

ISS SGANT Group Level Offloading Test Mechanism

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Abstract

The International Space Station (ISS) Space-to-Ground Antenna (SGANT) is used for ISS communication with earth through the Tracking and Data Relay Satellite (TDRSS). Due to the different speeds of travel between earth, ISS and TDRSS, a steerable SGANT was required on the ISS.

The mechanical design of SGANT is an unbalanced mechanism with insufficient strength and driving torque to support and drive itself in a 1G environment. For ground testing, a specially designed offloading mechanism is required. Basically, the test mechanism must offload the SGANT in a two-axis operation, allowing the SGANT to move within a specific range, speed and acceleration; therefore the SGANT can move from elevation 0° to 90° and be tested at both the 0° and 90° positions. The load introduced by the test equipment should be less than 10.17N-m (7.5 ft-lbf). The on-ground group level tracking test is quite challenging due to the unbalanced antenna mechanical design and tough specification requirements.

This paper describes the detailed design, fabrication and calibration of the test mechanism, and how the above requirements are met. The overall antenna is simplified to a mass model in order to facilitate the offloading mechanism design and analysis. An actual SGANT mass dummy was made to calibrate the system. This paper brings together the theoretical analysis and the industrial experience that were relied upon to meet the above-mentioned requirements for the ground test. The lessons learned during the calibration phase are extremely important for future double or multiple offloading system designs. The ISS SGANT QM and FM units passed their ground test and the SGANT/Boom fit check successfully, and the Flight Model (FM) was delivered to SSPF in April 1998. It is now installed on ISS and functioning well, as shown in Figure 1.

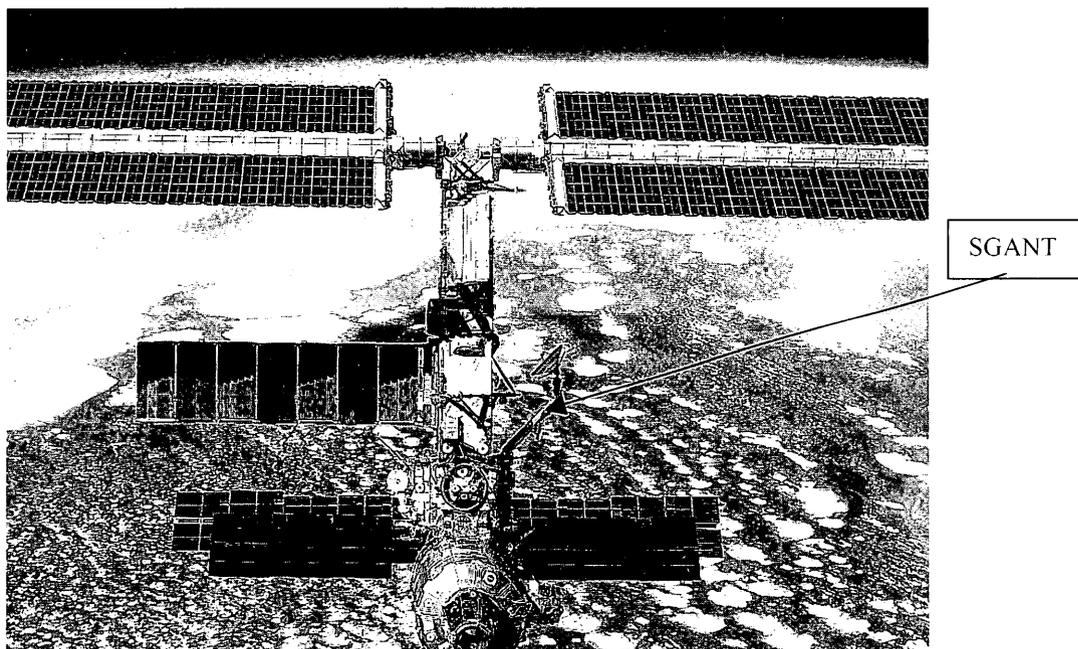


Figure 1. SGANT Antenna on ISS

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Introduction

In the space industry, it is common, during on-ground testing to provide a “zero G environment” for gravity-sensitive hardware. The SGANT is an orbit replaceable communication and tracking antenna. It provides the Ku-band signal transmitting and receiving capability between ISS and TDRSS. In orbit, it is mounted on a rigid mast on the space station with the Space-to-Ground Transmitter and Receiver-Controller (SGTRC) mounted close to the base of the mast. The SGANT is used for communication with the TDRSS satellites which are in geo-synchronous orbit. The space station on which the SGANT is mounted is in a 90-minute Low Earth Orbit and maintains a constant attitude with respect to the ground below. The space station therefore performs one complete rotation with respect to TDRSS about every 90 minutes. This rotation is imparted to the base of the SGANT which must therefore be steered to compensate. To simulate the steering operation and verify the auto tracking function of the antenna, an on-ground tracking test is definitely a must.

The on-ground group level tracking test is a challenge due to the unbalanced antenna mechanical design and tough specification requirement. The specification requirements are summarized below (Ref. 1).

1. Balance and/or offload the SGANT to allow two-axis operation in a 1G environment.
2. Let the SGANT move over a range of at least $\pm 5^\circ$ in each axis at any angular speed up to $3^\circ/\text{second}$, and at any angular acceleration up to $5^\circ/\text{second}^2$. The additional torque imposed not exceeding 10.17N-m (7.5 ft-lbf) and 27.12 N-m (20 ft-lbf) maximum, to either of the gimbal axes, respectively.
3. Limit the static torque on each gimbal axis to less than 10.17N-m (7.5 ft-lbf) when the SGANT is stationary at the center of this $\pm 5^\circ$ angular range in each axis, to prevent unwanted rotation when the SGANT is turned off.
4. Provide $\pm 5^\circ$ motion for two SGANT positions, namely $EL=0^\circ/XEL=0^\circ$, and $EL=90^\circ/XEL=0^\circ$.
5. Provide a facility by which the elevation axis of the SGANT can be rotated to its 90° position using its own power without imposing an additional torque requirement of more than 27.12 N-m (20 ft-lbf) to the elevation gimbal axis.
6. The fixture shall be sufficiently light and rigid for the first resonant frequency around either of the SGANT rotation axes to exceed 2.5 Hz.
7. Avoid applying loads to the SGANT during any phase of the ground test, which corresponds to factors of safety less than 100%.
8. Be dynamically simple.
9. Be attached to the SGANT at an existing attach point.
10. Define the exact angles involved for software limiting.

During the Preliminary Design Review, a counter balancing weight mechanism was proposed. However, once the detailed design and analysis started, problems were encountered. The balance weight mechanism creates a lot of unnecessary load and friction on the flight gimbals. Some of the load requirements are very difficult to meet. As a result, the balancing weight mechanism approach was finally abandoned. In its place, many alternative proposals were considered, the most successful one being the spring motor offloading test mechanism. To design the offloading mechanism, the following steps defined herein were taken. Ultimately, the project was successful.

Simplification of the Antenna Structure to a Mass Model

Simplifying the overall SGANT antenna structure to a mass model eliminated much unnecessary analysis work during the design phase. All SGANT antenna components were simplified to mass points and, using a weightless bar, all mass points were connected together to form the model. The process of simplifying the SGANT antenna

to a mass model is summarized in Figure 2. Information was based on the antenna mass report from the CAD design model.

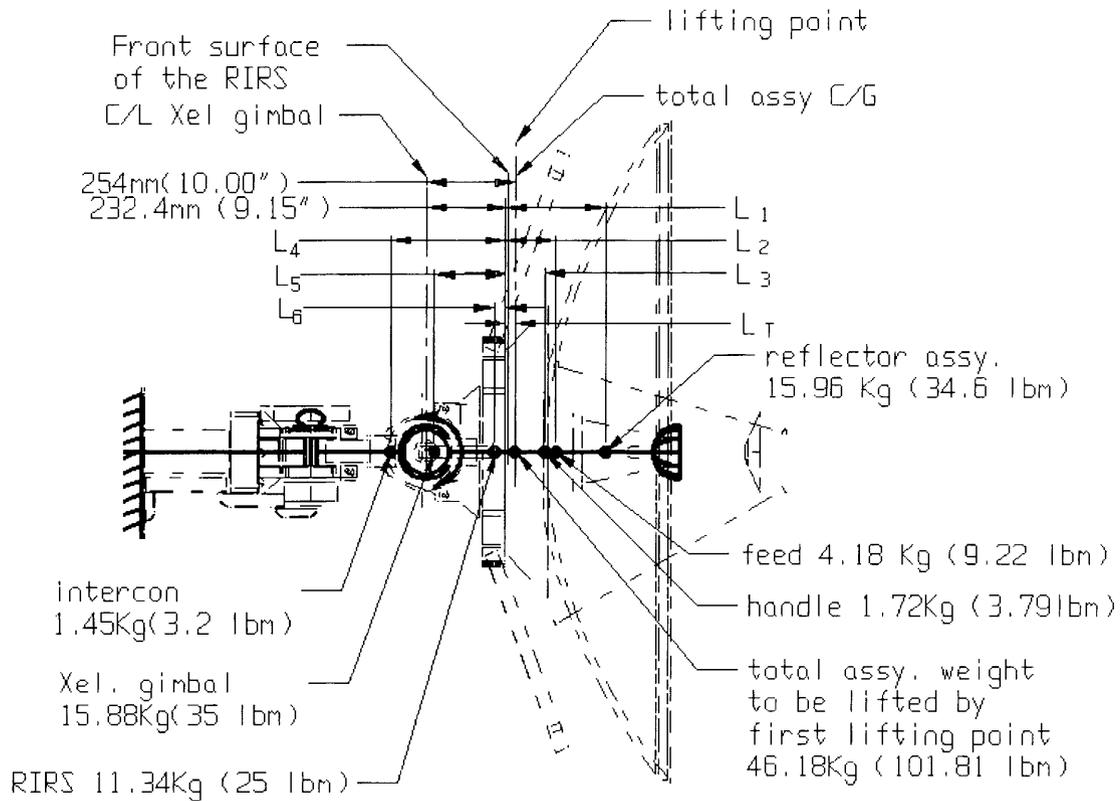


Figure 2. Simplification of the antenna system to a mass model

One can see that the model includes all the necessary mass and C/G location information related to further work. In the following sections, this model will be frequently used for the offloading system analysis and design.

Location of the best offloading points

A theoretical analysis of the simplified model helped find the balanced offloading point, which is a key for the overall offloading system design. Ideal offloading points are those that can balance the overall system in order to eliminate the torque introduced by the SGANT weight and the offloading system in both the EL (elevation) and XEL (Cross elevation) gimbals.

From detailed analysis and a series of offloading tests on a mass dummy (the mass dummy design is discussed later), it was found that for a two-axis gimbale system like the SGANT the best way to offload the overall system was to theoretically split the system in two, then use two offloading mechanism systems to take care of each portion at the subsystem balancing point. This approach can reduce the load on both gimbal axes. In practice, it was also realized that in the SGANT on-ground test configuration, the mass load on the EL gimbal will be carried by its bearings, and the margin of load capacity on these bearings is sufficient to carry that load. Therefore, the following calculations take into account the load introduced by the offloading mechanism only, and the mass load of the SGANT weight introduced into the EL gimbal driving mechanism train is neglected.

The system was split into front and rear systems, as shown in Figure 3. Since the rear system is relatively simple, a lifting test from mass dummy defined its offloading point. This point was selected to be at the existing Motor Drive Amplifier lifting interface. The final application shows that this point is very close to the rear system C/G. This is why, in both Figure 2 and Figure 3, the component mass and C/G of the SGANT rear system are not shown. Should the rear system be more complicated, the calculation could be done in the same way as that used to define the front system offloading point.

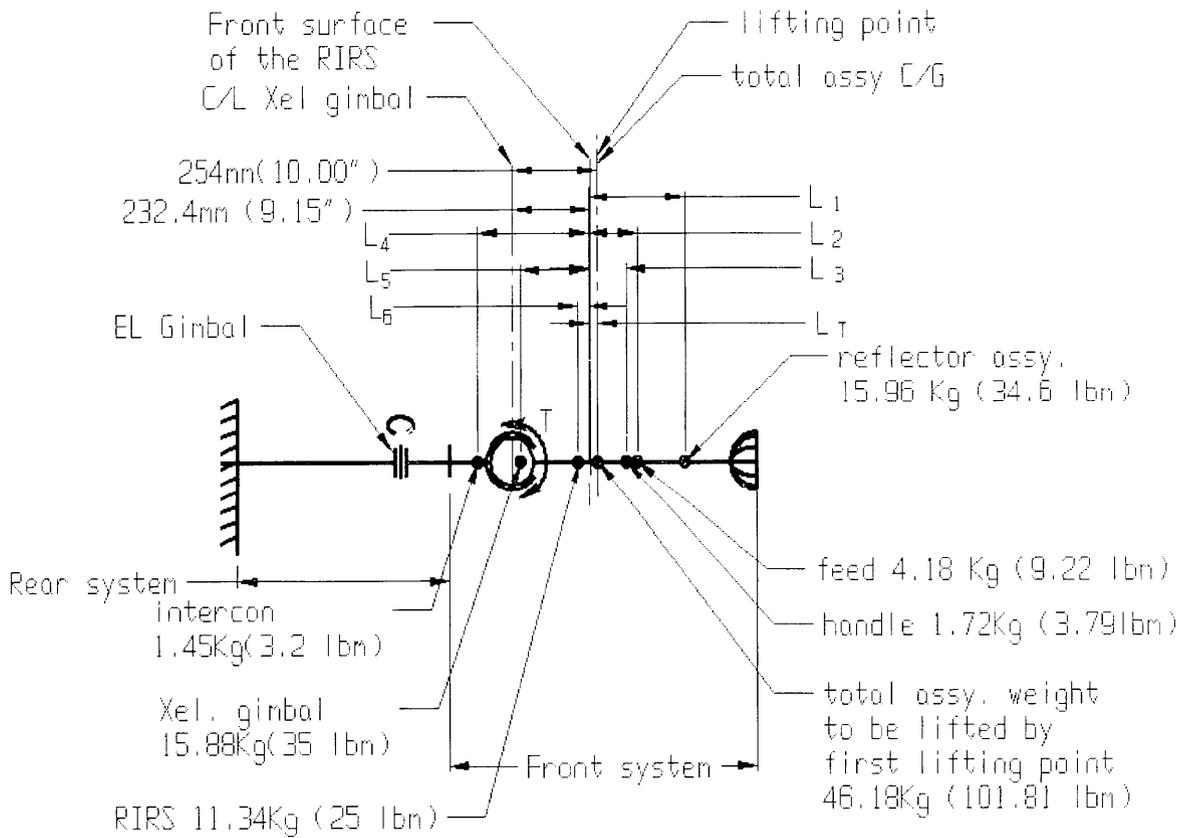


Figure 3 SGANT simplified mass model

Since the MGSE (Mechanical Ground Support Equipment) interface was supplied at the RIRS front surface (another existing lifting point in the SGANT), the front system lifting point was defined from the RIRS surface as follows (refer to Figure 3):

$$\begin{aligned}
 & \text{Since } \sum_1^n M = 0 \\
 & M = W * L \\
 & W_T * L_T - W_1 * L_1 - W_2 * L_2 - \dots - W_n * L_n = 0 \\
 & L_T = \frac{\sum_1^n M}{W_T}
 \end{aligned}$$

Where:

W_T – Total Mass of the Front Subsystem

L_T – Distance of the total mass C/G to RIRS front surface

W_n – Subassembly Mass

L_n – Distance of the Subassembly mass C/G to RIRS Front Surface

The calculation results on the front subsystem shows that the theoretically balanced lifting point should be 26 mm (1.03”) in front of the RIRS front surface.

Analysis of the load introduced into the gimbals by the offloading system

As per specification requirement No. 1, the load introduced by the offloading mechanism is calculated as follows. The internal friction of the spring motor offloader is omitted from the following calculation. The worst case to be considered is when both the EL and XEL gimbals are at the 5° position.

Torque load introduced into EL Gimbal

In this calculation, the side load contribution is the major concern due to the large distance between the loading point and the EL gimbal center. Refer to Figure 4.

$$T_{Le1} = F_{Le1} \bullet D$$

Where:

T_{Le1} – Maximum torque load on EL gimbal

$F_{Le1} = W_1 \bullet \tan \alpha$ – Side load from the offloading mechanism

D – Distance from the lifting point to EL gimbal center

$$\alpha = \tan^{-1} \left(D \bullet \frac{\tan b}{H} \right)$$

H – Offloading cable length

α – Worst case offloading cable angle

F – Load on offloading cable

After applying all the actual data into the above-mentioned formula, the maximum moment is 6.24 N-m (55.24 in-lbf), which is about 34% less than the target load limit. The fabrication and mass analysis report error is considered less than 10% based on EMS experience. The total margin left is about 24%, therefore, the offloading geometry arrangement is acceptable.

Load introduced into the XEL gimbal

Since the distance from the loading point to the XEL gimbal center is 330.2 mm (13”) less than for the EL gimbal, the side load is not a concern in the XEL case. Only the acceleration torque required from the XEL gimbal needs to be considered. Refer to Figure 5.

$$T_{LXel} = F_{LXel} \bullet R$$

Where :

T_{LXel} – acceleration driving torque required from the Xel gimbal

$$F_{LXel} = \frac{W_1}{g} \bullet a \text{ --- acceleration force required}$$

$a = \alpha \bullet R$

α – max. angular acceleration

R – lifting point rotation radius

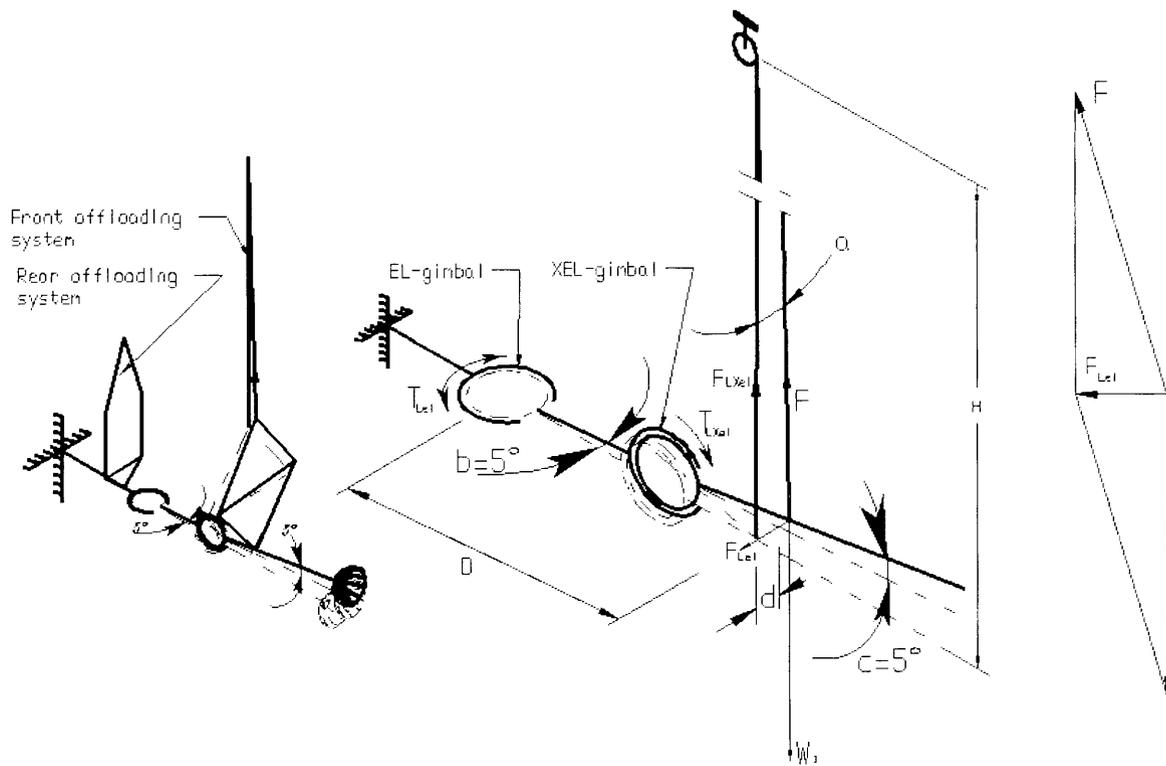


Figure 4. Load introduced into EL gimbal

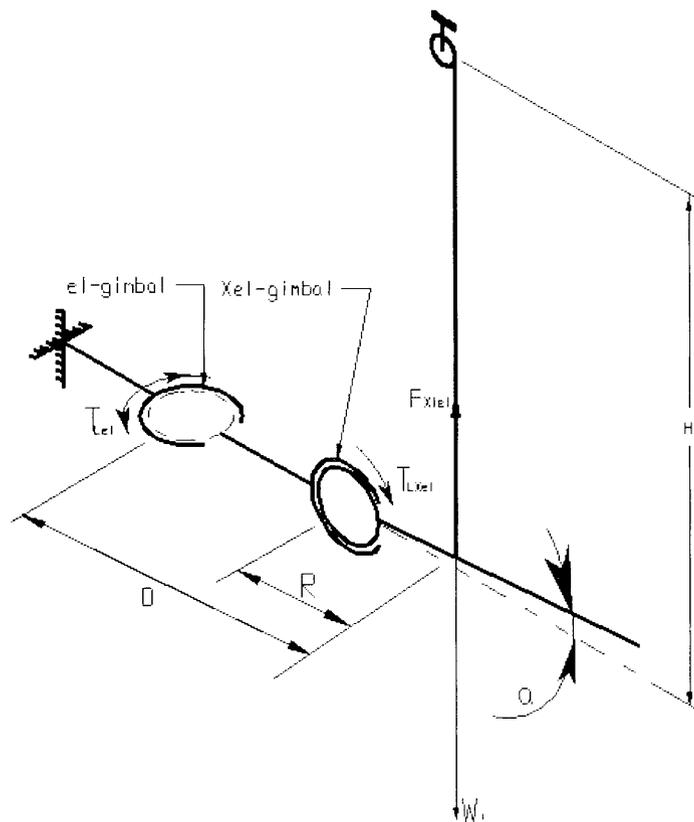


Figure 5. Load introduced into XEL gimbal

After applying all the actual data into the above equations, the maximum driving torque required is found to be only 2.41 lb-in, which is far from the target load limit, and again the geometric arrangement is acceptable.

Calculation of software limits

Software limits are the second layer of safety device, it is used to avoid extra load caused by over-travel of the gimbal. During the SGANT group level tracking test, if for any reason the gimbals should reach the software limit point, the power would turn off or the driving mechanism would be disabled to protect the SGANT.

In requirement 2, the target offloading mechanism design load is less than 10.17 N-m (7.5 ft-lbf), which should be the number used to determine the allowed gimbal over-travel angles. The calculation method is as follows:

Calculation of the EL gimbal software limits

With reference to Figure 4:

$$\beta_{\text{lim}} = \tan^{-1} d/D$$

where :

$$\beta_{\text{lim}} \text{ --- Software Stop angle}$$

$$d = H \cdot \tan \alpha$$

$$\alpha = \tan^{-1} F_{\text{lim}} / W_1$$

$$F_{\text{lim}} \text{ --- Maximum load (Introduction requirement 2)}$$

$$F_{\text{lim}} = T_{\text{lim}} / d$$

$$W_1 \text{ --- Subsystem weight}$$

Applying all the actual data to the formula, the calculated software limit is 7.525°. 7.5° is the limit selected.

Definition of the XEL gimbal software limits

This calculation is omitted because the torque load introduced by the offloading system in the XEL case is relatively small. The software limit was set at 7.5° to make it the same as the EL gimbal. It is clear that the gimbal will not encounter problems within that limit.

Mechanical design of the test system

After all of the above-mentioned offloading points were defined, the mechanical offloading system was designed as follows. It includes a main structure to support the system on the compact antenna range turntable, the constant force spring motor offloading system, the SGANT transfer and installation system, the hard mechanical stops and an electrical stop system. The offloading methods are the main topic covered in this paper.

During brainstorming sessions, many possible methods were listed for the offloading test. The cable pulley and weight system and the constant force spring motor offloading system received the highest tradeoff scores in all respects. Figures 6 and 7 show these two different offloaded test system designs.

The cable pulley and weight system was the first one designed into a CAD model, since it was less costly and easier to build. But moving the weight system required a lot of space and the detailed design work would have taken a lot more hours than the spring motor offloading system. Once the main structure and 90° turn system design was completed, the spring motor offloading system came to our attention and the design was quickly switched to Figure 7.

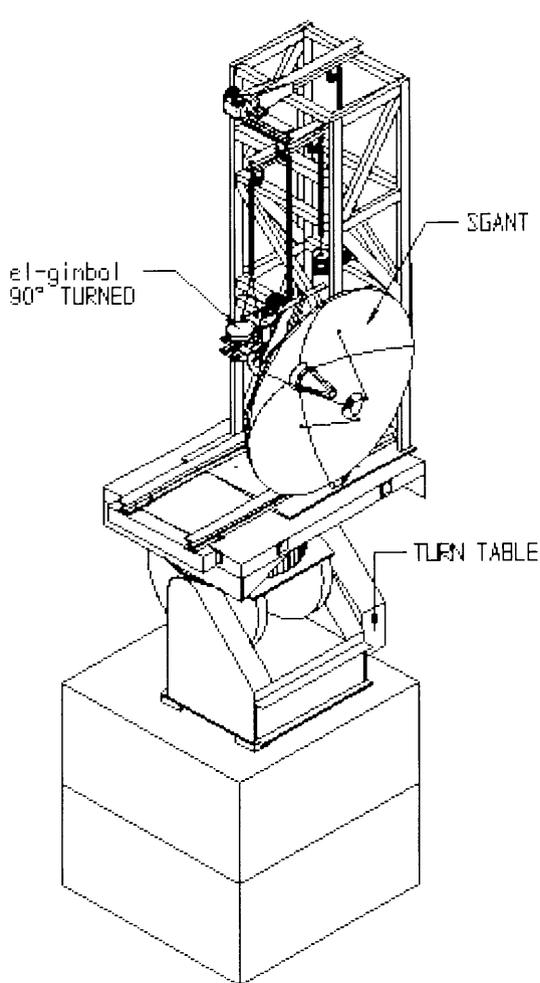


Figure 6. Cable pulley and weight offloading system

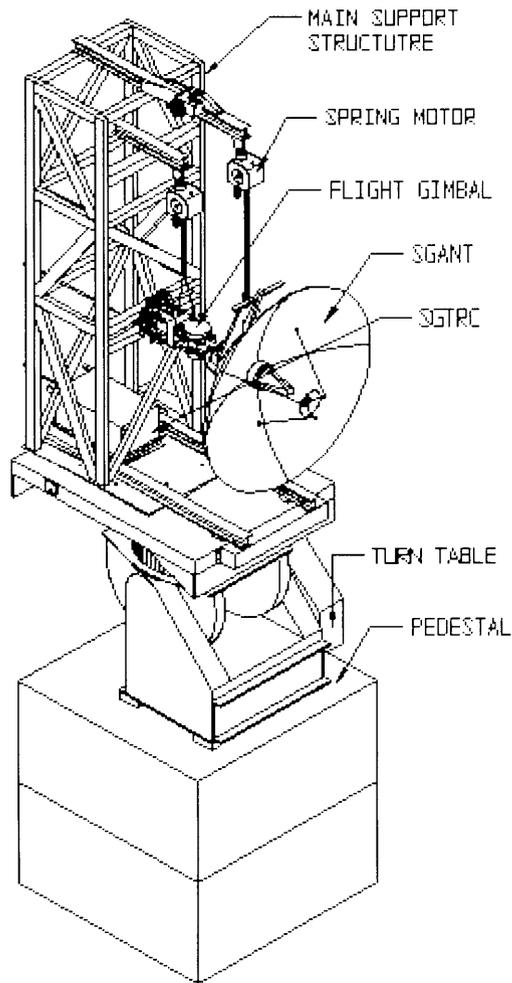


Figure 7. Spring motor offloading system

The main component of the spring motor offloading system is a constant-force spring motor. The design of a constant-force spring motor reflects the basic principles shown in Figure 8. Here, one can see that the so-called constant-force spring has minimum loading capacity variance when used between points A and B in the graph. Then a cable wound onto a tapered drum is used to compensate the loading capacity variance in order to achieve constant force output on the loading cable (Ref 2.).

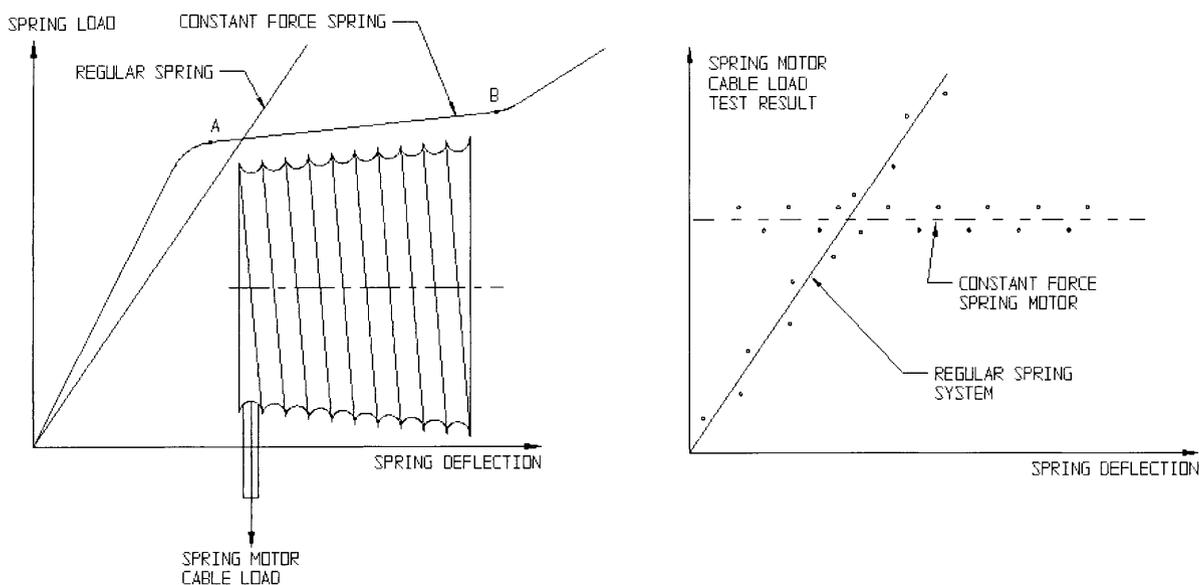


Figure 8. Constant-force spring motor

In addition to the offloading system, the overall mechanical design includes a main support structure on a Scientific Atlanta turntable, to support the overall system in the compact antenna range at EMS. The system includes an SGTRC support structure and wave-guides. The SGANT installation system includes a lifting setup and a transfer support structure and, of course, safety devices of various kinds.

Offloading system calibration and lessons learned

The calibration of the test system setup is shown in Figure 9.

Using a mass dummy to calibrate a complicated flight system test setup can protect the flight hardware; it allows the setup to be verified before the flight hardware is installed into it. The mass dummy must be representative of the mass of the flight system. In the case of the SGANT, at the time that the mass dummy was being designed, the SGANT CAD model design was unfinished and full information was not available. Therefore a mass C/G tuning system needed to be added to the system. A partial Design Verification Test Model (DVTM) gimbal was finally used to represent the gimbal movement and most importantly, torque sensors were installed into both the EL and XEL gimbal axes to measure the overall system load introduced into the flight SGANT by the offloading system (Figure 9).

Mass dummy design

The mass dummy design is shown in Figure 10. The C/G tuning weights need to be sufficient to compensate any design change and manufacturing error. So, the tuning masses have to be relatively large and have a large range of motion.

The purpose of the torque measurement assembly is to qualify and monitor the overall test process from beginning to end. The design is shown in Figure 10, in which torque sensors are installed on the DVTM gimbal. One side is installed on the moving portion of the gimbal and the other is mounted on the stationary side. A Micro B reading instrument is connected to the sensor. At a stress-free condition, the instrument reading should be set to zero.

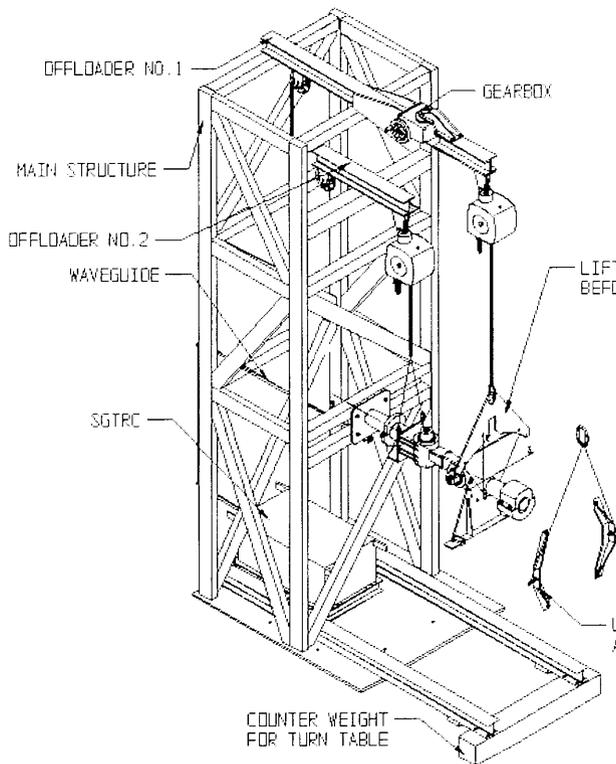


Figure 9. Calibration setup

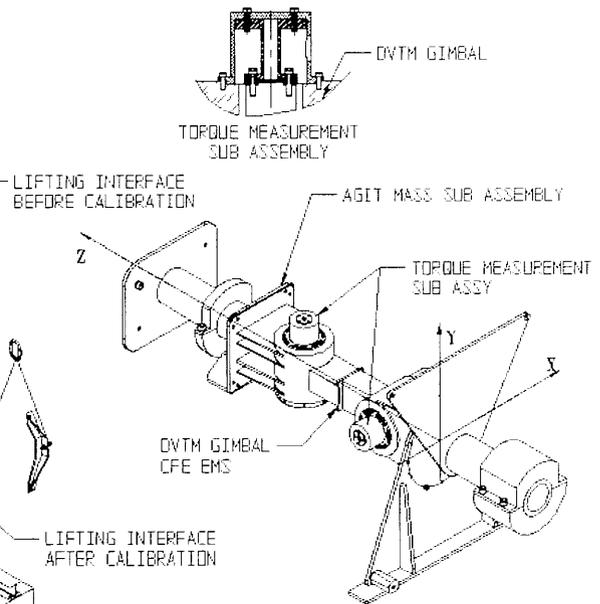


Figure 10. Mass dummy design

SGAG Test Fixture Calibration Report

1. The table below lists the maximum torque load on the DVTM gimbal during horizontal lifting operation:

	Max. load allowance	Max. load recorded*
XEL Gimbal	27.11 N-m (240 lbf-in)	-2.711 N-m (-24 lbf-in)
EL Gimbal	27.11 N-m (240 lbf-in)	1.8 N-m (16 lbf-in)

2. Maximum torque load on the DVTM gimbals during transfer between the horizontal lifting configuration and rest on the temporary support structure:

	Max. load allowance	Max. load recorded*
XEL Gimbal	27.11 N-m (240 lbf-in)	1.8 N-m (16 lbf-in)
EL Gimbal	27.11 N-m (240 lbf-in)	30.05 N-m (266 lbf-in)**

3. Maximum torque load on the DVTM gimbal when the dummy mass is installed on the SGAG test fixture (when EL Gimbal is at the 0° test configuration):

	Max. load allowance	Max. load recorded*
XEL Gimbal	27.11 N-m (240 lbf-in)	8.7 N-m (77 lbf-in)
EL Gimbal	27.11 N-m (240 lbf-in)	10.06 N-m (89 lbf-in)

4. Maximum torque required to drive the gimbal within $\pm 5^\circ$ when the EL gimbal is at the 0° test configuration:

	Max. load allowance	Max. load recorded*
XEL Gimbal	27.11 N-m (240 lbf-in)	9.38 N-m (83 lbf-in)
EL Gimbal	27.11 N-m (240 lbf-in)	7.63 N-m (67.5 lbf-in)

5. Maximum torque load on the DVTM gimbal when transferring the dummy mass from the 0° to the 90° configuration:

	Max. load allowance	Max. load recorded*
XEL Gimbal	27.11 N-m (240 lbf-in)	0.8 N-m (7 lbf-in)
EL Gimbal	27.11 N-m (240 lbf-in)	0.34 N-m (3 lbf-in)

6. Maximum torque required to drive the gimbal within $\pm 5^\circ$ when the EL gimbal is at the 90° test configuration:

	Max. load allowance	Max. load recorded*
XEL Gimbal	27.11 N-m (240 lbf-in)	9.38 N-m (83 lbf-in)
EL Gimbal	27.11 N-m (240 lbf-in)	7.64 N-m (67.5 lbf-in)

* Maximum loads determined by dummy load measurement.

** Locking pin engaged, load acceptable.

Based on the calibration report, one can observe that during the hoist and transfer operation, a large unexpected torque load was introduced into the flight gimbals, which is over the maximum load limit. It was considered a potentially fatal load to the flight gimbals. These operations were repeated several times to find out the reason. The operator was instructed to reduce the hoist speed to the minimum. However the recorded loads were unpredictable, between 22.5 N-m (200 in-lb) and 56.5 N-m (500 in-lb). Finally, two gimbal lock pins 9.53-mm diameter (3/8" dia.) were installed into the flight gimbals, especially for the hoist and transfer operation. Without the calibration exercise the flight gimbals could have been destroyed during the test.

Lessons Learned

For a multiple gimbal mechanism, the gimbals must be locked for transfer and hoist lifting operations.

Define the loading point

Since the front of the RIRS (a part of the SGANT) provides some MGSE holes for a tooling interface, and the calculation showed that they are very close to the ideal offloading point, it was decided to directly hook up from the MGSE holes with a bracket, a solution that was in the original design. It is illustrated in the calibration setup in Figure 9.

The first calibration showed that driving about only 2 degrees off from the starting point, a potentially fatal load was introduced into the XEL gimbal. A quick analysis on the mass model is shown in Figure 11, where one can see that force F2 increases rapidly when the XEL gimbal starts to move.

After modification, the lifting point was moved to the position shown in Figure 11. The mechanism used to move the lifting point is shown in Figure 9. The load introduced into the XEL gimbal is now extremely small, within its 5 degrees driving range, and is barely detectable.

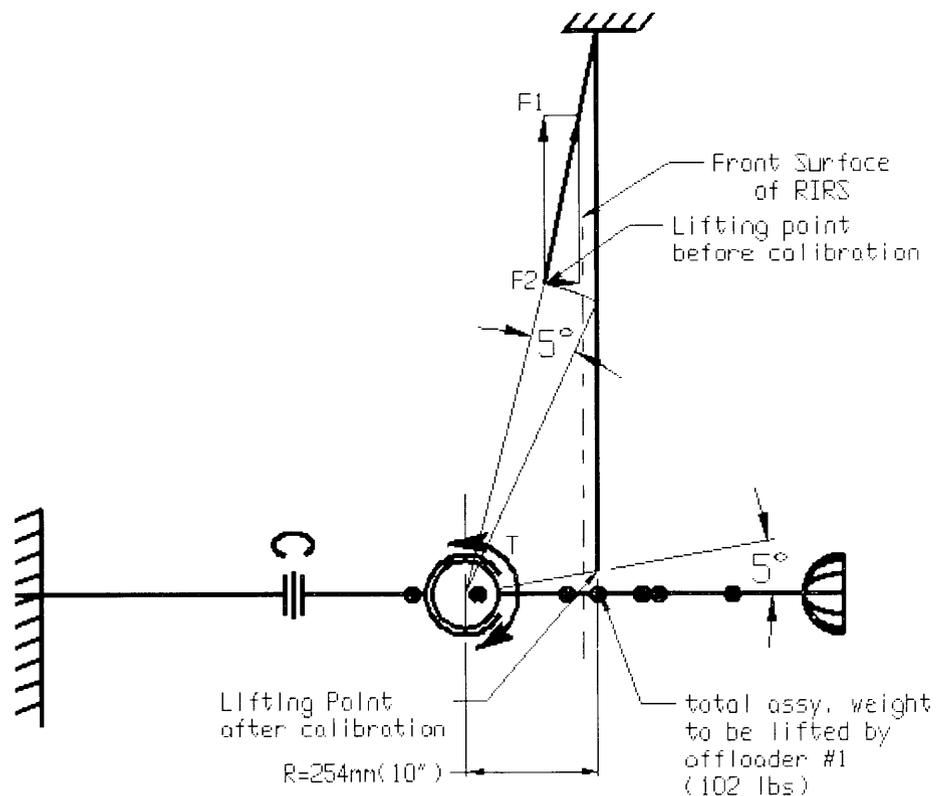


Figure 11. Lifting point selection mistake

Lesson learned:

To define the offloading point, simply lining up the offloading point to the C/G is not enough. The selection should be based on the analysis on all 3 dimensional locations to get the best offloading results.

Moving the SGANT between $EL=^\circ/XEL=0^\circ$, and $EL=90^\circ/XEL=0^\circ$

In requirement 4 it is stated that the test system must provide a $\pm 5^\circ$ motion for two SGANT positions, namely $EL=^\circ/XEL=0^\circ$, and $EL=90^\circ/XEL=0^\circ$. Refer to Figure 6 and Figure 7.

To turn the antenna system on the test setup from the 0° to the 90° testing position, logically the telemetry from the gimbals driving system should be used. Using this telemetry to synchronize the offloading system drive in order for the gimbal and the offloader to move from one position to another. To do so, a servo system is required. However, for the SGANT the servo system was eliminated as a cost-saving measure. It was decided to use an operator to crank the gearbox and synchronize the drive manually. Let us see the results.

The problem started in the calibration phase. The synchronized drive of the overall system was almost impossible to control manually. Two technicians had to be trained for a week on the mass dummy to perform the transfer drive. In addition, a five degrees warning limit switch had to be added to the system. During the transfer, whenever the flight gimbal and the offloader had an angular difference of 5 degrees or more, the alarm switch went on and the operator had to adjust the offloader position. In the meantime, the power went off, and the system had to be restarted. It became the most time-consuming operation of the SGANT group level test phase. The total cost in hours was much more than a servo driving system. Since the operator had to climb up to the top of the main structure about 15 meters high, safety also became an issue.

Lesson learned:

Synchronizing the drive of two mechanical systems manually is a very difficult task. Depending on the accuracy required a servomechanism should be used to automate the task and obtain a proper result. Figure 12 shows the system after final calibration and modification.

Conclusion

The method finally used to offload the SGANT two-axis gimbale system with two synchronized offloading systems has been proven to be correct. The torque load introduced into the system is kept well below acceptable limits. The methods used in this case can be developed and used to design other multi-gimbal system offloading mechanisms. Calibrating the system using a mass dummy to represent the flight hardware and installing the necessary instruments to measure torque loading is an efficient method to help prevent the possibility of damage to flight hardware.

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References

1. Arbery, Graham, SGS Control system ground test requirements specification. p12, 1995, EMS Technologies
2. Caravaggio, Levino, Large item offloading, 31 March 1992 Spar Aerospace Ltd.
3. Zhang, Xilin, ISSA MGSE user's manual 1998 14 April. EMS Technologies.

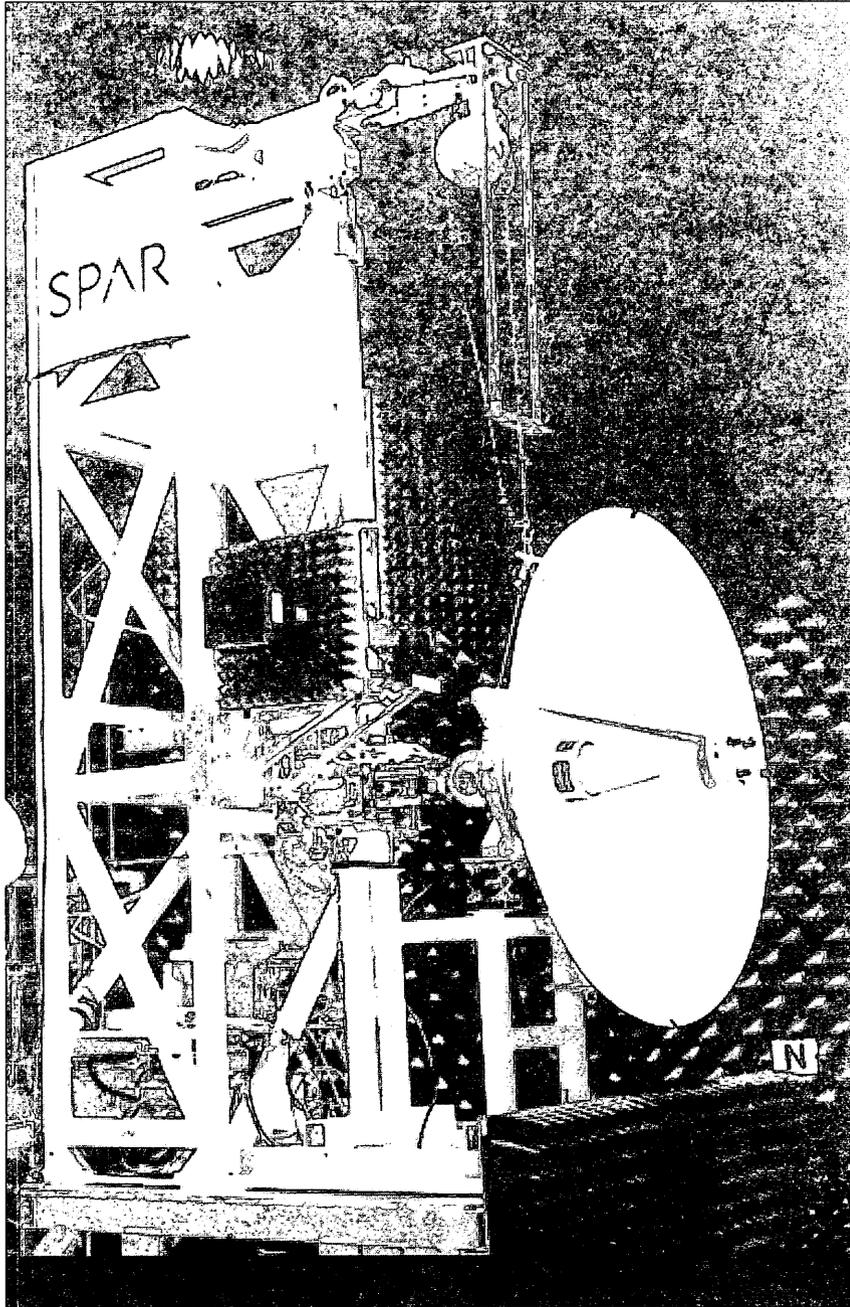


Figure 12. SGANT Group level test set up