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ASTRO
RESEARCH
CORPORATION

CARPINTERIA, CALIFORNIA

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SECTION 1
INTRODUCTION

As part of an on-going study for developing efficient structures for geosynchronous spacecraft solar arrays, Astro Research Corporation (Astro) is currently developing a prototype deployer for the STACBEAM (Stacking Triangular Articulated Compact Beam). The STACBEAM is a product of earlier phases of this program in which various structures were investigated for deployment and support of an accordian-folded solar array blanket (see Ref. 1). A prototype of the STACBEAM was constructed as a point design for support of a 23.9-kW blanket and is described in Reference 2.

An early version of the deployer was constructed and is documented in Reference 2. In concept, it is identical to the one now being developed, having "starwheel" passive holding devices and a grasping transporter. It differs in its inertial frame: the early deployer was designed so that the packaged beam and the starwheel assemblies were mounted in a reciprocating mechanism and the graspers were stationary. A bay was deployed by moving the package away from the deployed portion of the beam. This simplification was made for demonstration purposes. A more energy-efficient method is used here in that the package is held fixed and only the deploying beam moves.

SECTION 2
REQUIREMENTS

The general requirement of the deployer is that it extend the packaged STACBEAM to the deployed condition. It must do so one bay at a time in a predictable, repeatable manner with minimal accelerations. The deployer itself is required to be deployable to minimize package size. It must hold the STACBEAM securely against launch loads and provide a stable platform during deployment. It must allow for attachment of the payload in the packaged condition.

2.1 STACBEAM EXTENSION

The STACBEAM to be deployed is shown in Figure 1 and has a beam diameter of 0.900 m, a bay length of 0.428 m, and an effective member diameter of 5.08 mm. The deployed beam length is 31.7 m and, thus, requires 74 bays. Packaging is characterized by folding of longerons toward the beam axis so that the packaged bay length is two member diameters. The packaged 74 bays therefore require a length of 0.752 m.

Deployment is sequential; that is, the STACBEAM extends one bay at a time. Thus, there are three regions of the beam which are of interest:

- o The fully packaged portion of the beam, which is held in the deployer
- o The fully deployed portion of the beam, the base of which is held by the deployer
- o The one bay in deployment transition, secured at both ends by the deployer

2.2 DEPLOYER DYNAMICS

An arbitrary requirement has been established to deploy the full beam length in 20 minutes. Since the deployer reciprocates, moving two bay lengths for every bay deployed, the average deployment velocity must be

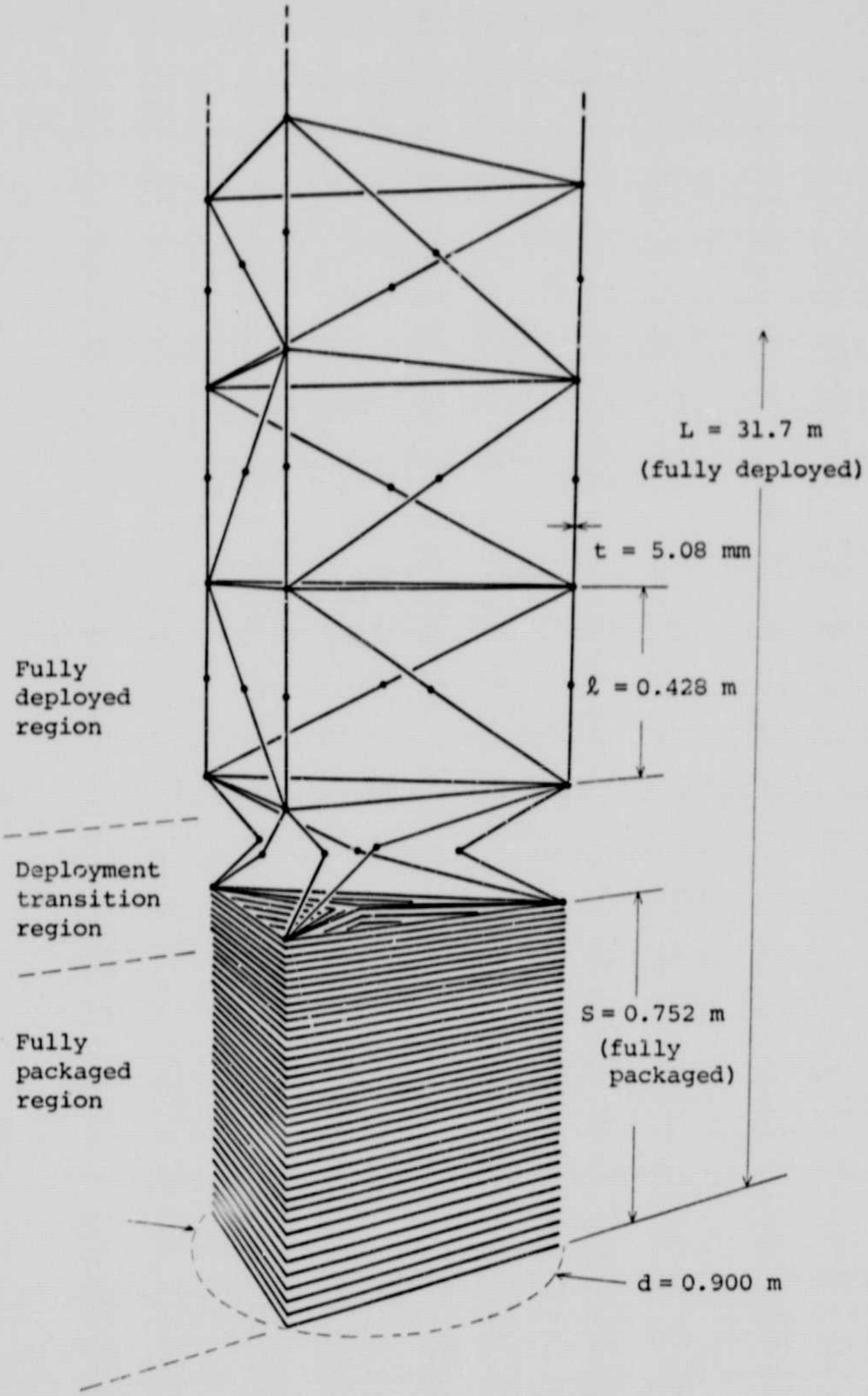

Figure 1. STACBEAM configuration. *088B*

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$$V_{dep} = \frac{2L}{T} = \frac{(2)(31.7)}{(20)(60)} = 0.0528 \text{ m/s} = 2.08 \text{ in/s}$$

Each of the 74 bay deployments occupies a 16.2-second time window.

The reciprocating aspect of the deployer creates a need for acceleration management. In the worst case, near full beam deployment, approximately 90 kg of structure and payload are being moved in a configuration such that two longerons are in compression. If a 12-N limit per longeron is assumed, the acceleration in this case should not exceed

$$a = \frac{F}{m} = \frac{(2)(12 \text{ N})}{90 \text{ kg}} = 0.27 \text{ m/s}^2$$

which is about 0.027 g. Designing for this worst case yields the velocity profile shown in Figure 2.

A "smart" deployer would vary this velocity profile according to need; real-time monitoring of member loadings to achieve maximum accelerations would result in minimum deployment time.

Precision deployment requires close synchronization of the three mechanisms which extend each of the corners of a batten frame. The use of three separate drives reduces mechanical complexity but introduces the need for electronic sensing and control.

2.3 PACKAGED REQUIREMENTS

In order to minimize package volume, the launch dimensions of the deployer should approximate those of the packaged STACBEAM. Thus, the deployer is triangular in form, operating on the three corners of the beam, and of length as close as possible to the packaged beam length. It is required then that the mechanism deploy itself from the packaged to an operating condition so that stiffness is maintained out to the end of the transition region.

Provision must be made in the deployer for attachment of the payload along the length of the beam. This attachment must exist in the packaged as well as the deployed condition. Therefore, the deployer must be open on the side through which the beam interfaces with the payload.

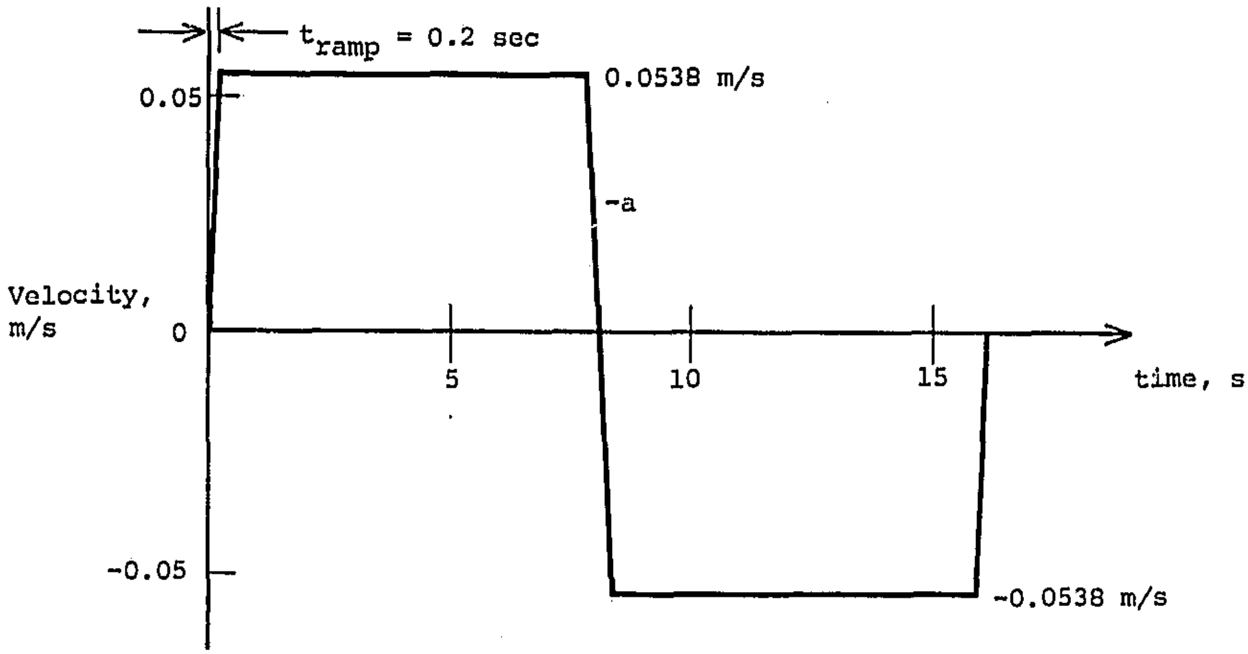

Figure 2. Deployer transporter velocity profile. 087A

SECTION 3
HARDWARE DESCRIPTIONS

The deployer consists of two major sections which are shown in Figure 3. The fixed structure is attached to the spacecraft, holds the packaged STACBEAM securely for launch, and provides a stable base for the deployed beam. The operating structure is movable within the primary structure and contains the mechanisms for deploying the beam.

3.1 FIXED STRUCTURE

A detailed illustration of the fixed structure is shown in Figure 4. Items comprising the fixed structure are described in the following sections.

3.1.1 Base Truss

This is of welded construction and consists of aluminum channels in a triangular array. It is configured to be large enough to fit around the packaged STACBEAM and serves as the stable base for the deployer.

3.1.2 Column

Each column of the fixed structure is assembled and consists of two side plates and a face plate, each screwed along its length to the guide posts. The guide posts provide structural unity to each column and also hold the operating structure.

3.1.3 Guide Rails

A pair of guide rails is attached along the entire length of the face plate. These hold the packaged STACBEAM in place and guide it into the deployment mechanism.

3.1.4 Starwheels

The starwheels are identical to those used in the earlier breadboard model of the deployer. They are designed to allow entry of a STACBEAM batten

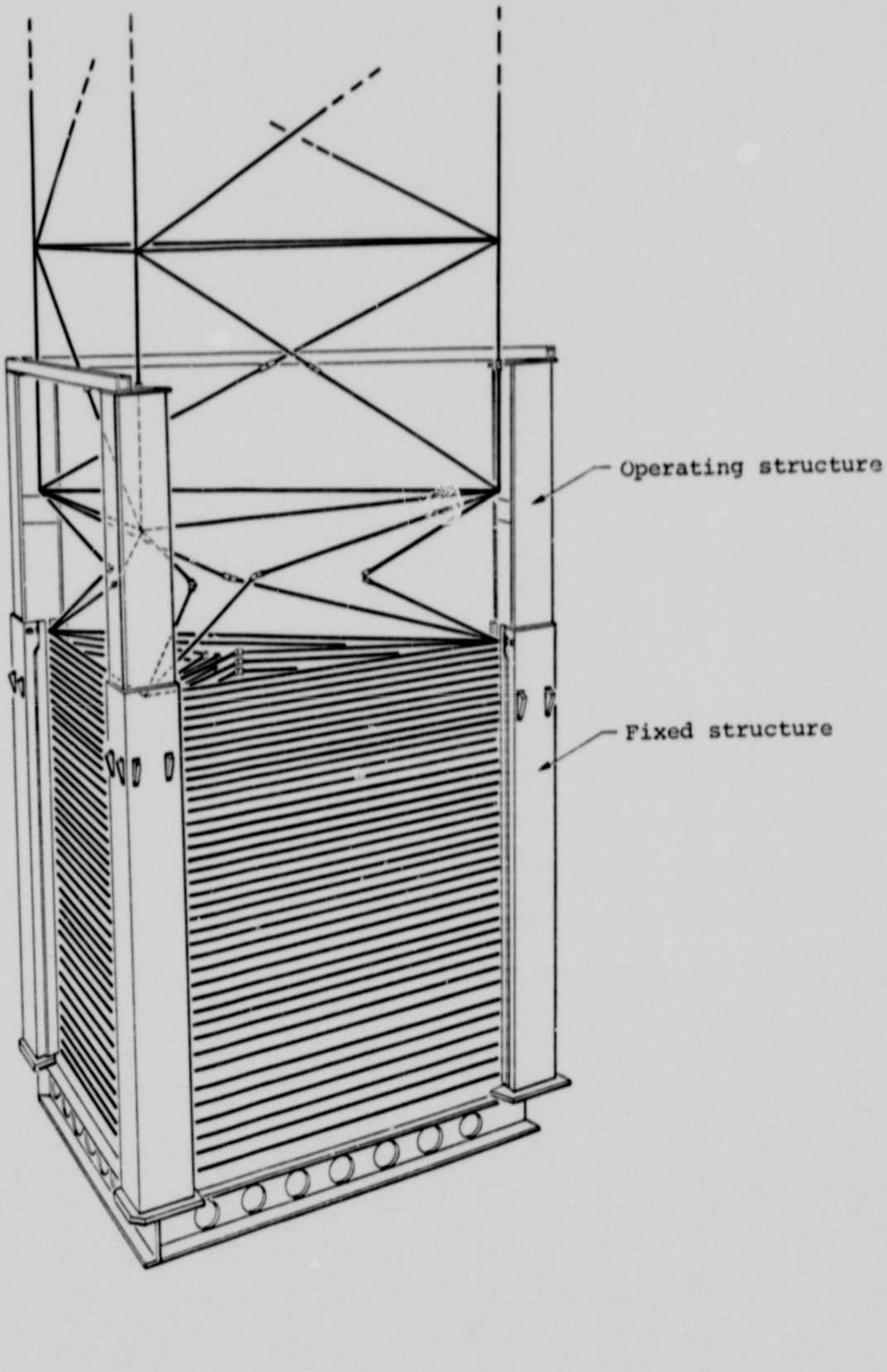

Figure 3. Deployer.

089B

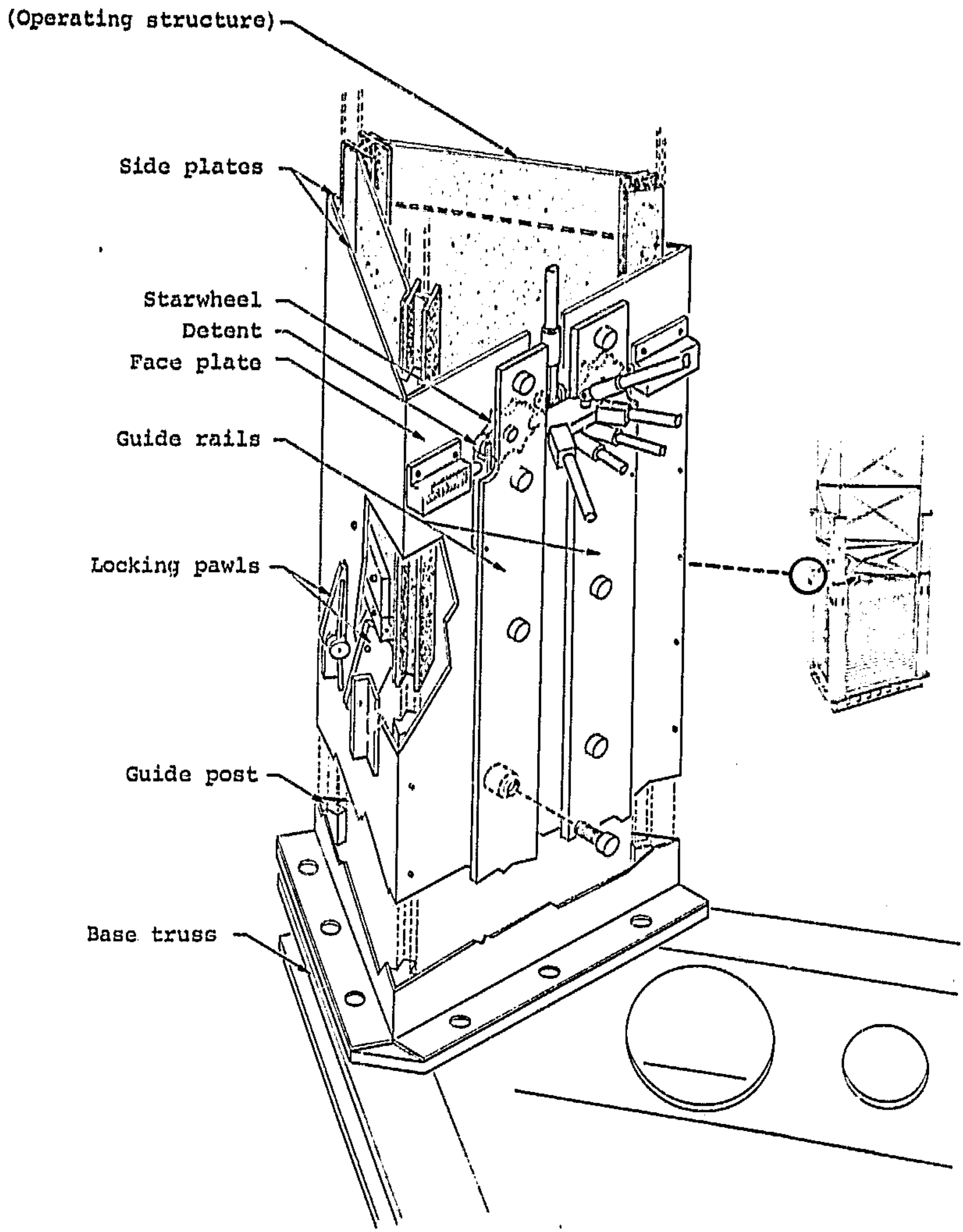

Figure 4. Components of fixed structure. 090B

corner body in the direction of deployment and to hold it in a relatively strong detented position. No provision is made for synchronizing the pairs of starwheels by gearing, as this was found to be unnecessary in the early model.

3.1.5 Locking Pawls

These spring-loaded devices provide a positive locking force against the deployed operating structure. They are unlocked in the launch condition, allowing relative motion of the fixed and operating structures and trip into place at the end of motion.

3.2 OPERATING STRUCTURE

The operating structure is shown in Figure 5. It is movable within the fixed structure from an initial retracted position in the launch configuration to the operational extended position. It is locked in the extended position by the pawls. The operating structure is composed of items described in the following sections.

3.2.1 Column

There are three columns in the operating structure. Each has two sides and is open toward the inside of the deployer. A column consists of two stiff side plates which are screwed at their ends to two end plates and are bonded along their lengths to three guide posts. The guide posts interface with those of the fixed structure previously described, provide for deployment of the operating structure, and primarily serve as transporter guides.

At each end of the column, a limit switch is mounted to indicate the position of the transporter.

3.2.2 Transporter

The transporter shown in Figure 6 is the primary element of the deployer. The jaws, which grasp a corner body of a batten frame, are mounted on it. The transporter moves on a lead screw moving a batten corner out of the starwheels to a full bay length away thus causing deployment of a single bay.

EFFICIENT STRUCTURES FOR GEOSYNCHRONOUS SPACECRAFT SOLAR ARRAYS

FINAL REPORT, PHASE V

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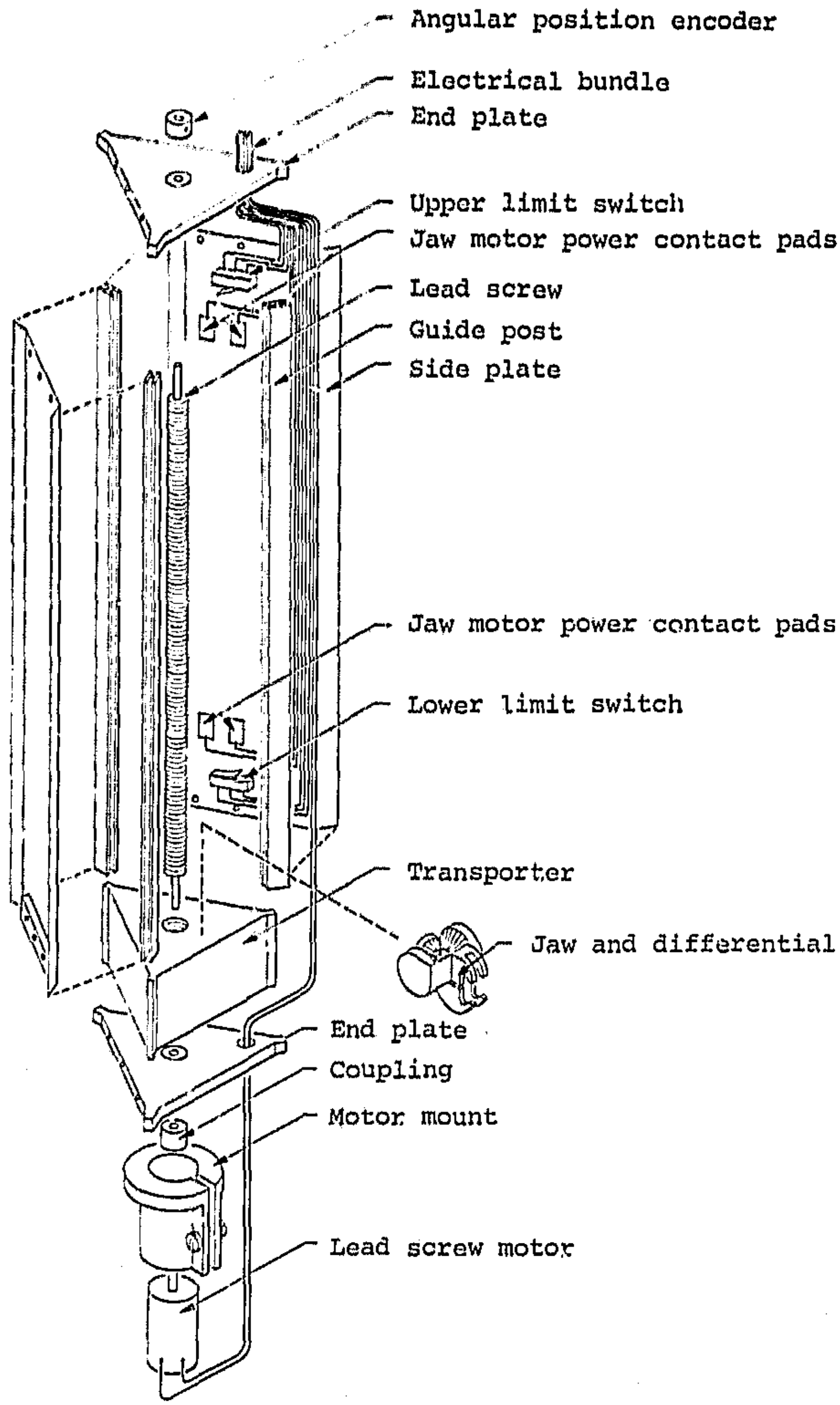

Figure 5. Components of operating structure. *091B*

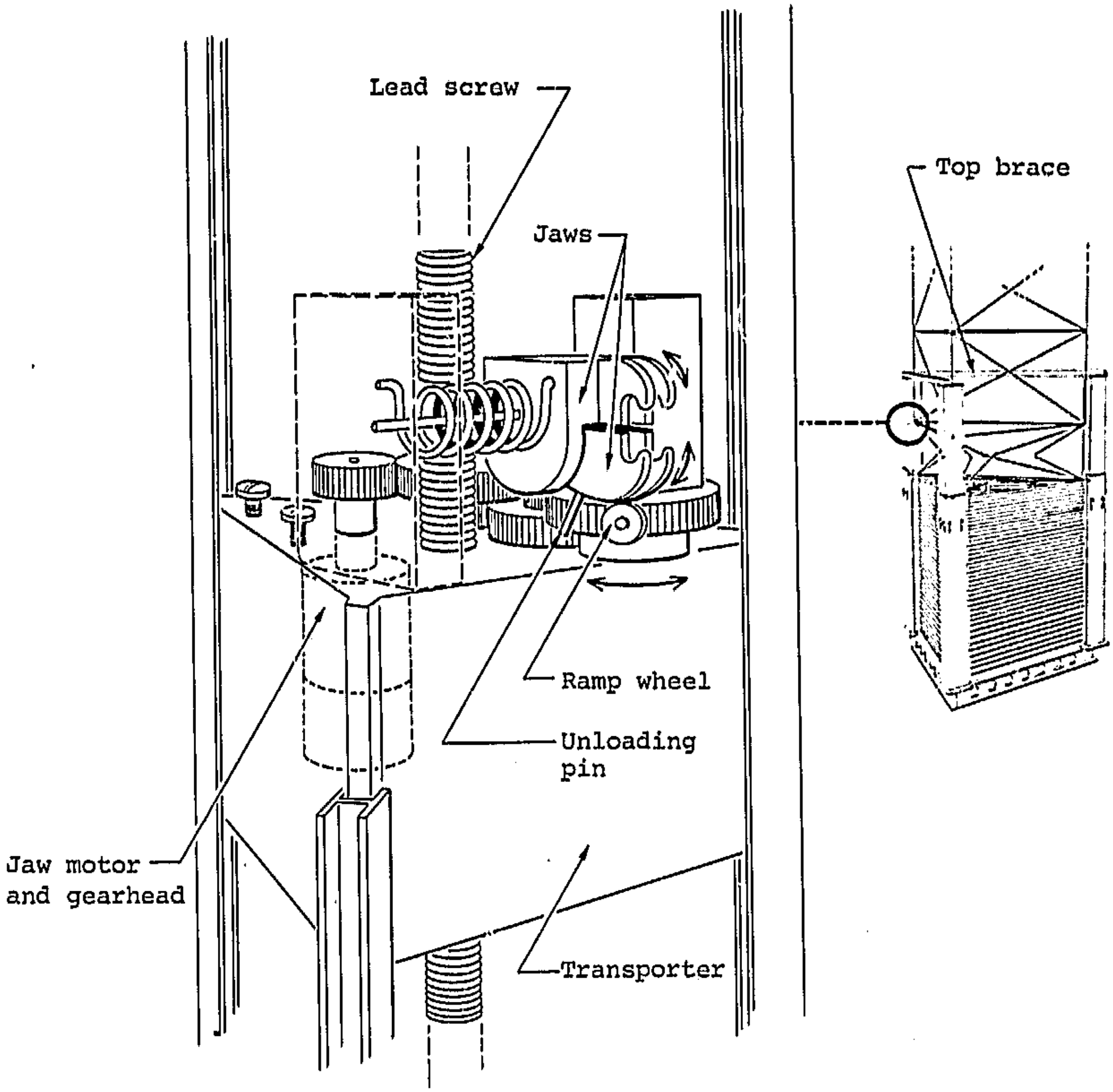

Figure 6. Transporter and jaws.

092A

3.2.2.1 JAWS

The jaws are shown in Figure 6 and are mounted in opposing pairs which are connected by a differential. The geometry of the jaws is such that a batten corner body is captured and immovable when the jaws are closed and is released when the jaws are opened. Such motions of the jaws require a reliable mechanism which went through several designs as follows.

The initial design specified a worm drive which impinged directly on the barrel of one of the jaws. Rotation of the worm drive caused rotation of the jaw, and the other jaw rotated because of the differential. This design, after construction and testing of the jaw assembly, proved to be plagued with problems related to the worm gear (motor lockup, thread skipping, and excessive friction).

Redesign led to the configuration shown in Figure 6 whereby a ramp is moved under the lower jaw. The ramp is, in actuality, a small wheel which is set in the periphery of a rotating plate driven by a motor through a gear train. This assembly opens or closes the jaws in about a second. Further redesign was found to be necessary so that jaw opening is caused by positive motor drive rather than by spring unloading.

3.2.2.2 LEAD SCREW

The lead screw is threaded through the center of the transporter and is powered by a motor at the base of the operating column. The lead screw has 16 threads per inch and a 3/8-inch diameter. It is supported by roller bearings which are set in the end plates.

The available thrust T at the transporter depends on the lead screw diameter d, pitch p, on the motor torque τ, and on the coefficient of friction μ

$$T = \frac{2\tau/d}{(p/\pi d + \mu)}$$

If we assume τ = 15 oz-in (Micro Mo Series 3557, 12 Vdc) and μ = 0.20 (delrin against aluminum), the available thrust is

$T = 20\ lb$

which is sufficient to overcome ordinary deployment loads.

The unloaded motor speed is listed as 5,250 rpm; the operational transporter speed is about 4 inches/second indicating a loaded speed of about 4,000 rpm. Further speed reduction to about 3 inches/second has resulted from synchronization.

3.2.3 Synchronization

A high degree of synchronization of position of the three transporters is required in order that the beam is deployed in an erect manner. This synchronization is achieved through the use of active feedback of shaft position signals to electronic circuitry which controls lead screw motor actuation. At the top of each lead screw is a disk with a single magnet imbedded on its periphery so that a Hall effect sensor notes each revolution of the lead screw. These signals are monitored continually and separately for each of the three corners of the deployer, and the position of the three transporters is held within one thread spacing.

3.2.4 Control

In addition to synchronization of the lead screw speeds, control of the mechanism is required for proper deployment. The control box shown in Figure 7 was developed by Astro by internal funds for research and development.

3.2.4.1 JAW MOTORS

Electrical switching is provided which actuates all jaw motors simultaneously. A three-position switch causes each to open, close, or remain as is (no power). The wiring is routed to the jaw motors by contact pads on the inside surface of the operating column. Wipers on the transporter make contact with the pads at the end-of-travel positions.

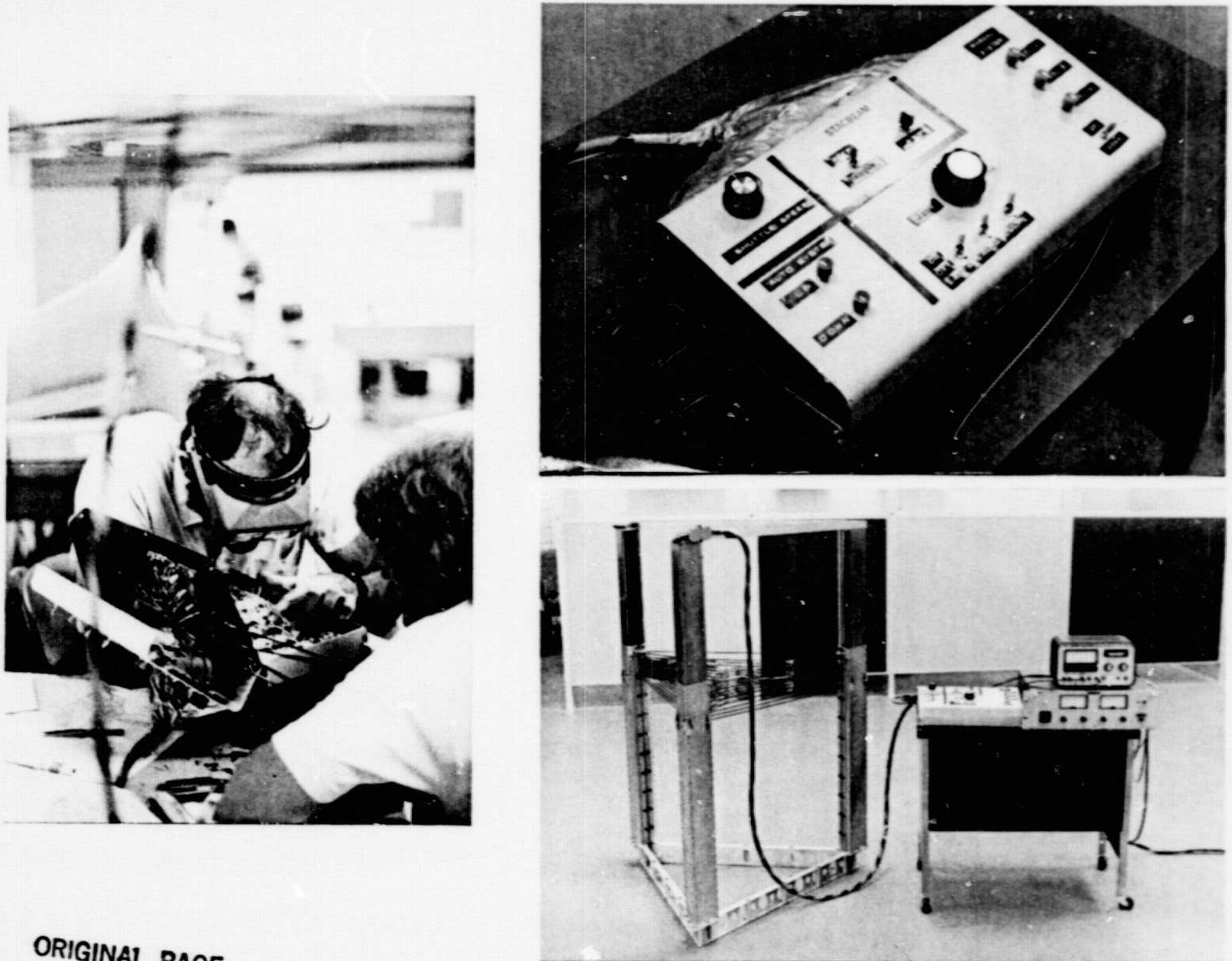

Figure 7. Electronic controller. P028(a-c)

3.2.4.2 LEAD SCREW MOTORS

The lead screw motors are controlled by electronic logic. Deployment of a bay is initiated by switch actuation, and each transporter proceeds with synchronization until reaching its upper limit switch and stops at the point of the next Hall effect signal. Transporters are lowered by switch actuation and proceed with synchronization, each stopping when reaching its lower limit switch.

3.2.5 Top Brace

The top brace is shown in Figure 6. It is of welded construction and composed of 1-inch square aluminum tube. One side of the triangle remains open to allow for the payload attachment to the packaged STACBEAM. The function of the top brace is to maintain proper separation between the three corners (two separations held by direct attachment to the brace and the third by bending stiffness). The top brace also serves as a conduit through which control wiring passes.

3.3 SEQUENCE OF OPERATION

The sequence of operating during deployment of the entire STACBEAM is as follows.

3.3.1 Initial Operation

The launch condition of the system is such that the operating structure is inside the fixed structure. The total height of the deployer is slightly greater than the stacked height of the STACBEAM. The top bay of the beam is doubly held by the starwheels and jaws. The transporters are thus at the upper ends of the columns of the operating structure.

The first operation of the deployer is to drive the lead screws such that the transporters tend to move down the operating columns. Since the transporters are fixed at the top of the stack, the operating structure is driven out of the fixed structure to the configuration required for deployment. The mechanism of the locking pawls then fixes this configuration.

3.3.2 Single-Bay Deployment

The lead screws are synchronously driven counterclockwise so that the transporters move upward (toward deployment). Each of the three currently held STACBEAM corner bodies is lifted out of the starwheels, which temporarily assume a waiting orientation. The transporters move a distance of precisely one baylength. Transporter velocities are closely controlled and varied during this entire operation in order to manage the loads developed in the beam. When this distance is attained, the three corner bodies of the next batten frame are lifted into the starwheels and are passively held against any loads except those which can be applied by the transporters.

3.3.3 Transporter Retraction

The jaws are actuated such that they release the batten frame corner bodies. The lead screws are synchronously driven clockwise so that the transporters move down (toward the package). The transporters stop when the jaws are precisely at starwheel level. The jaws are then actuated in order to grasp the batten frame corner bodies.

At this point, a test is conducted to determine whether or not the lowermost packaged bay has been deployed. If not, the operations in Section 3.3.2 are performed. If so, deployment is halted.

SECTION 4
ASSEMBLY AND TEST

Assembly and testing of the deployer were conducted in several stages. Early in assembly, individual components were tested, and adjustments were made to ensure proper operation. Testing was extended to the electronic unit, as it was interfaced to the deployer, and finally to the completed deployer and STACBEAM as a functioning system.

Figure 7 shows various views of the electronic controller. The functions of the controller are to synchronize the three transporter positions and to control the operation of the motors for jaw and lead screw operation, as discussed in Sections 3.2.3 and 3.2.4. Separate 5- and 12-Vdc power supplies are required. A switch provides a choice between automatic and manual control whereby manual control makes each motor separately switchable, and automatic control synchronously deploys a single bay. The controller is connected to the deployer by a cable with a removable connector.

Further controller modifications are required for the following reasons. Deployment velocity is now constant (at about 86 mm/sec), and sinusoidal ramps are needed in order to minimize loads directed into the beam. Monitoring of jaw position is necessary in order that full automation can be attained. With this capability, the operations of Sections 3.3.2 and 3.3.3 can be made to proceed automatically such that the entire beam is deployed by a single actuating command.

The photographs shown in Figure 8 were taken at a point in assembly when the inside face plate was removed from the fixed portion of one corner. Thus, several features were made visible: the lead screw motor and mount, the lower limit switch for transporter motion, and the wire routing. Also shown in Figure 8 are the transporter, the jaw drive gear train, and the Hall effect switch at the top of the lead screw for angular position encoding.

Figure 9 shows the deployer and STACBEAM. The sequence of STACBEAM deployment, discussed in Section 3.3, is seen in the photographs. The initial

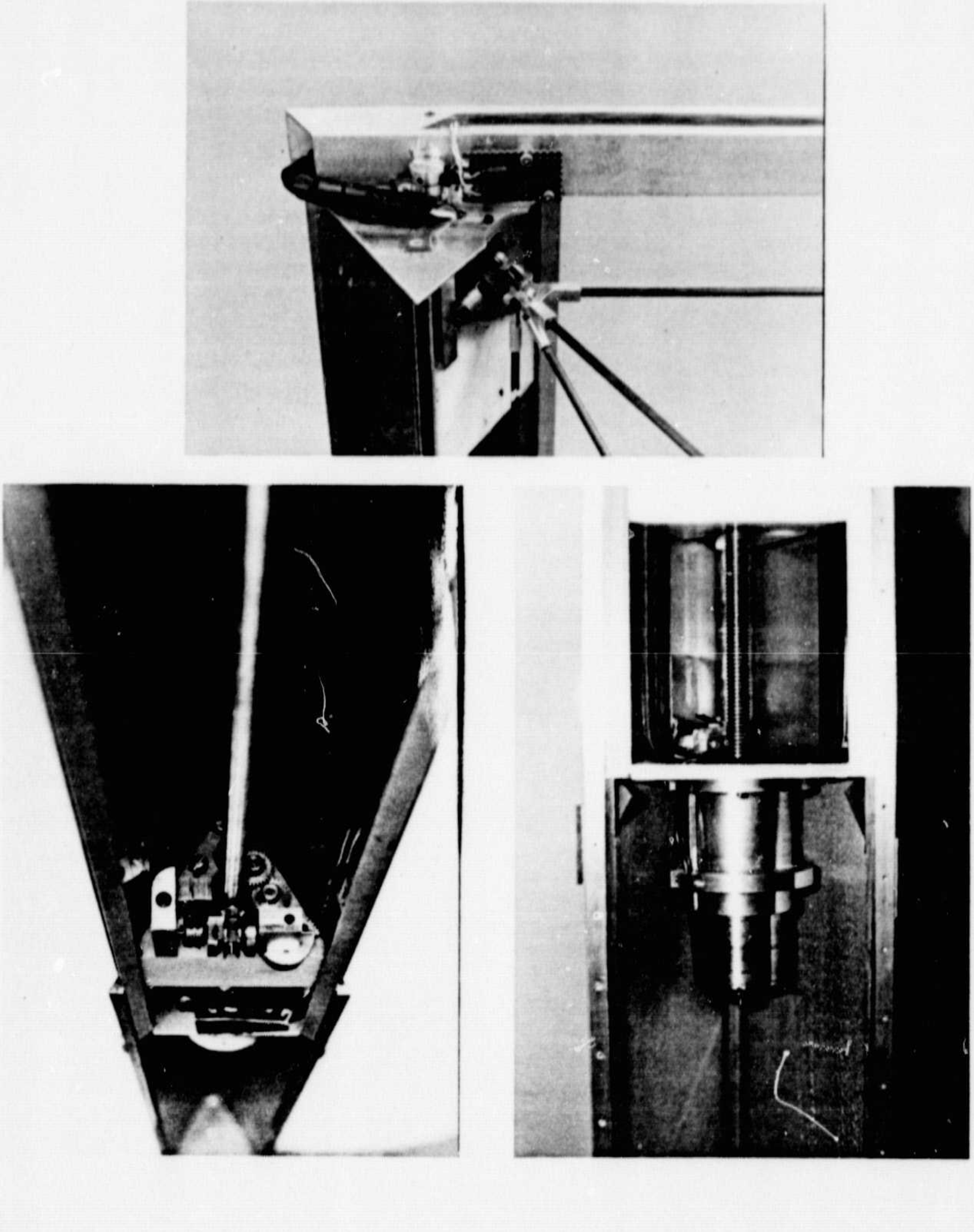

Figure 8. Lead screw. P027(a-c)

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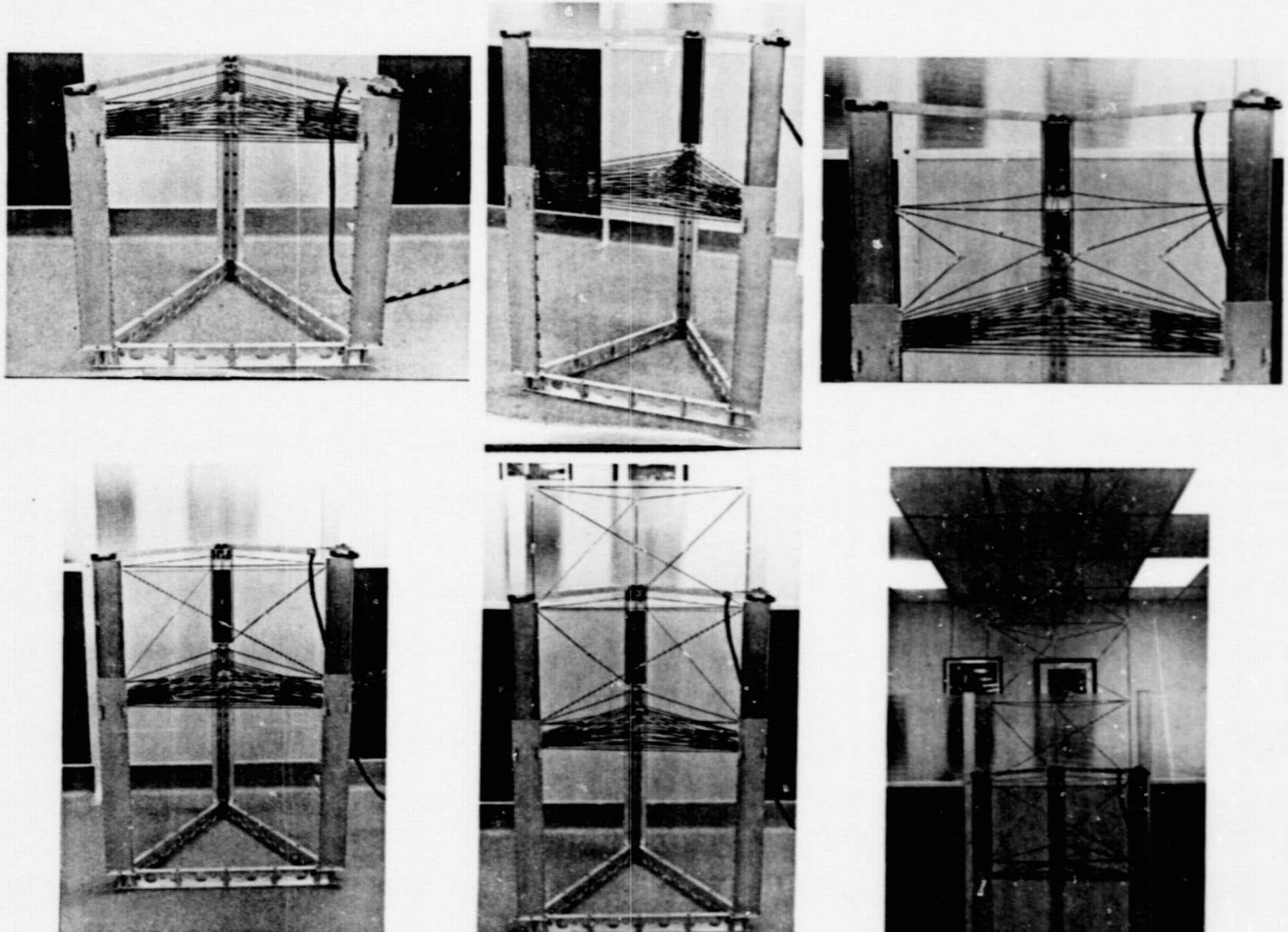

Figure 9. Vertical deployment. F029(a-f)

deployment of the deployer operating structure was done by hand since motorized deployment currently requires excessive torque of the lead screw motors to lift the operating structures against gravity and against the friction of the locking pawls.

Subsequent deployment of the STACBEAM itself proceeded successfully. A single bay extends in about 5 seconds, which is the time required to move the transporter the length of the lead screw. Jaw actuation time is approximately 2 seconds. The operational time period between successive bay deployments is then 14 seconds so that the 74 bays of the full beam would deploy in 17 minutes.

A tendency has been observed for the lead screws to vibrate. This has been alleviated by lubrication damping, but is due to shaft whirl, whereby the rotation speed corresponds to the shaft resonant vibration frequency. A pinned shaft of free length s has a natural flexural frequency of

$$f = 1.56 \sqrt{\frac{EIg}{w's^4}}$$

where E is the modulus of elasticity, $I = \pi/4\ r_i^4$ is the area moment of inertia, and $w' = \delta\pi r^2$ is the linear weight density for a threaded shaft of minor diameter r_i and pitch diameter r. For the present case, $E = 10 \times 10^6$ psi, $r_i = 0.149$ inch, $r = 0.166$ inch, $\delta = 0.10\ \text{lb/in}^3$, and $s = 20.8$ inches for the aluminum lead screw. Then,

$$I = 3.87 \times 10^{-4}\ \text{in}^4$$

$$w' = 8.66 \times 10^{-3}\ \text{lb/in}$$

$$g = 386\ \text{in/s}^2$$

$$f = 48\ \text{Hz}$$

This shaft frequency is an approximation: addition of a point mass to account for the transporter lowers this frequency, while consideration of the decrease in shaft length due to the guided transporter increases the frquency. Rotation at this frequency corresponds to the transporter speed of 3 in/s.

During deployment, each longeron is extended separately as shown in Figure 10. The jaws are shown ready to clamp onto a corner body which is held

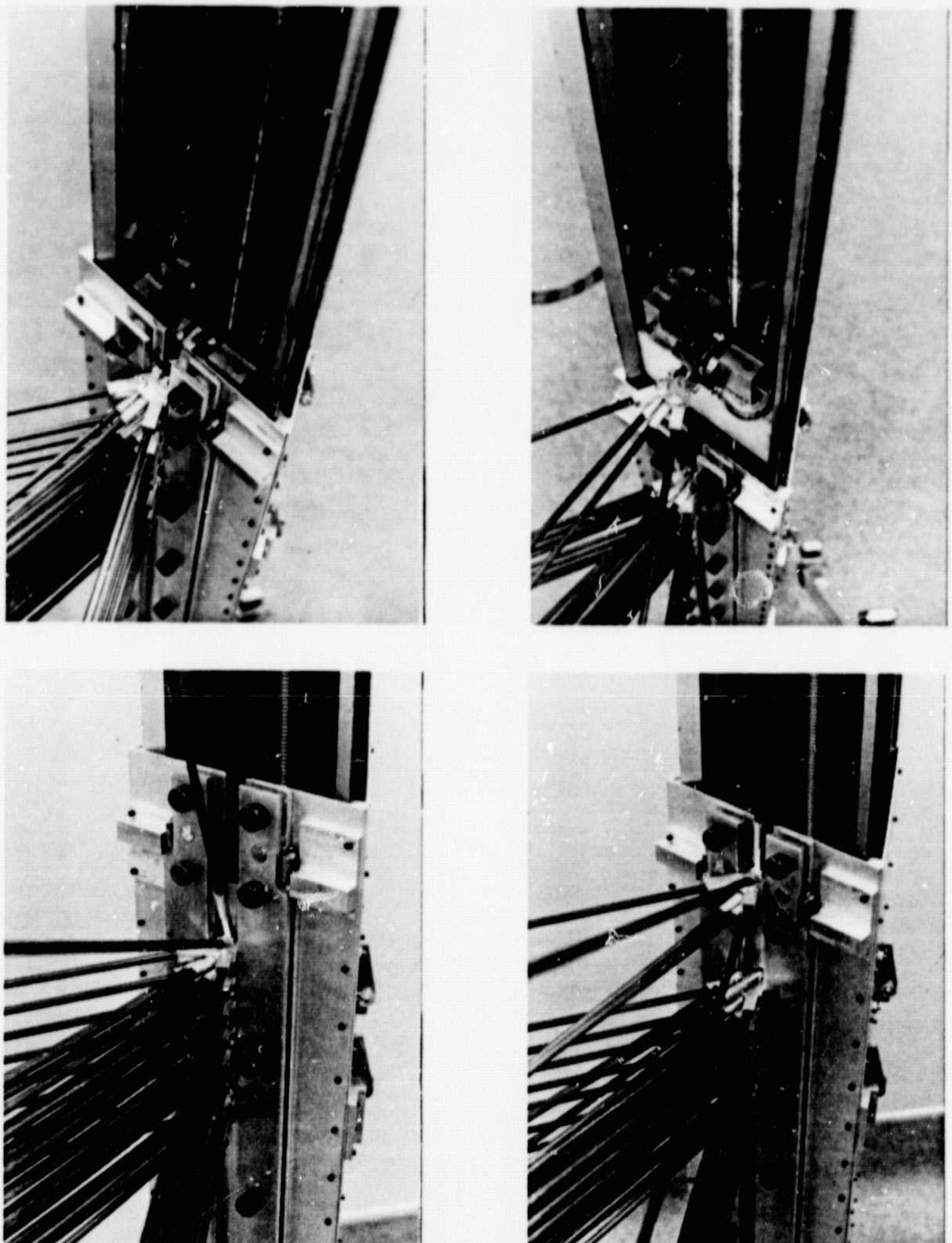

Figure 10. Detail of vertical deployment. *P030(a-d)*

in the starwheels (upper left photo). Next, a corner body is shown lifted out of the starwheels held by closed jaws (upper right photo). A nearly straight longeron indicates an almost fully deployed bay (lower left photo). The fourth picture then shows the corner body at the bottom of the newly extended longeron securely held in the starwheels.

Figure 11 shows a horizontal deployment. No problems were observed in terms of deployer operation; several successful horizontal bay deployments were achieved. Some flexing of the deployer itself was observed, as was an occasional buckling of a compressioned diagonal in the fully deployed region of the STACBEAM.

The mass of the engineering prototype deployer, unloaded, is 15.5 kg. This mass is 50 percent greater than the mass of the 74-bay STACBEAM which it deploys and is nearly 2.5 times the predicted flight deployer mass of 6.4 kg (see Ref. 1, p. 40). The greater mass of the prototype deployer is due to the use of aluminum and stainless steel in the columns, rather than graphite composite, in order to simplify fabrication.

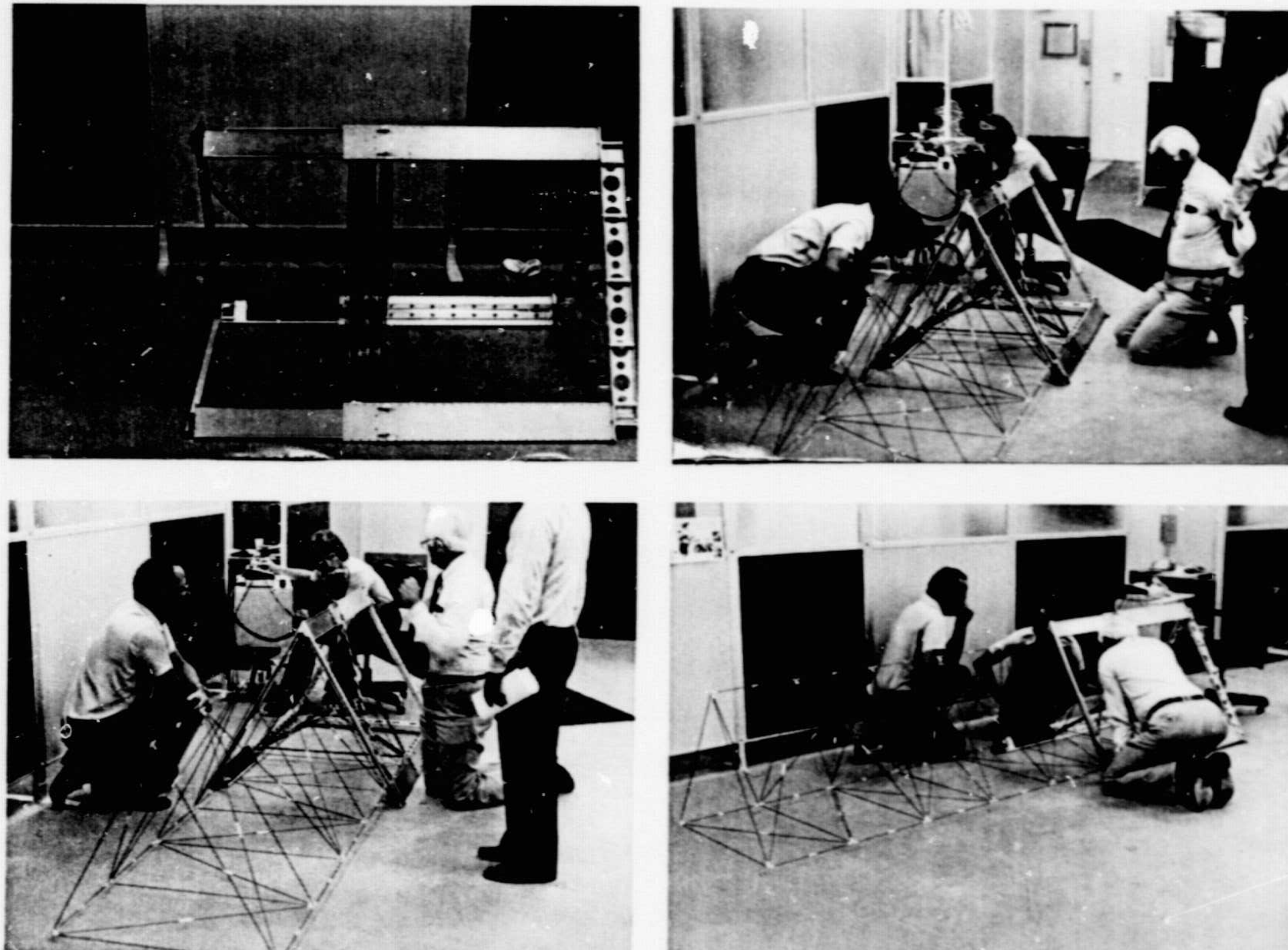

Figure 11. Horizontal deployment. P031(a-d)

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

As a result of this study, a motor-driven deployer has been developed for the STACBEAM. Successful deployments of the eight-bay model of the STACBEAM of Phase IV have been performed. Problems which were discussed in Section 4 remain to be addressed: 1) the whirl-induced vibration of lead screws; 2) the nondeployment of the operating section of the deployer; and 3) the limited sophistication of the electronic controller. Any further work on the controller would continue to be funded by Astro.

It is recommended that further tasks be performed in the areas of beam design modification, model construction, testing, and conceptual investigation.

A problem which exists in the STACBEAM of Phase IV is hinge pin retention; the pins are not held positively in place and, hence, randomly fall out. This problem was solved for a similar but larger-membered structure by using pins with a short threaded section which attaches securely to one of the hinged members, and an adaptation of this method is recommended here.

Modification of the joint designs for acceptance of tubular graphite/epoxy members would quadruple beam strength with no mass increase and would require only minor changes of the present design. In addition, the structural effects of the incorporation of standoffs should be investigated, including analytical determination of beam vibration frequency.

It is recommended that an eight-bay model be constructed using the above design modifications. This beam would attach to the STACBEAM Phase IV model.

A testing program which would determine the structural characteristics of individual members, the assembled models, and the deployer of Phase IV is recommended.

Finally, it is recommended that methods be proposed for retracting and continuously deploying the STACBEAM.

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