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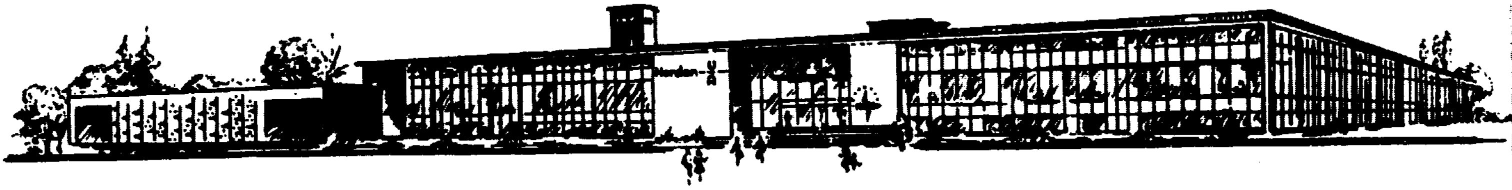

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FINAL REPORT FOR LASER SPACE RENDEZVOUS & DOCKING SYSTEM TRADE-OFF STUDY

Report For The Period
27 May 1975 Through 21 December 1975

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SUMMARY

The scope of this contract has been to continue the "CO_2 Laser Radar for Rendezvous and Docking Trade-Off Study," and to specifically address two areas in greater detail. These are: a) the use, design, and fabrication feasibility of scanning the laser beam by swiveling the outside mirror with a ball joint swivel system, and b) the applicability of graphite reinforced epoxy material for the construction of reflective optics.

This report is divided into two sections. The first section reports on the applicability of graphite reinforced epoxy composite materials. In this section, the results of the study indicate that, although it is feasible to utilize graphite-epoxy for many of the structural members and optical surfaces, the actual cost will be more than that of many other suitable materials. This stems from the fact that the graphite-epoxy fabrication will require a significant amount of special tooling, and this tooling will be amortized over a small number of actual sensors. In addition, the weight advantage of graphite-epoxy over beryllium, which is an established technology, is minimal.

The second section explores the use of the ball joint swivel system. This section concludes that, although the ball joint system is inherently less accurate than the mirror scanner, it is accurate enough to perform the scanning function. Further, a suitable ball joint is currently available and in production for an unrelated military program. It is possible that the use of this ball joint will result in a simpler and more cost effective scanning mechanism.

1. EPOXY GRAPHITE COMPOSITION MATERIAL TECHNOLOGY

Material Characteristics

The primary material requirements for our applications are dimensional stability and high strength to weight ratio.

The epoxy graphite composite materials were investigated and two reports of experimental studies were obtained. The studies were performed in the 1972 - 1974 time periods.(1)(2)

Graphite epoxy is a very promising material because of its high strength to weight ratio as well as the possibility of obtaining a near zero coefficient of thermal expansion. These properties exist longitudinally in the direction of the graphite fibers. Across the fibers the material strength and its expansion coefficient are basically that of the epoxy resin.

The raw material generally comes in the form of a tape consisting of a group of fibers in a tacky uncured resin matrix. In fabricating a graphite epoxy part, the tape is placed into a mold with the thickness built up in many plies or layers. The orientation of the individual tape layers is arranged to provide the desired directional properties.

If, for example, a zero expansion coefficient in all directions in a plane is desired, this can be implemented by orienting three consecutive layers, each 60° displaced from the other. The cross section would be built up in layers to the desired thickness and could have substantially uniform mechanical properties. Because the fibers have to be divided so that they are oriented in 3 directions, the tensile strength and the modulus of elasticity is divided by (very nearly) three as compared to its properties in a uniaxial (anisotropic) configuration. The characteristics of uniaxial and isotropic graphite-epoxy composite as well as of several other materials of interest, are tabulated in Table 1.

The use of graphite epoxy composites as a material for building the telescope optical elements and other parts of the optical train of the Space Tug Rendezvous Sensor has to be considered from the standpoint of its competitiveness with Beryllium. The construction of 10.6 micron reflective optics using Beryllium is currently an established technology.

Since there is a substantial amount of engineering and preparatory expense in designing the molds and the fiber lay-up in fabricating graphite-epoxy composites, the material would

TABLE 1 - CHARACTERISTICS OF SEVERAL STRUCTURAL MATERIALS

Item No.	Material	Youngs Modulus PSIx10^{6}	Ultimate Tensile Strength PSIx10^{3}	Thermal Coefficient Expansion IN/IN/°Fx10^{-6}	Density LB/IN^{3}	Thermal Conductivity BTU/FT-HR/°F
1	Gr-Ep Uniaxial	42.5	79.8	-.60	.063	.78, 5.8
2	Gr-Ep Isotropic	14.98	28.1	+0.05	.063	.78, 5.0
3	ULE	9.8	7.0	.033	.0795	.757
4	Fused Quartz	10.6	UNKNOWN	.272	.0796	.796
5	Beryllium	52.5	44.0	6.4	.066	87.0

apparently be cost effective as compared to beryllium only if a number of units were to be produced in order to amortize these engineering and tooling expenses.

A beryllium structure or optical element expands and contracts with temperature. beryllium metal has an anisotropic crystal structure. In the last few years, however, the techniques of fabricating the material to have nearly isotropic properties have been developed. The finished structures are stable. The high heat conductivity of beryllium minimizes warpage during temperature changes by minimizing the temperature differential throughout the material. This high heat conductivity is an important and unique characteristic of beryllium.

Beryllium has proved to be suitable both for optical surfaces as well as for the related structures, and the effects of temperature changes are minimized when the entire structure is constructed of beryllium.

OPTICAL SURFACE APPLICATIONS

Graphite epoxy composites have been used experimentally as both optical surfaces and as backing material for optical surfaces, i.e., polished quartz disks, and/or surfaces of ultra low expansion (ULE) Titanium Silicate Glass. This effort is described in reference 1.

The graphite epoxy composites have generally proved to be unsuitable because of dimensional instabilities in the material.

One of the major problems relating to structural stability seems to be the moisture content of the graphite epoxy composite. The resin is hygroscopic and tends to reach some equilibrium point between the relative humidity in the air and its own moisture content. Experiments to measure outgassing in a vacuum indicated that the gas was mostly water vapor. Tests indicated that the moisture content did alter the optical characteristics of the test piece approximately in proportion to the change in moisture content.

The tests being referenced were made with four inch square pieces anl with graphite epoxy backed quartz disks 6 inchest in diameter. These dimensions are slightly larger than the 7.62 cm diameter and 9x13 cm primary and pointing mirrors which will be required for the Space Tug ladar.

Variations in the moisture content of the material cause dimensional changes which are in the 100 micro inch range. These structures are therefore inadequate for optical surfaces at 10 microns (400 microinches) wavelength.

In our application, the material would most simply be fabricated in an atmosphere containing humidity, and would be used in a vacuum. If, furing fabrication and storage before launch, the material can be protected from humidity, then the subsequent drying and outgassing effects in space would be minimal. Logistically, it would be very difficult and expensive to construct and test a system in a special environment prior to launch.

It has been reported to us, verbally, that a metal coating process is currently used with graphite epoxy composites. This is supposed to hermetically seal the material so the moisture content does not change. The process is considered to be proprietaryand no details seem to be available. Results are lacking, and the process seems to be in the initial stages of development.

The test of graphite epoxy backed quartz disks did show that dimensional stability improved with the thickness of the quartz. The quartz sections were 0.005" and 0.035" thick, respectively. The 0.005" section was unsatisfactory and almost impossible to fabricate, and the 0.035" specimens were marginal event at 10.6 microns. (The tests were done with visible light.)

At the present time, graphite epoxy glass systems use (it is reported) 0.062" thick ULE glass as a facing which is apparently satisfactory for visible wavelength applications, and obviously for 10.6 micron applications also. It was noted that an "egg crate" structure behind the mirror gave superior surface stability than a solid graphite epoxy laminate backing.

It is significant to note the graphite epoxy composite material, as fabricated, is as yet imperfect. The development reports cite numerous defects, i.e., voids and microscopic cracks in the molded test pieces. This might be reasonably expected since the graphite fibers, which give the material its dimensionally stable properties, would exert stresses and strains on the surrounding epoxy resin which tries to expand and/or contract with temperature, state of cure, etc. The difference between the graphite fibers and the resin causes stresses within the composite material.

The measured changes in deflection were on the order of $10\text{x}10^{-6}$ to $20\text{x}10^{-6}$ inches per inch of length. The total distortion of the mirror surface varies approximately as the square of the linear dimension since the entire surface becomes curved. This degree of instability is too much for a 3 inch mirror to be used at 10.6 μ.

Structural Applications

The application of the graphite epoxy composites as a structural material is, of course, much less critical than its application as an optical surface. The most difficult structural tolerance problem in the Space Tug Rendezvous Sensor relates to the alignment of the wavefronts of the local oscillator and the received signal. A misalignment of one wavelength across the detector aperture will reduce sensitivity by 3 dB. This is an angle of

$$\theta = \frac{\lambda}{d} = \frac{10.6\text{x}10^{-6}}{.7\text{x}10^{-3}} = 15.1 \text{ milliradians} = .87^\circ$$

Simple graphite epoxy test structures, over a period of years, have shown alignment stabilities of .8 minutes or .2 milliradians,[1,2] nearly one hundred times better than the rendezvous sensor requirement. Because the optical train of the Rendezvous Sensor is complex, the net effect of 4 or 5 individually misaligned elements can be several times that of a single misaligned element, however, a total misalignment error of one-tenth wavelength is almost negligible in effect. Errors in structural alignment can also increase the field of view to be searched, and could result in steering errors. It is probably possible to build a self-check feature into the Rendezvous Sensor to zero reference the angle pointing system. This would calibrate out any slow changes in alignment caused by dimensional instability of a graphite epoxy composite structural material. The graphite epoxy material appears to be adequately stable for the maintenance of structural alignment.

Many of the stresses in the Space Rendezvous Sensor structure are inertial in nature, i.e., they are induced by the accelerations which the Space Tug will undergo during launch and orbit placement. On the ground, the corresponding stress will be due to gravity. In addition to the stresses induced by gravity, or by vehicle acceleration, there are stresses induced by mechanical motion of the scanning mirror, or other moving parts. The scanning mirror motion is, by far, the largest component and will put a repeated cyclical stress on the Rendezvous Sensor structure.

Because of pointing accuracy requirements, the portion of the telescope structure that supports the pointing mirror gimbals needs the most in the way of dimensional rigidity and stability.

The high ratio of strength to weight of the graphite epoxy composites are very advantageous since the stresses are minimized. The composite material is essentially fully elastic up to the point of rupture, i.e., any yield under stress goes to zero when the stress is removed.

The telescope structure is stressed during large mirror motion reversal, but not during the portion of the scan when the Rendezvous Sensor is actively transmitting and receiving signals. This is because there is no acceleration of the pointing mirror during that time.

As a result, the deflection of the optical structure of the Rendezvous Sensor should be zero. In addition to the inertial forces derived from the large mirror, the high speed scanning mirror will generate an 8 kHz vibration on the structure. This should be well above the natural vibration resonances of the telscope, and should have negligible effect.

The graphite epoxy material, being very elastic, may tend to ring on the structure and may have resonances at the frequency of the large mirror which is about 8 Hz. These stresses and structural deflections have to be damped out or suppressed.

Conclusions

The main impetus behind consideration of graphite reinforced epoxy materials is the potential for either weight or cost savings over the use of more conventional materials. It can be noted from Table 1, that the composite material is only slightly lighter than the beryllium, which has been the preferred material for 10.6 micron space optical applications.

The supporting structure is the largest weight component of the Rendezvous Sensor optical train. The present status of graphite epoxy technology permits us to use it for the structure although, at this date, its use would be a high risk item as compared to Beryllium.

It is quite likely that structural members would be anisotropic and the design of the overall structure to exploit the qualities and limitations of graphite epoxy composites would be substantially different from that using Beryllium.

Up to now telescope components for optical systems appear to be limited to mirror backings and to cylindrical tubes.

At the present time, there is no doubt that the Rendezvous Sensor structure and optical surfaces could be fabricated from an epoxy graphite composite. This would necessarily involve the fabrication of molds, and several steps of related tooling. Since only a limited number of Rendezvous Sensors will ever be constructed, it is questionable whether the small weight advantage will make this cost and effort worthwhile.

2. BALL JOINT SCANNING

As a part of this effort, the laser scanning requirements were re-examined, and the feasibility of using a ball joint swivel system as a means of scanning the CO_2 laser beam was considered. In addition, the availability of a suitable ball joint, which could perform the mirror scanning function, was investigated and the impact performance, cost. and relative accuracy compared with the baseline system design as described in the final report issued under Contract NAS8-30738.

System Parameters

For the configured Space Rendezvous sensor, the overall field of view is 30° by 30°, defined by gimbal limits. The field of view to be searched has been determined by the anticipated accuracy of the space vehicle navigational parameters, and is a 5° by 5° solid angle. The assumed instantaneous field of view (i.e., resolution element) is a cone, one-sixth milliradian acorss, or about 0.01°.

The beam scanning system is required to search the 5° by 5° solid angle, where the target is known to be, in 10 seconds or less. It must also be optically efficient, use a minimum of drive power, and be lightweight and reliable.

The Rendezvous and Docking sensor uses a very efficient passively Q-switched pulsed CO_2 laser transmitter to search a solid angle, with one pulse transmitted in each resolution element.

If the a priori detection probability is uniform, it is optimum to perform a uniform search pattern. When an optical sensor is used, and diffraction limited performance is desired, it is difficult to obtain a wide acceptance angle in the optical transmitting and receiving path.

To search the field of view, it is necessary that the beam be directed sequentially at each of the elemental areas, each element being covered by the spot size of the beam. The elemental areas may overlap and two or more pulses may cover each area for greater probability of target detection and/or lower false alarm rate.

Design Considerations

In the following analysis, for simplicity, one pulse per unit elemental area in the field of view is assumed for the search mode. This does not imply any loss of generality and is consistent with the Rendezvous Sensor baseline design.

The field of view can be most simply covered by scanning systematically in a linear raster, as shown in Figure 1. In this scan path, each elemental area is covered once and the time efficiency is defined by:

$$\text{Eff} = \frac{t_s}{t_s + t_r}$$

where: t_s = time per scan line

t_r = turn around time

The beam can be deflected by a single mirror in a two-axis gimbal. In this, the energy required to drive the scan is a function of the velocity of the scan and time to reverse the scan at the end of each line. The efficiency increases as t_r/t_s is decreased. For the case of a linear raster, the energy required to reverse the scan using electric motors varies as $(t_r)^{-2}$ (with scan velocity constant) consisting of I^2R losses in the drive motors as they go through zero velocity during direction reversal, or as the square of the (angular) scan velocity (if t_r is constant).

These relationships derive from the need to oppose the momentum of a moving mirror at the end of a scan line by a reversing input to the drive motors, as well as to accelerate the mirror in the opposite direction for the next scan line. Electric motors are particularly inefficient during reversal. About 90% of the electric power supplied to the motor is consumed in I^2R losses. In the projected design of the space tug rendezvous sensor, this conventional approach results in drive power exceeding the ratings of reasonably sized drive motors, in both electric power and maximum torque.

Reducing the scan velocity reduces the reversal time for the same expenditure of the motor drive power; however, if the maximum time for scanning the entire field of view is limited, the minimum scan velocity is thereby defined.

An alternate possibility is a resonant sinusoidal mirror drive. It requires a minimum of mechanical drive power, however, the peak scan velocity is $\pi/2$ times the average. This requires, in turn, $\pi/2$ the number of search pulses, increasing the transmitter power requirement by 57%. Since the transmitter power is typically much higher than the servo power used for pointing, a small loss in transmitter efficiency is much more costly in terms of overall power drain than an increase in mechanical drive power. A linear scan with a rapid turnaround at the end of each scan line is most efficient from the viewpoint of a minimum number of scan pulses, and for a minimum scan time.

Wide angle scanning can be most readily implemented by a two-axis gimballed plane mirror in front of the primary mirror (or objective lens) of the optical system. This method of scanning avoids off-axis aberrations since the telescope optics are always used on-axis. The large plane mirror, however, is relatively large and speed limited.

Narrow angle scanning can be implemented by small movable mirrors behind the telescope. For a field of view of 2°, close to diffraction limited optics can readily be achieved. The scanning mirrors are quite small, but must be moved over a much larger scan angle (by the telescopic magnification factor). The scan mirror is, however, reduced in size by the telescope magnification factor, and can be scanned quite rapidly. It is this technique, which is currently proposed in the baseline scanner that has been described in the final report issued under Contract NAS 8-30738.

Use of a Ball Joint Swivel System

It is possible to implement a ladar design using a ball joint swivel system to control an outside steering mirror. In its most elementary mechanization, the large pointing mirror is driven by the ball joint swivel system.

If a ball joint support is to be utilized for scanning the front mirror, the telescope design will have to be modified accordingly. The baseline rendezvous sensor optical configuration uses a classical Gregorian telescope design with holes in the pointing and secondary mirrors of the optical train. This design was selected because it has a field of view sufficient to permit the resonant mirror scanner to be used. For a scanning system which uses an outside mirror to deflect the beam, the field of view requirements are relaxed and, simultaneously, it is no longer convenient to permit a hole in the outside mirror. A Cassegrain telescope has been selected to satisfy these modified requirements. This will entail some modification of the original form factor. A block diagram of a possible realization of a Cassegrain telescope is shown in Figure 2.

Many elements of the optical train, such as the range angle compensating mirror and the Brewster angle beamsplitter, are unaffected. The primary virtue of the ball joint swivel system is in the rapid cyclic scan of an entire fixed size field of view. The field of view of the rendezvous sensor is 5° by 5° located within a 30° by 30° window. If the ball joint swivel were mechanized to optimally scan a 5° by 5° field of view, it would have to operate within a set of gimbals to provide the desired 30° by 30° coverage. This mechanization and the optical train are illustrated in Figure 2.

It should be noted that cyclic scan mechanism is suitable for track-while-scan only and would be disadvantageous for use with the precision target ranging processes described in the laser space rendezvous and docking tradeoff study (which requires continuous target tracking and integration of many pulse measurements). For this mode, the scan mechanism would be disabled, and the pointing mirror steered for precision track.

Spherical Ball Bearing Mirror Deflection Mechanism Realization

A likely mechanization of a mirror deflection mechanism, using spherical ball bearings, is shown in Figure 3. In this design, a spherical bearing is located behind the optic surface of the mirror on the axis of symmetry. Angular deflection is caused by two sets of cams and push rods located off-center. The cams will rotate through 360° while rotating the mirror ±5° about a center as required for the rendezvous sensor.

The mirror has to be spring loaded to keep it in contact with the cam drivers, and for it to be firmly seated on the spherical bearing. In order to minimize mirror bending, the spring loads should, ideally, be at or near the respective pressure points of the cams and the bearing. This, however, is difficult to implement, and the springs will actually be installed opposite the cam pressure points, with the structure reinforced to withstand the resulting bending moment.

The optic surface of the mirror will move with both translation and tilt (angular deflection). Since the mirror is planar, the translation has no optical effect. Because of the location of the bearing and the drive mechanism, optical train layouts with ray paths through a hole in the mirror are undesirable. It is possible to offset the spherical bearing from the mirror center; this would have the additional effect of increasing the deflection base, thereby easing tolerances. An off-center mounting also has the effect, however, of increasing the moment of inertia about the deflection axes. During rapid scanning of the mirror up to 3 times greater deflection forces will be required as compared to a center bearing location (depending on the amount of bearing offset from the center). There will also be substantial shaking forces on a line perpendicular to the mirror surface whenever the mirror is scanned rapidly, as during the target search phase. It is these considerations which led to the center ball joint Cassegrain telescope design for the deflection system.

Angular Error

The angular error is a function of the bearing runout as the mirror angle changes. If the bearing were ideally spherical all angular errors would be correctable with an initial setting. Departures from sphericity will cause a fluctuation, h, as shown in Figure 4. The angular error θE is:

$$\theta E = \frac{h}{d} \text{ in radians.}$$

For a center located bearing, d is about 30 mm for a 77 mm mirror. In the offset case, d would be about 45 mm.

The amount of angular error which can be tolerated is a function of the laser beamwidth of the rendezvous sensor and the amount of beam indexing per pulse. In the case of the rendezvous sensor, the optical beam moves in 166 microradian steps. An error of 83 microradians is marginal in that beam positions could be confused. A maximum angular error of 60 microradians would be reasonable. The beam deflection error is twice the mirror deflection error. This imposes a 30 microradian limit on θE. For the center located bearing case

$$\theta E\text{-}30\text{x}10^{-6} = \frac{h}{30\text{x}10^{-3}} \; ; \quad h = 900\text{x}10^{-9} = .9 \text{ microns}$$

For the offset bearing case:

$$\theta E = 30\text{x}10^{-6} = \frac{h}{45\text{x}10^{-3}} \; ; \quad h = 1350\text{x}10^{-9} = 1.35 \text{ microns}$$

The error analysis where h is the bearing runout assumes that the push rod is fixed and the total error due to bearing runout. If the bearing were regarded as fixed, the same angular error would be derived from the equivalent error h in the cam and push-rod dimensions. The allowable error in h is actually a total system runout error. The angle point accuracy is dependent on the combined dimensional accuracy and stability of the cams and push-rods, and the spherical support bearing.

In the design shown, the angle resolvers are on the cam drive shaft(s). This location gives a mechanical magnification to the resolver motion which is advantageous. This is because the 30° by 30° field of view may be divided into 3142 increments of .167 milliradian each. A 12-bit resolver with 4096 angle increments equivalent to 360 degrees, attached to the cam gives 3142 elements in 276.1 degrees rotation. Digital resolvers are preferred because of their compatibility with on-board computer facilities.

An alternate design which might have advantages, would be to attach angle or motion transducers to the mirror, and to control the dirve mechanism by a feedback loop. This would allow the spherical bearing, the cams, push-rods, etc., to be less accurate and to wear more during life. The measuring transducers would, via the beedback loop and a control computer, simply null out any inaccuracies in the drive elements. This has the advantage of removing the load from the precision elements, and removing precision requirements from loaded elements of the deflection system. It does, however, increase the complexity of the design considerably.

The simplest such design would be to attach a set of two-axis gimbals to the mirror to carry angle resolvers. The mass of the mirror would then be supported on a spherical bearing. The gimbals would only support the angle resolvers and could be smaller or lighter than in the case of a gimballed mirror which represents the original design. It is not certain that a spherical bearing mirror design with a set of gimballed resolvers would be more desirable than the original gimballed mirror and resolver design.

Ball Joint Availability

A survey of potential ball joint vendors was initiated and the Fafnir Bearing Company of New Britain, Conn., was the only bearing manufacturer found who was capable and willing to produce a spherical ball bearing to the required accuracy for the mirror deflection system.

A preliminary sketch of the bearing which resulted is shown in Figure 5. The bearing design is available in 24-26 weeks ARO. We have an informal budgetary quotation for quantities of 100 at $596 each.

In small quantities we estimate (based on verbal inquiries) the cost to be about $1200 each, with 24 weeks lead time.

The design is based on a bearing already in high volume production which is even more accurate than our requirements, i.e., 18×10^{-6} inches versus 25×10^{-6} inches. For our requirements, extra processing for vacuum operation, i.e., special lubrication processing is required. There are several suitable lubrication processes available.

The spherical ball bearing specifications to Fafnir are shown in Appendix A.

Performance And Accuracy Comparison

A. Performance

The optical performance of the rendezvous sensor, using a Cassegrain optical train, will be slightly better than with the baseline Gregorian configuration. This is due to the improved optical efficiencies which result from the simplified configuration, and to one less mirror with a smaller hole.

The cam drive for the mirror will involve several design trade-offs. Sliding friction and cam wear will be serious factors. If we examined Figure 3, we see that in addition to the spherical bearing, there are at least four other necessarily equally precise bearings for the cam shafts. The drive system will use more power due to cam-follower friction. If roller cam followers were used, friction would be reduced at the expense of two additional very precise bearings.

B. Accuracy

The accuracy of a gimballed mirror design, as originally described, is believed to be superior to that of the spherical ball joint swivel system with a cam drive.

In the original baseline design, the torque motors and the angle resolvers are directly connected to the pointing mirror axes. There are only two lightly loaded bearings on each axis. The drive to the mirror is a true torque as compared to an off-center force.

In the ball joint swivel system all of the shaft bearings are radially loaded, and the spherical bearing is axially loaded with combined static and live loads. Any variations in the spring

loading due to temperature, aging, or repeated flexure would cause a shift in the pre-loaded position of the mirror. This could cause significant angular error.

C. Conclusion

All factors considered, it will be possible to realize the required scan using either the original resonant mirror configuration, or a ball joint swivel system. The complications associated with each system are equivalent in relative complexity. At this time, there are several unrelated military applications for the ball joint swivel scan and if the technologies associated with this technique are further developed on other programs, it will definitely be advisable to consider this as the baseline scanning technique.

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