had not deployed from the FASTSAT. The team believed the experiment was a failure.

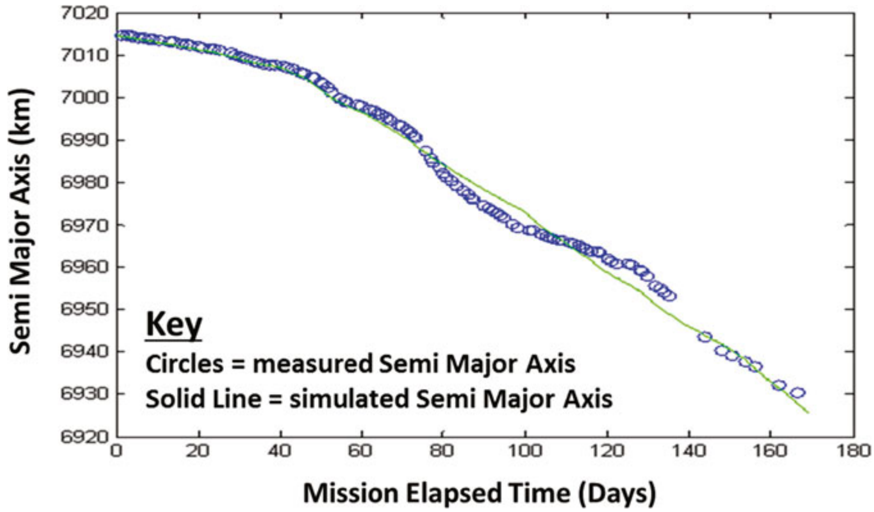
16.3 Ralph Vandebergh photographed the NanoSail-D2 from the ground on April 24, 2011 (Courtesy of Ralph Vendebergh)

Then, on January 17, 2011, the NanoSail-D2 spontaneously deployed from the FASTSAT and began its pre-programmed mission. The spacecraft's radio beacon began broadcasting as planned and the sail then unfurled on schedule. The radio data was short-lived, since the onboard batteries were only capable of keeping the transmissions alive for between 12 and 24 h after they began. Amateur astronomers took pictures of the Nanosail-D2, confirming that the sails had fully deployed (Fig. 16.3).

SOME RESULTS FROM THE NANOSAIL-D2 MISSION

NanoSail-D2 (NSD) was inserted into a 71.9° inclination orbit at an altitude of 654 km. Despite its high initial altitude, NSD's orbit decayed rapidly due to the high area/mass ratio (A_m) of the sailcraft. For NSD, approximately $A_m = 10\ m^2/4\ kg = 2.5\ m^2/kg$. This ratio would ultimately determine NSD's orbital lifetime.

Remark: The reader may wonder that any sailcraft—as discussed in the previous chapters—requires a sufficiently high area on mass ratio for raising orbit. Why, then, did NSD's orbit decay? This would have happened even if its attitude had been quite favorable to get energy from sunlight. The main reason is that its altitude has been constantly lower than 750–800 km. As a point of fact, below such range, the dragging effect due to the Earth's high-atmosphere is always greater than the propulsive effect caused by sunlight. The range reported above depends on the solar activity (explained in Chaps. 18 and 19), the fact that Earth orbit varies between 0.983 and 1.017 AU, and that the high-atmosphere density is not so low as one might think at first glance. Of course, one may induce a decay by sail even from altitudes (not too much) greater than 800 km if the sail is oriented such a



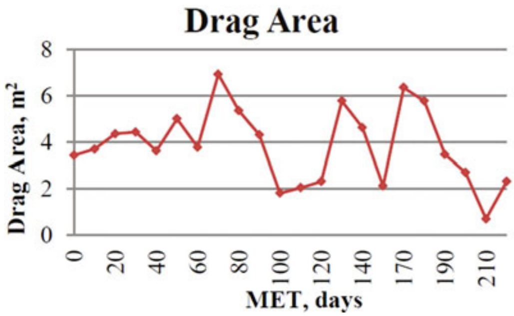
16.4 Theoretical models of NanoSail-D2's altitude compare favorably with measured results (Courtesy of Andy Heaton of NASA MSFC)

way to use sunlight for losing orbital energy. In such a view, the NSD mission by NASA MSFC has become still more important, as explained below.

NSD's orbital altitude decay rate was modeled by Andy Heaton of NASA MSFC and his analysis aligns well with the measured Two Line Element[1] (TLE) data, as shown in Fig. 16.4. Heaton used detailed atmospheric model and daily values for solar activity to ensure accurate atmospheric density. Based on the TLE data, the sailcraft's orbital velocity was well characterized. Assuming a drag coefficient of 2.20 (approximately that of a flat plate), and based on the optical ground observations that established that the sailcraft was spinning at a rate far greater than its orbit rate, Heaton's model of NanoSail-D2's orbital decay aligns well with measured data.

As NanoSail-D2 orbited the Earth, its orbit and orientation were affected by solar radiation pressure, aerodynamic drag, gravity, and center of pressure offsets in the sail system. These disturbances were not constant and varied dramatically throughout each orbit. Chelsea Katan of Embry-Riddle Aeronautical University used the NanoSail-D2 TLE's and calculated that the sailcraft's orientation was changing throughout its orbital life (Fig. 16.5). She found that the *effective* drag area of the sail varied from less than 1 m^2 to almost 7 m^2, strongly implying that the sail was not uniformly tumbling (which would have likely resulted in an approximately uniform effective drag area); rather it was changing orientations and maintaining some of them preferentially [1].

[1] A NORAD two-line element set consists of two 69-character lines of data which can be used with orbital models to determine the position and velocity of a satellite.



16.5 The effective drag area of NanoSail-D2 was calculated using a software known as the Satellite Took Kit and TLE data. Again, *MET* Mission Elapsed Time (Courtesy of Chelsea Katan)

APPLICATION OF NANOSAIL-D2 TECHNOLOGY

Using sails as aerodynamic drag devices for de-orbiting spacecraft in LEO is perhaps the nearest term application of the technology. Several companies and universities are investigating this approach and they are using the results of the NanoSail-D2 in their design and mission planning. For example, MMA Design launched into orbit their DragNET De-orbit System aboard a US Air Force Space Test Program satellite (STPSat-3) in November 2013 with the goal of demonstrating the system as a viable end-of-life satellite de-orbit system. The DragNET, like NanoSail-D2, consists of a thin membrane with booms and will have a deployed area of 14 m^2. The company claims that the system will de-orbit a 180 kg spacecraft from altitudes up to 850 km in less than 10 years [2].

REFERENCES

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2. Fernandez, Juan M., et al. "Design and development of a gossamer sail system for deorbiting in low earth orbit." Acta Astronautica 103 (2014): 204–225