# ADVANCED BOOM SYSTEMS FOR SOUNDING ROCKET RESEARCH

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## ABSTRACT

The third payload in the SPIRIT series from the Pennsylvania State University, ESPRIT, was successfully launched in July 2006. The ESPRIT boom system was designed to meet Langmuir Probe experiment requirements through an interconnected rigid system mounted underneath an ejectable nosecone. During testing, a deployment envelope was tested that encompassed the operational spin rates of Terrier – Improved Orion launch vehicle. The successful flight has paved the way for other advanced designs. Based upon test experience and flight data, the new systems will allow various mounting options and compatibility with a variety of probes while retaining the high spin deployment capability.

## 1. BACKGROUND

As a part of NASA's Student Launch Program, the Pennsylvania State University created the Student Projects Involving Rocket Investigation Techniques, SPIRIT, campaign to enhance the real-world experience of Penn State undergraduate students. The third payload in the series, ESPIRIT, Engineering/Scientific Projects for Research and International Teamwork, was an international endeavor between the Pennsylvania State University and Norwegian investigators and students from the Universitetet i Oslo, Høgskolen i Narvik, and Universitetet i Bergen. Developed in conjunction with NASA's Wallops Flight Facility, the payload's scientific mission was investigating charged particle dynamics in the lower ionosphere and examining noctilucent clouds in the mesosphere.

One on-board investigation technique was the Langmuir probe experiment, which used *in situ* measurements to meet the objective of determining the electron density and other characteristics of the D and E regions. However, the payload shockwave could have disrupted the electron distribution in the plasma near the payload during flight, and thereby biasing measurements. In order to gather reliable data, the small probes were required to extend past this affected region into an area of undisturbed plasma.

For the SPIRIT III payload, the minimum separation distance between the skin and the interior part of the probe was specified by the experimenter to be about 0.5 meters. A new boom design was required because this distance precluded the reuse of the SPIRIT II design, which had less stringent length requirements and therefore had a simple single hinge design. The design team chose to meet the experiment requirements with a rigid double hinged system that was strong enough to deploy at the operational spin rate of the Terrier-Improved Orion launch vehicle. As part of the international collaboration with Norway, an inherited flight-ready system was used as a basis for the ESPRIT design. The University of Oslo provided the Pennsylvania State University with three pictures of a design that flew on the Hotel Payload ICI-1 from Andøya Rocket Range in November 2003, one of which is shown in Fig 1.

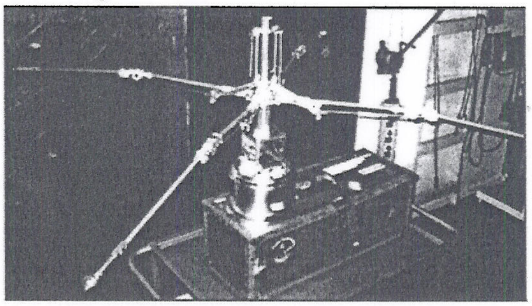

*Figure 1. UiO Boom Design, in deployed configuration*

## 2. ESPRIT Boom Design

### 2.1. Constraints

The major constraints of the ESPRIT system can be separated into two categories, experimental and physical. The most important experimental constraints were the minimum probe distance of 0.5 m from the skin and 8.5 cm length of the cylindrical probe assemblies. In addition, due to the placement of the magnetometer just above the boom system, the booms had to be magnetically clean.

The physical constraints included the straight taper nosecone and large center shaft. The straight taper nosecone provided considerably less internal volume than an Ogive or parabolic shape, especially where the hinges were required to be located. The large diameter center shaft was required to house additional experiments and provide a mount for the nosecone ejection system. However, the most stringent requirement was operational spin rate of the Terrier-Improved Orion launch vehicle, 4.5 – 6.5 Hz. Since no de-spin or Attitude Control Systems, ACS, were planned for the payload, the booms would have to accept the large dynamic loads associated with deploying at such high spin rates.

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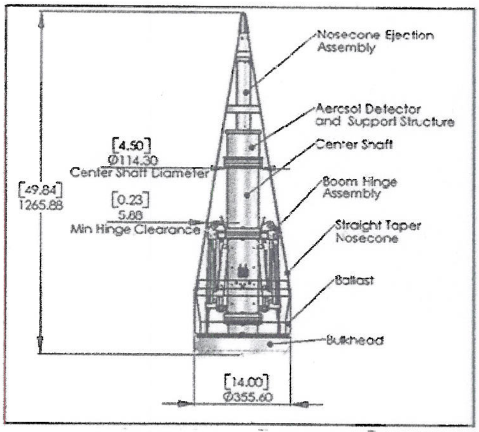

*Figure 2. ESPRIT Boom Geometric Constraints (bracketed dimensions in inches)*

### 2.2. Design Features

The Pennsylvania State University boom system design took advantage of the positive characteristics of the University of Oslo design while building upon them to meet ESPRIT requirements. The major aspect that was transferred between the two designs was the rigid interconnection of the booms. Utilizing a slide riding on a linear bearing, the design ensures a symmetric and simultaneous deployment of both arms, reducing the amount of coning that could be induced on the payload from an unbalanced rotation. If only one boom deployed, the resulting imbalance in the system would eventually place the rocket into flat spin, with disastrous effects on the onboard experiments. In addition, the inner and outer boom arms were rigidly connected with a smaller support tube, as shown in Fig. 3. This connection allowed a fluid deployment, with both the inner and outer booms unfolding simultaneously.

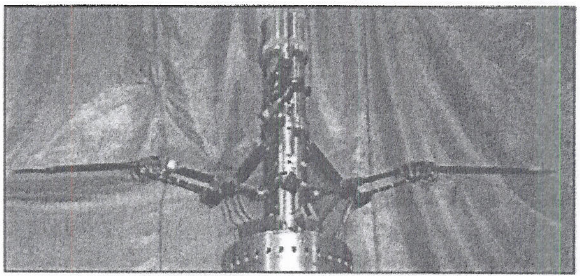

*Figure 3. ESPRIT boom system during testing*

The rigid, interconnected design was constructed primarily from aluminium and carbon fiber for weight and magnetic cleanliness concerns. The carbon fiber tubes were created by wrapping a unidirectional carbon fiber prepregnated tape around a mandrel with the majority of the carbon fiber running longitudinally. This configuration provided a high flexural stiffness of 1875 MPa that prevented the booms from oscillating after deployment, an important consideration for payload coning. This stiffness is much higher than that of graphite, a popular material for earlier boom arms. In addition, carbon fiber can withstand the large tensional forces associated with high rotation speeds.

Other materials were used where appropriate, such as titanium hardware and probe supports and ground stainless steel for the guide shaft and slide assembly. Another material utilized extensively in the system was bronze, primarily for bushings. Four of these flanged bushings were press fitted at each pivot point to preclude two parts made of the same material from contacting each other and binding. The bushing flanges provided a small, uniform bearing surface and BMS5-95 Class B sealant provided dissimilar metal protection on non-exposed portions of press fit parts. Originally, the bushings were designed to use SAE 841 bronze, a common material for terrestrial mechanical systems which contains 18% SAE 30 oil by volume to provide lubrication. However, they failed outgassing tests, as the Total Mass Loss (TML) far exceeded NSROC design specifications. Flight bushings were machined from SAE 660 bronze.

One final mechanical feature of the ESPRIT design was the incorporation of multiple locks; which upon deployment, rigidized the system, again minimizing the amount of coning induced on the payload. This problem was judged to be important enough that two types of locks were developed. Upon deployment, the boom system was locked both in the center shaft and the outer hinges, leaving only the outer boom arm to flex. The internal shaft locks consisted of spring pins that activated as the center slide rose to its deployed position. High spring constants used so that deployment momentum was diverted into retracting the stiff springs. The hinge locks were not as robust, but provided a secure, vibration proof cantilever mount for the outer boom arm. They were constructed from grade 5 titanium leaf springs mounted to the inner hinges that grabbed the outer boom hinges when deployed. The locks were among the majority of the 50+ system parts, shown in Fig. 4 that were machined by students. Professional machine shops were only utilized for larger or complicated parts that Penn State did not have proper equipment to manufacture.

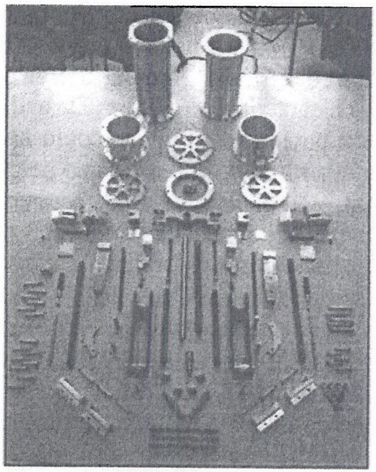

*Figure 4. ESPRIT boom components*

### 2.3. Testing

In order to determine the suitability of the boom system for flight, a series of spin tests at NASA's Wallops Flight Facility were undertaken. A total of four test sequences, including a total of 10 deployments, were accomplished at rotational frequencies between 3.5 and 6.6 Hz. This large deployment envelope allows the booms to be useful on any NSROC flight vehicle. Various problems were encountered, especially at higher spin rates where the deployment time was less than 0.2 seconds. These included stress concentrations at the carbon fiber-aluminium joints and probe mounts as well as locking and overextension issues. The high stresses were lowered by increasing fillet radii, tapering and reducing overall weight of parts. The probe mounts were completely redesigned to incorporate a titanium support shaft, which could cope with the stresses as well form a strong electrical connection to the probe. Overextension was eliminated by increasing the spring constants of the locks and adding hard stops.

### 2.4. Flight Performance

During final testing and in flight, the booms were monitored by microswitches and accelerometers. The microswitches were incorporated into a redundant system that positively confirmed both the beginning and end of deployment, while the boom mounted accelerometers had the primary goal was measuring once-per-revolution flutter. This motion could be created by a slightly asymmetric weighting of the boom arms or inadequate damping of transient oscillations after deployment. As shown in Fig. 5, they monitored the portion of the booms outboard of the hinge locks in both the $e_\theta$ and z axes. Accelerations in these directions are referred to as shimmy and flutter, respectively. This information can be used to determine the boom system's affect on payload flight dynamics.

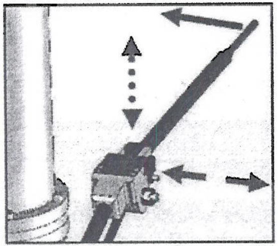

*Figure 5. Accelerometer Sensing Directions (Dotted line denotes flutter, dashed line denotes shimmy and solid arrow denotes payload rotation direction)*

Testing with the accelerometers on the spin and vibration tables did not yield much information because the gain in the circuitry was set too low for good data resolution. However, the peak the impact acceleration upon extension was logged at 33g. For flight, the gain was increased for better resolution of small amplitude vibrations. Unfortunately, a temperature offset factor was not taken into consideration during the implementation of the accelerometers, so the absolute acceleration cannot be established. For the analysis, only the relative magnitude of the accelerations was considered. During flight, the two shimmy accelerometers received little stimulation and only recorded engine ignition and boom deployment accelerations. Few, if any accelerations were expected in this dimension outside of major flight events. The flutter accelerometers also measured flight events, but yielded more information. Fig. 6 is a close-up of the deployment section of the flight data, showing the relative magnitude of flight events.

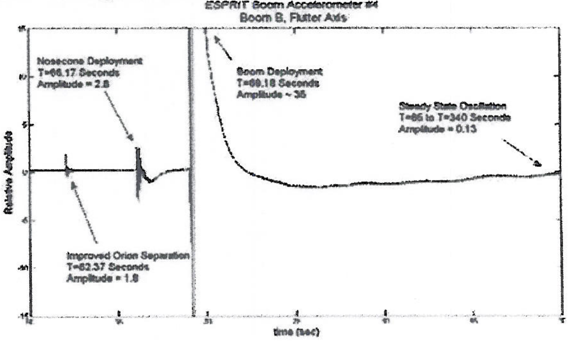

*Figure 6. Flutter Accelerometer Deployment Data*

However, the accelerometer data differed after T=75 seconds, as shown in Fig 7. After a settling period, the Boom B locked and entered a steady state 0.25 Hz oscillation until the payload re-entered the atmosphere. The fact that the accelerations had an amplitude of only 0.6% of the deployment acceleration, indicates that the boom fully locked into place.

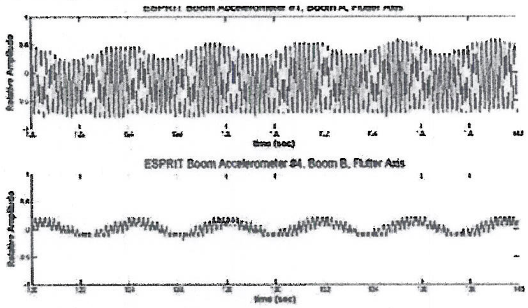

*Figure 7. Flutter Accelerometers Steady State Data*

Unlike Boom B, Boom A had more activity during the deployed portion of flight. A Fast Fourier Transform of both sets of data, shown in Figs 8 and 9, reveals that Boom A was oscillating at 5.186 Hz. This frequency differs from the payload coning frequency of 0.25 Hz and payload spinning frequency of 5.449 Hz. Although the oscillation amplitude was not high, the data indicates that the boom did not fully lock. Due to the coning of the payload, an unlocked boom would experience periodic accelerations with the same frequency as the payload rotation. Most likely, the titanium sheet bent, a possibility proven in testing, and instead functioned as a damper, which lowered the oscillation frequency slightly from the payload spinning frequency.

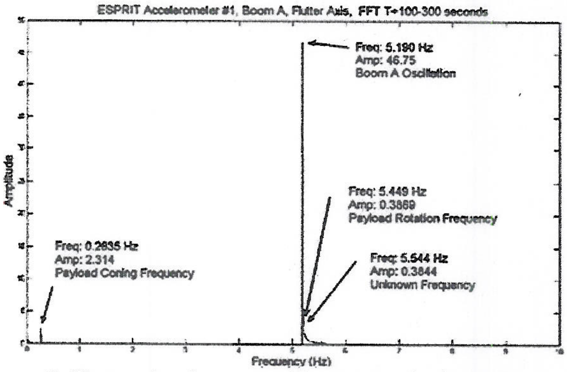

*Figure 8. Flutter Accelerometer Frequency Analysis, Boom A*

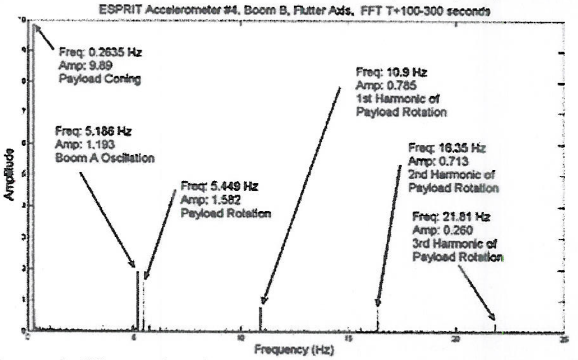

*Figure 9. Flutter Accelerometer Frequency Analysis, Boom B*

Overall, the oscillations did not have much effect on the flight performance of the payload other than increasing the payload coning angle. This is a testament to the resilience of the design, as it allowed the Langmuir Probes to gather valuable data about the ionosphere with an unlocked boom.

## 3. FUTURE DESIGNS

### 3.1. Improvements to Current System

During testing it was obvious that high deployment stresses were the limiting factor in the design, as three sets of composite boom arms were required for the test sequences and flight. While stresses were partially alleviated with minor tweaks, expansion of the system to include four arms of a longer span would be difficult without more efficient energy and momentum management. While retaining the basic ESPRIT design, a braking system was developed to slow the deployment, reducing stresses. After considering various design possibilities, a completely mechanical gearing system was devised. It has the advantages of simplicity, redundancy and magnetic cleanliness.

Shown in Fig. 10, gears convert the linear motion of deployment into pressure applied to two brake pads. The brake pads function like those found on disk brake systems in automobiles, clamping onto a stationary guide shaft and converting kinetic energy into heat. The system was designed to allow the booms to initially deploy uninhibited to gather some momentum and then gradually slow them down. The braking would cease before reaching the deployed position to ensure enough momentum is available to engage the locking mechanisms. The key to a proper deployment would be smooth transitions between the three phases of the braking procedure. Stress calculations indicate that a tip to tip boom span of 2.25 m could be obtained before major changes to the rest of the assembly would be required.

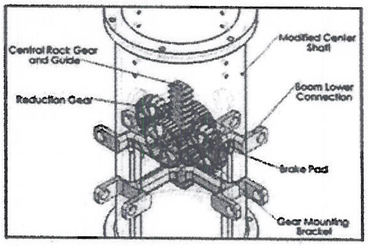

*Figure 10. Geared Momentum Management System*

### 3.2. Payload Mounted Alternatives

In addition to creating an enlarged system housed underneath the nosecone, experience with the ESPRIT system is being applied to smaller designs mounted within the payload skin. This is important as the number of sounding rockets launched is decreasing, so multiple payloads are being combined on each rocket. Space underneath the nosecone will be scarce, because in addition to multiple institutions competing for it, it is an attractive location to mount recovery systems.

In order to mount inside the skin, the stowed form factor of the booms must be reduced even further to allow space for other electronics. Currently, the empty space in the Ecoma rocket's ballast module is being utilized as the worst case scenario, as the booms must fit into a 0.35 m diameter by 0.17 m tall cylinder. Most NSROC payloads are moving to a 0.43 m diameter skin, so the design can be easily adapted to the larger payload. As no direct experiment requirements have been issued yet, ESPRIT specifications are assumed, including the 6.5 Hz deployment spin rate and 0.5 m skin to probe separation. The large and complex ESPRIT boom system would not efficiently use the space available inside the payload, so smaller assemblies featuring three telescoping boom sections would be required.

Based upon experience with the ESPRIT booms, only minimum technology advances are required before either an advanced energy management or telescoping system can be successfully tested and implemented into a payload. Penn State has many opportunities to feature such systems on upcoming payloads and welcomes international partners for collaborative experimentation.

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