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## *Surveyor* Spacecraft Automatic Landing System

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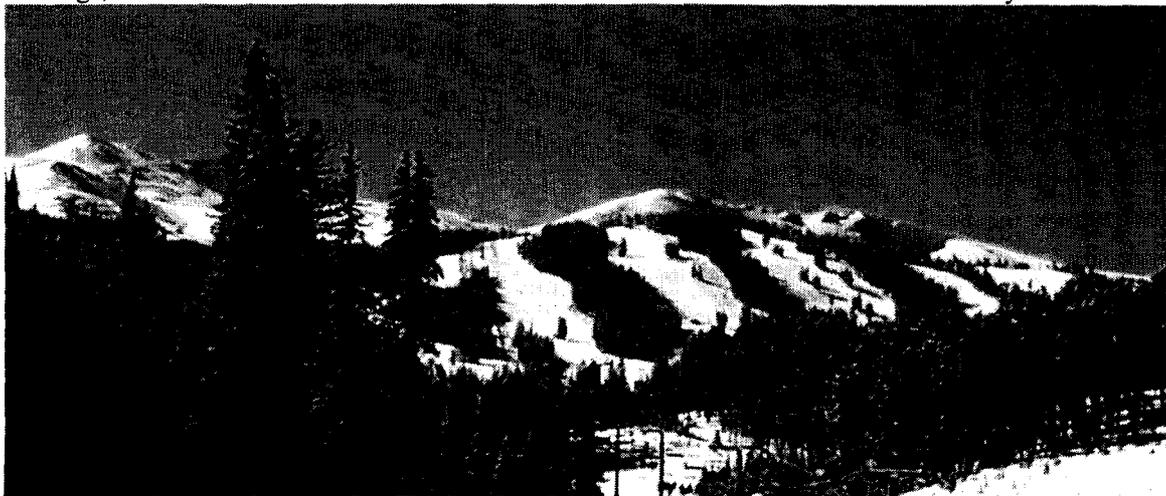
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# SURVEYOR SPACECRAFT AUTOMATIC LANDING SYSTEM

Sam W. Thurman\*

The *Surveyor* Project achieved five successful lunar landings between 1966 and 1968, following an intensive five-year development effort. One of the many significant accomplishments made by *Surveyor* was the development and validation of the first-ever automated soft-landing system. This paper provides a historical overview of *Surveyor*, with emphasis on the guidance and control aspects of the spacecraft's terminal descent system. Driving requirements and other important design considerations are described, along with the configuration and operational sequence of the actual flight system.

## INTRODUCTION

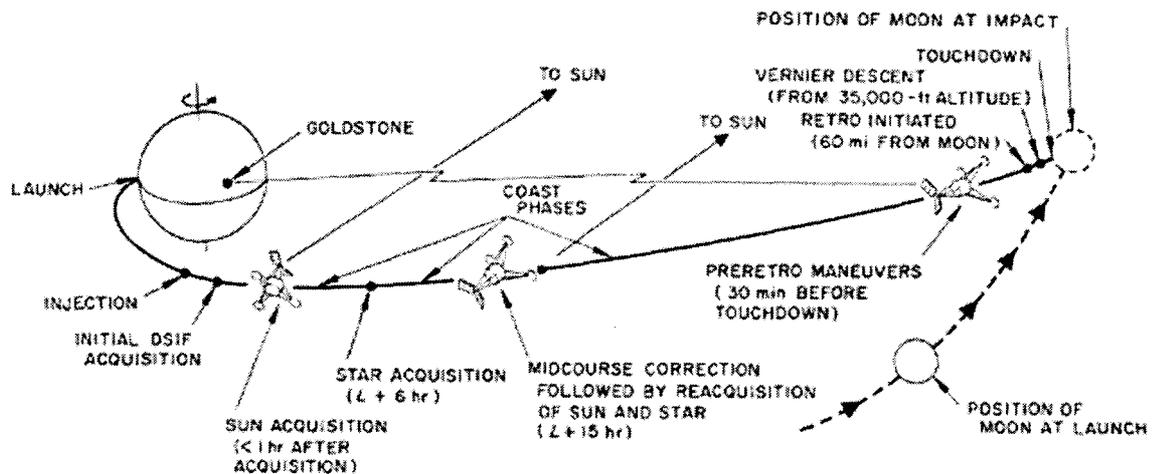
The *Surveyor* project was conceived primarily as a series of robotic precursor missions to prepare the way for human missions in the *Apollo* project. One of the key requirements identified early in the spacecraft development effort was the need for automated execution of the sequence of events occurring during the terminal descent phase.<sup>1-5</sup> During this phase the spacecraft had to decelerate from an approach velocity on the order of 2,000 m/s relative to the lunar surface to a speed of approximately 3.5 m/s just prior to touchdown, in a matter of 3-5 minutes. The dynamics and short duration of these events precluded reliance on ground-based commanding. Another significant challenge was to develop a test and validation approach for such a complex, mission-critical system.<sup>5,6</sup> This paper surveys the development and flight of this first-ever automatic soft-landing system, bringing together information and illustrations from a host of historical *Surveyor* documents.

## SURVEYOR MISSION OVERVIEW

An illustration of the mission profile is shown in Fig. 1 for a representative mission.<sup>7,8</sup> The *Surveyor* spacecraft was launched from Cape Canaveral Air Station (known in the *Surveyor* era as "Cape Kennedy") on an Atlas/Centaur launch vehicle. The nominal ascent trajectory was targeted towards a pre-determined landing site so that the approach velocity and time of landing satisfied constraints associated with the spacecraft's  $\Delta v$  capability and the view periods available from the prime tracking station within NASA's Deep Space Network, (then called the Deep Space Instrumentation Facility, or DSIF) located near Goldstone, California. The spacecraft was three-axis stabilized during cruise, via sensors using the Sun and the star *Canopus* as attitude references, and a cold-gas reaction control system for attitude control. Total flight time to the lunar surface was approximately 66 hr.

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**Figure 1: Surveyor Representative Mission Timeline**

A single midcourse maneuver was performed approximately 15 hr following launch, using the spacecraft's vernier engines, which were also used for descent and landing. The components of the velocity change vector, or  $\Delta v$ , to be implemented for this single course correction were determined by an unusual scheme employing optimization methods.<sup>4,9</sup> The  $\Delta v$  vector consisted of two components; the first component was designed to null the predicted miss relative to the target landing site, while the second, orthogonal component was chosen to maximize the probability of landing safely prior to exhaustion of the vernier propellant supply. This was done because the vernier system propellant was used for both the midcourse maneuver and the terminal descent phase.

Following the midcourse maneuver, the spacecraft returned to its nominal cruise attitude while its flight path was re-determined from additional DSIF tracking data. As it approached the lunar surface, the spacecraft's deceleration to a soft landing was accomplished in two stages. Most of the vehicle's approach velocity was removed by a solid propellant retro motor; the residual velocity following burnout was nulled using a system of three liquid propellant vernier engines, guided by the spacecraft's Radar Altimeter/Doppler Velocimeter System (RADVS). After touchdown, the spacecraft established radio contact with the DSIF using a steerable, high-gain antenna, and embarked on its surface mission. Between the accuracy of the ground-based tracking system used to compute midcourse maneuver and retrorocket burn parameters, and the spacecraft's ability to execute those maneuvers, the spacecraft reached the lunar surface with an accuracy of 15 to 20 km ( $1\sigma$ ) relative to the target landing site.<sup>10</sup>

A variety of scientific instruments were developed for the *Surveyor* landers, including a television camera with a steerable field-of-view, an articulated soil mechanics/surface sampler, and an alpha scattering instrument used to make the first measurements of the chemical composition of the lunar surface. Although nominally designed for operation during the lunar daytime, several *Surveyor* spacecraft were successfully reactivated following the frigid two-week nighttime interval and operated over multiple lunar days in some cases.

## TERMINAL DESCENT SYSTEM

The configuration and principal components of the spacecraft design as implemented for the first two *Surveyor* missions are shown in Fig. 2.<sup>7,8</sup> The key mission requirements driving the overall design of the vehicle included the need for an automated soft-landing capability, the functionality necessary for cruise and lunar surface operations (power, command/telemetry, data management, instrument payload accommodation) and the desire to accomplish the missions on an ambitious schedule, making use of the existing technological state of the art. The original spacecraft design weighed approximately 2,200 lb at launch and could be packaged within the 10 ft conical Centaur fairing (with its landing legs stowed for launch), constraints imposed by the initial capability of the Atlas/Centaur vehicle that were later increased as improvements in performance became available. The spacecraft was designed such that subsequent modifications made in the later missions to carry additional instruments were accomplished without fundamental changes.

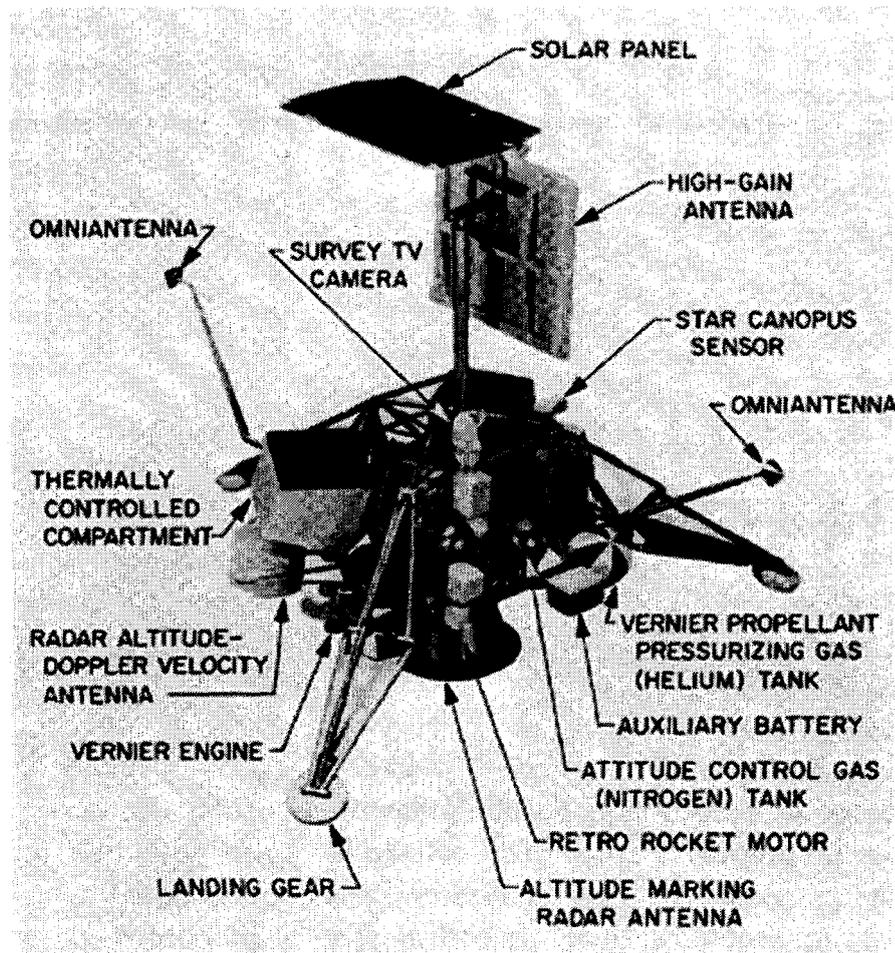


Figure 2: *Surveyor* Spacecraft

## Guidance and Control Instrumentation

For cruise attitude determination, the spacecraft was equipped with two sun sensors and a Canopus star sensor. Three rate integrating gyroscopes and an accelerometer aligned with the vehicle's longitudinal (thrust vector) axis were used during rotational maneuvers and powered flight, for attitude and vernier throttle control. The spacecraft was also equipped with two different radar systems. The first was an Altitude Marking Radar (AMR), used to generate a signal to start the solid propellant retro-motor burn, while the second was the Radar Altimeter/Doppler Velocimeter System (RADVS), used to measure slant range and velocity vector components for terminal descent guidance. The RADVS was an L-band FM-CW system employing two 36 in. parabolic antenna assemblies (one of which is visible in Fig. 2), each of which was subdivided into halves, to mechanize the system's four radar beams.<sup>7,8</sup>

## Vernier Propulsion Components

The vernier propulsion system was one of the most difficult developments undertaken by the *Surveyor* project. The system consisted of three thrust chamber assemblies, three pairs of fuel and oxidizer tanks, a high-pressure helium tank, and a host of lines and valves needed for loading, test, and operation of the system. A close-up of a vernier engine assembly is shown in Fig. 3. One of the three engines could be gimbaled  $\pm 6$  deg, about an axis allowing its use for roll control of the spacecraft. Hypergolic propellants were used; the fuel was monomethyl hydrazine monohydrate, with nitrogen tetroxide used as an oxidizer. Each engine's thrust level was individually throttleable between 30 and 106 lb. The fuel and oxidizer tanks were not pressurized until 7 min prior to the midcourse maneuver, at which time a pyrotechnic squib was fired, allowing the helium regulator to pressurize the tanks at a nominal 730 psi, which was maintained for the remainder of flight.<sup>7,8</sup>

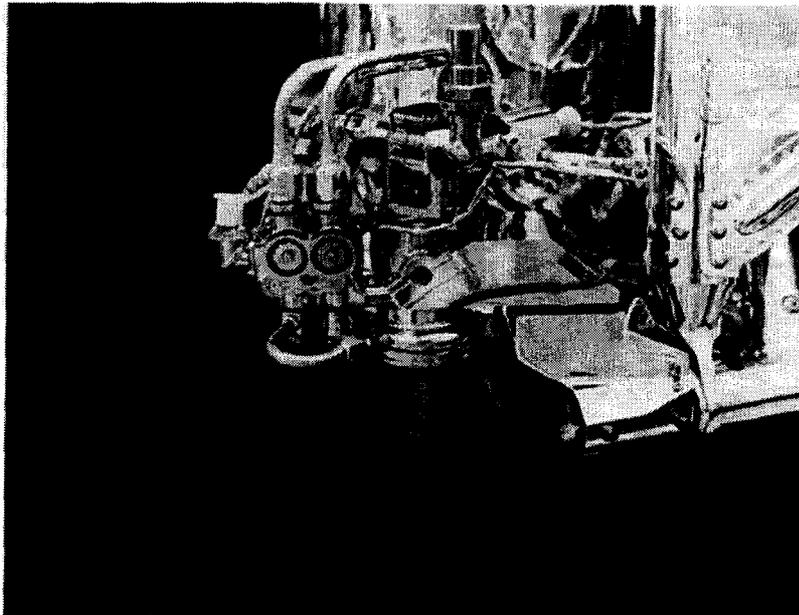


Figure 3: Vernier Engine Assembly

## Terminal Descent Sequence

The sequence of events culminating in touchdown is illustrated in Fig. 4.<sup>7,8</sup> The altitude, velocity, and timing information shown are representative of a nominal mission sequence.

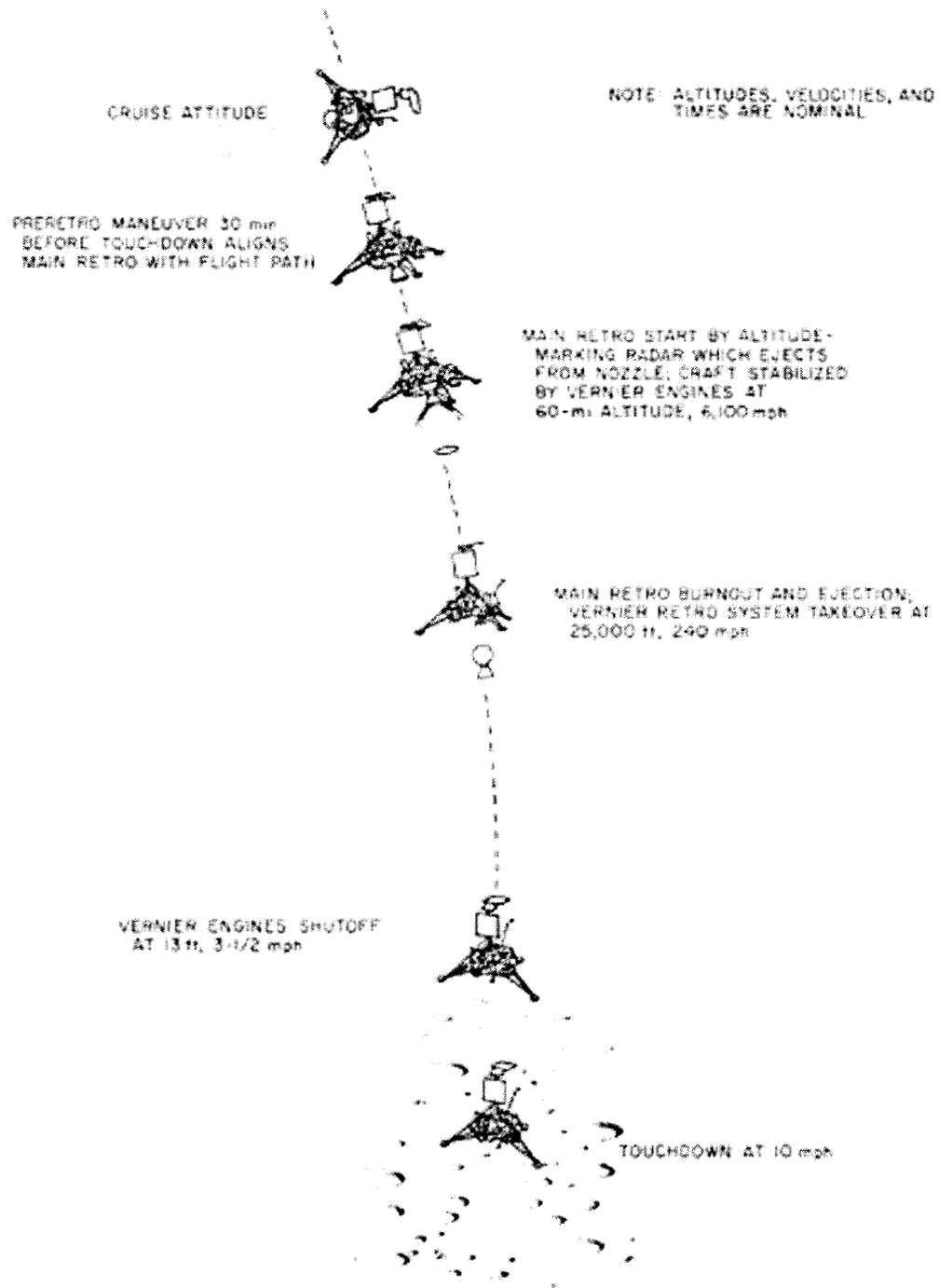


Figure 4: Terminal Phase Sequence of Events

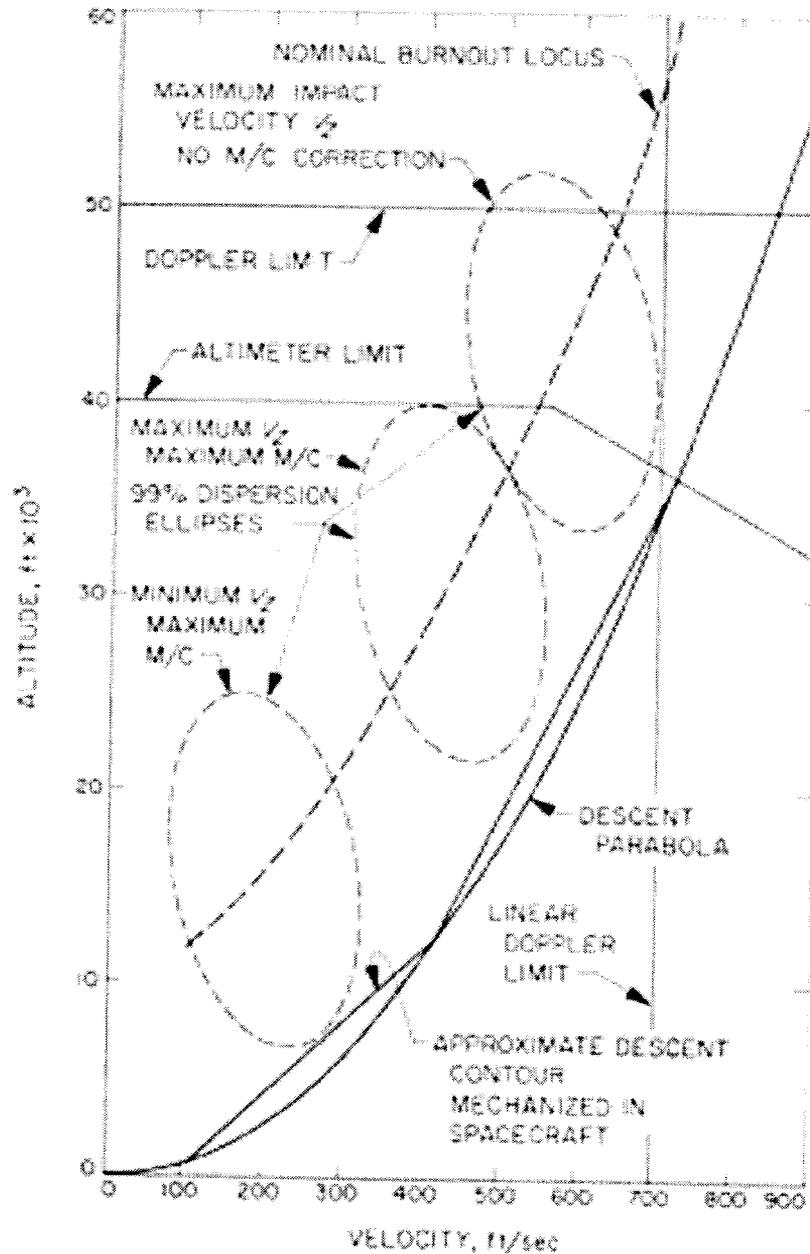
In preparation for the terminal phase of flight, the spacecraft was commanded to an attitude aligning its thrust axis with the predicted velocity vector at the time of retro-motor ignition. The main retro burn was initiated by a *mark* signal generated by the AMR at a slant range of 60 miles. The vehicle's vernier engines were started just prior to retro ignition, and provided attitude control to maintain the spacecraft in a constant inertial attitude during the retro burn. As a back-up measure, a second *mark* signal was commanded from the ground in case the AMR-initiated mark signal was not issued automatically. The nominal burn time of the retro motor was about 40 s; with the onset of thrust decay, the vernier engines were throttled up, then the retro motor case was jettisoned after a 12 s sequenced delay.

The main retro burn removed at least 95% of the spacecraft's approach velocity, leaving the vehicle in an altitude range between 10,000 and 50,000 ft, with a velocity between approximately 100 and 700 ft/s. Following main retro case separation, the vernier engines were throttled down to achieve a constant thrust deceleration of 0.9 lunar  $g$ . The spacecraft's attitude was commanded to hold the pre-retro orientation until the RADVS indicated surface acquisition. At this point, the vernier phase guidance logic was initiated, commanding the spacecraft to align its thrust axis opposite the velocity vector, and to follow a preprogrammed velocity magnitude profile as a function of altitude, called the "descent contour." This procedure causes the spacecraft to execute a "gravity turn," in which the action of lunar gravity drives the flight path into alignment with the nadir direction.<sup>3,4</sup>

### **Vernier Phase Guidance**

The vernier engine throttle settings were controlled using a proportional-plus-derivative feedback loop closed around the measured vs. desired velocity magnitude as a function of altitude, represented by the descent contour. Slant range data from the RADVS were used in mechanizing the descent contour as opposed to a true altitude measurement, an approximation that proved adequate as the flight path angle approached nadir. The descent contour terminated at a predetermined altitude and descent rate. Once the spacecraft reached this point, a constant velocity descent was initiated until a pre-determined termination altitude was reached, at which point vernier engine cutoff was commanded, and the vehicle fell to the lunar surface.<sup>3,4</sup>

The descent contour designed for the Surveyor missions is shown in Fig. 5, along with the principal constraints and dispersions associated with terminal descent system operation. The approach trajectory and solid retro motor burn parameters were carefully chosen such that the burnout conditions achieved, accounting for all relevant dispersions, would have a high probability of occurring within the altitude and velocity limits associated with the RADVS. The descent contour was designed to approximate a parabola, representing a constant deceleration trajectory, with the deceleration rate chosen to be near the maximum capability of the vernier engines, for the greatest fuel efficiency. Some margin was held against the maximum vernier engine thrust level, though, since some fraction of their capability was utilized for attitude control via differential throttling. As shown in Fig. 5, the actual descent contour consisted of several straight-line segments, chosen to approximate the shape of the constant deceleration parabola. This mechanization approach was chosen for implementation in the flight control electronics using linear circuit elements.



**Figure 5: Descent Contour and Retro Burn Dispersions**

### Test and Validation

System-level testing, verification, and validation of *Surveyor's* descent and landing system represented yet another significant, first-of-a-kind challenge. This challenge manifested itself in two principal ways. The first was addressing the system-level characterization of performance, given the interactions between multiple subsystems, each with uncertainties in its own performance. The second, and perhaps greatest, challenge was end-to-end testing of the vernier descent phase, given the dramatic

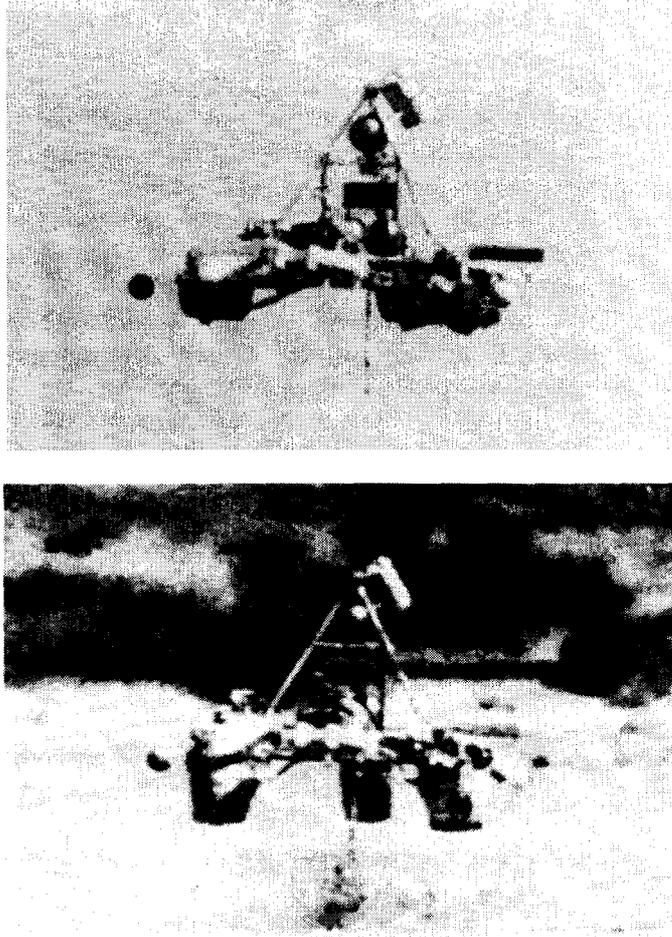
differences between the lunar environment in which the spacecraft would fly, and the terrestrial environment in which it could be tested prior to launch.

Subsystem testing included static firings of test models of the main retro motor and vernier engine assembly, static and dynamic tests of various mock-ups of the landing legs and crushable blocks mounted underneath the vehicle's primary structure, and extensive testing of the RADVS.<sup>5</sup> Due to the large altitude/velocity regime of RADVS operation, a series of 18 tests were conducted using a specially modified RADVS-equipped helicopter, ultimately executing a series of 53 flight profiles designed to simulate various mission-like scenarios to the maximum extent possible. These tests were conducted at the White Sands Missile Range near Alamogordo, New Mexico. The helicopters used in the testing were equipped with a complete mock-up of the RADVS, employing a special test fixture that positioned the two antenna modules in the same relative locations and beam pattern geometry as on the actual spacecraft.<sup>6</sup>

To obtain probabilistic estimates of end-to-end system performance, the project team developed several analytical and numerical tools. In many respects analytical considerations exerted substantial influence over the terminal descent system design, following the project's development paradigm of simplicity wherever feasible. Analytical approximations were used extensively for preliminary design, for both ease of use and because of the relatively limited capability available for computer simulation at that time. Ultimately, a Monte Carlo simulation of the complete mission was developed, incorporating models for the spacecraft's guidance and control system, including the midcourse maneuver, main retro burn, and vernier descent to touchdown. This simulation capability also incorporated dispersions associated with the ground-based radio navigation system used in the missions, enabling a comprehensive statistical treatment of injection errors, ground-based navigation errors, midcourse maneuver execution errors, retro burn errors, and vernier descent errors.<sup>4</sup>

The most complex and elaborate system-level test was designed to encompass the entire vernier descent phase, and was also performed at White Sands Missile Range. The primary objective of this test was verification and validation of the guidance and control system for this phase. A special mock-up of the *Surveyor* spacecraft was developed whose weight in terrestrial gravity was 1/6 of the flight spacecraft. This vehicle was equipped with a complete vernier engine system, RADVS, inertial sensors, and flight control electronics. It was also aerodynamically balanced to minimize these effects when operating in the Earth's atmosphere.<sup>5</sup> These modifications, coupled with aerodynamic balancing, scaled the vehicle's dynamic properties to approximate the flight spacecraft's dynamics in the lunar environment. Photographs of the actual test vehicle in flight are shown in Fig. 6.

The terminal descent test vehicle was initially tested while tethered to a tower. These initial static tests identified a problem with the vernier engine throttle valves, and an undesirable acoustic coupling between vernier engine and RADVS operation. Subsequently, modifications were made to the throttle valves and to the test vehicle configuration to deal with these issues. To conduct a complete drop test, the spacecraft was initially suspended beneath a balloon, and released after vernier engine start to descend following the programmed flight descent contour. These tests were ultimately successful, demonstrating the performance and integrity of the complete system.



**Figure 6: Vernier Phase System Test**

## **FLIGHT EXPERIENCE**

There were seven *Surveyor* missions conducted between May 1966 and January 1968, following a five-year development initiated in early 1961. Of these, five landed successfully and completed their surface missions, while two spacecraft were lost in transit. *Surveyors 2* and *4* were not successful (a convention was established of designating the successful missions with roman numerals, such as *Surveyor I*, while the unsuccessful missions were designated numerically, such as *Surveyors 2* and *4*). The early missions were targeted to scrutinize candidate landing sites for future *Apollo* landings, while the later missions were sent to landing sites of greater scientific interest, equipped with additional instruments to address selected science objectives

*Surveyor I*, launched on 30 May 1966, accomplished the first successful soft landing in history at an equatorial site in the Ocean of Storms on June 2. After touchdown, the spacecraft operated on the lunar surface for just over seven months, returning over 11,000 photographs. Following its successful launch in September 1966, *Surveyor 2*

experienced a vernier engine failure during its midcourse maneuver, causing a loss of attitude control that was ultimately unrecoverable.

One of the most remarkable examples of the flexibility of the spacecraft system occurred in the *Surveyor III* mission in April 1967. The vehicle's initial touchdown occurring with the vernier engines still firing, due to an anomaly in the radar signal processing logic (a main lobe signal was misinterpreted as a cross-coupled side lobe and rejected). The spacecraft subsequently executed two controlled rebounds above the lunar surface prior to receiving a thrust termination command from the ground.<sup>5</sup> The next mission in the series, *Surveyor 4*, was flown in July 1967. The spacecraft was approaching the lunar surface during its main retro burn when radio contact was lost 2.5 min prior to touchdown. No definitive cause of failure was ever identified.

*Surveyor V*, launched in September 1967, provided yet another example of both the skill of the flight team and the versatility of the spacecraft. Following its midcourse maneuver, a malfunction in the vernier engine pressurization system was identified; this would prevent the vernier propellant tanks from being fully pressurized prior to terminal descent. A series of attempts were made to correct the problem via ground commanding, all of which proved unsuccessful. In parallel with these troubleshooting efforts, a redesign of the terminal descent sequence was initiated, aiming to optimize the retro burn parameters to deliver the spacecraft to a much lower burnout altitude (4,000 ft versus a nominal value of 40,000 ft), allowing the vernier phase to be completed with a much smaller amount of usable propellant. This effort was completed within 40 hr, with updates to the terminal descent parameters commanded successfully from the ground within minutes of the revised retro burn start time. The spacecraft reached the surface safely, and was successfully arrested by its landing gear and crushable blocks on a 19.5 deg slope. The spacecraft went on to operate over three months on the lunar surface in the Sea of Tranquility.<sup>5</sup>

Beyond its contributions to lunar science and to *Apollo*, the soft landing approach pioneered by *Surveyor* provided an engineering legacy to subsequent robotic missions to the planet Mars. With some modifications, the powered descent approach implemented in both the *Viking Lander* (1976) and the *Mars Polar Lander* (1999) landing systems made use of *Surveyor's* gravity turn guidance logic coupled with Doppler radar and altimetry for navigation.<sup>11-13</sup>

## **SUMMARY**

The *Surveyor* project developed the first-ever automated system for controlled soft landing on another celestial body. This extraordinary feat was accomplished on a highly ambitious schedule driven by the intense competition between the United States and the Soviet Union in the field of lunar exploration. Schedule considerations weighed heavily on the system design, effectively constraining the development work undertaken to only those areas in which there were critical needs. Extensive, rigorous effort was devoted to subsystem and system-level test and validation of the spacecraft's terminal descent system. The success of five of the seven *Surveyor* missions nearly 40 ago years ago stands as a testament to the remarkable skill and ingenuity of the many people who dedicated years of their lives to these historic first explorations of the lunar surface.

## ACKNOWLEDGEMENTS

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