1 General

As reported in OVLBI memo #4 [1], it is necessary for the Green Bank Earth Station to support the following space research allocation bands:

Frequency(GHz)	Direction	Space Research Allocation
7.190-7.235	uplink only	primary
8.450-8.500	downlink only	primary
13.40-15.35	both directions	secondary

Specifically, to support the VSOP and Radiastron projects, the following frequencies must be supported:

Frequency (GHz)	Satellite	Use	Link	Polarization
7.2000 GHz	Radiastron	CW	uplink	RCP
8.4720 GHz	Radiastron	CW	downlink	RCP
14.200 GHz	VSOP	data, 150 MHz	downlink	LCP
15.063 GHz	Radiastron	data, 150 MHz	downlink	RCP
15.300 GHz	VSOP	CW	uplink	LCP

To satisfy the wide bandwidth requirement of the feed and optics on the antenna, an optics scheme was proposed [2], and adopted as our primary option at the OVLBI Earth Station preliminary design review [3]. This scheme proposed to use a frequency-selective-surface (FSS) as the means to split the beam at the secondary focus into an X-band component and a Ku-band component. This memo will discuss the prototype design and testing of the FSS that has been done to date.

2 Specifications

The FSS design needed, at the very least, to be nearly transparent at 8.5 GHz and highly reflective at 14.2 GHz. The close spacing of these two frequencies, a ratio of 1.67:1, meant that many typical FSS element designs such as dipoles, crossed dipoles, patches, or loops could not be used. A gridded square loop element was decided upon because it can diplex frequencies as close as 1.3:1 with little added crosspolarization. Also, a consultant was available at JPL, Dr. T.K. Wu, who had expertise and computer software that modelled the gridded square loop. A specification was written and sent to Wu to use as a guide in his design. The original specification was as follows:

Band	Frequency (GHz)	Transmission Loss	Reflection Loss
Transmission	7-9 GHz	$< .2$dB	——
Prime Transmission	7.15-7.28 GHz, 8.34-8.60 GHz	$< .05$ dB	——
Reflection	13.4-15.4 GHz	> 16.4 dB	< 0.1 dB
Prime Reflection	14.10-14.30 GHz, 14.90-15.40 GHz	> 19.4 dB	< 0.05 dB

Since Wu expressed some initial concern that this specification may not be achievable, we indicated that the performance should be optimized for 8.5 GHz, 14.2 GHz, and 15.063 GHz, the downlink frequencies. The specification, A34200N4, is attached.

3 Design

The first part of the FSS design was determining what the best approach would be. There are three basic types of frequency-selective-surfaces: a thin single-layer FSS, an FSS consisting of multiple layers of copper and dielectric, and a metal-only FSS consisting of a grid of waveguide slots. The second approach would require a complex fabrication and is difficult to model, and the third approach would be prohibitively expensive. Thus, the first approach, a single-layer FSS, was taken due to its inherent simplicity and low material loss.

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[1] L.R. D'Addario,"Requirements for the Feed and Optics for the 45 ft. Antenna in Green Bank," OVLBI–ES Memo #4, Sept. 7, 1990

[2] S. Srikanth, "A Possible Optics Scheme for the 45–Foot Antenna in Green Bank," OVLBI–ES Memo #5, Nov. 27, 1990

[3] L.R. D'Addario, B. Shillue, and D. Varney, "The Green Bank OVLBI Earth Station: Preliminary Design," July, 2, 1991

The next step was to determine what type of element was needed. The frequency response that we required ruled out simple elements with a single resonance. More complex elements that could meet our frequency requirements and that offered low cross-polarization include the Jerusalem-Cross, Gridded Jerusalem-Cross, Double-Square Loop, and Gridded-Square Loop. T.K. Wu suggested that the Gridded-Square Loop design would be the most appropriate, so that is what we had him design. It is likely that other element designs would also have worked. The final design decision was the type of backup structure to use. A previous NRAO FSS design had used a Kevlar honeycomb backup, which is very strong but also lossy. We decided to use a low-loss foam backup structure.

The FSS was simulated on a Cray X-MP supercomputer using a computer code developed by Robert Vacchione at the University of Illinois for the design of single layer FSS's with arbitrarily shaped element. The code uses the standard assumption that the FSS is infinite in transverse extent, so that the boundary conditions at the dielectric and copper interfaces need only be solved for a single element, and the results extrapolated according to Floquet's theorem for periodic structures. [4] The dimensions of a single element of this FSS are shown in Fig. 1. The FSS consisted of copper elements etched on a 3-mil Kapton substrate.

The computer code has a limitation in that the element is discretized into 32 x 32 unit cells. This means that if we want to fine-tune the design so that some dimension of the element, width or spacing, is not $\frac{n}{32} * p$, where p is the size of the unit element, and n is an integer from 1 to 32, we must use a less rigorous simulation. Although the element design has 4 degrees of freedom, this limitation is a hindrance because the frequency resolution for the change in a single unit-cell can be as large as $\delta f = \frac{1}{32} f_0 = 470$ MHz at $f_0 = 15$ GHz. Lumped element models for simulation of the gridded square loop based upon work by Lee and Langley[5] were developed as a secondary way of analyzing the FSS.

4 Materials

The substrate material used was a 3-mil thick Kapton substrate with a 1 oz. (1.4 mil) copper laminate. Kapton is a material with a good combination of electrical, mechanical, and thermal properties that also performs well at microwave frequencies. It had been used previously in the design of the VLBA FSS at the NRAO. Kapton is a DuPont product, but was purchased in laminated form from Westinghouse Fortin. The foam support material was Rohacell 51 from Rohm-Tech. A similar, more expensive material of lower loss called Eccofoam is available from Emerson and Cuming.

5 Fabrication

Artwork for the gridded-square loop FSS was generated in AutoCad at the NRAO at twice actual size. The HP ****** plotter was used, which was able to handle a drawing size of up to 22.75" by 34.375". Because of the tolerance limitations of the plotter, the dimensions of the AutoCad drawing did not correspond exactly to the plotter drawing, so the line widths and lengths in both horizontal and vertical directions were carefully calibrated. The result was that the plotted dimensions at twice size were within 0.5 mils of the desired values after repeated measurement under a microscope. Two plots of dimension 18.4236" x 27.6354" were made and carefully taped together, followed by a photoreduction of the plot done by Ron Monk at the Green Bank photo lab, thus generating the 18.4236" x 13.8177" circuit mask.

The circuit mask is used by the vendor, Precision Prototypes, to fabricate the copper pattern on the Kapton. First, a 16" x 20" Kapton substrate is supplied because the vendor requires a one inch border around the edge of the pattern. The copper-laminated Kapton is spun with photoresist and then baked. Then the resist layer is exposed to light through the mask for a controlled time. The emulsion layer of the mask must be in contact with the resist. The exposed areas of resist are then washed off in a developing solution, and the panel is placed in a copper etch, again for a carefully controlled amount of time.

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[4] Amitay, Galindo, Wu, "Theory and Analysis of Phased Array Antennas," Wiley Interscience, New York, 1972, Chapter 2, pp. 37-74

[5] Lee, C.K. and Langley, R.J., "Equivalent-Circuit Models for Frequency-Selective Surfaces at Oblique Angles of Incidence, IEE Proc., Pt. H, Oct. 1985, pp. 395–399

6 Measurement

The first FSS panel size was approximately 18 x 14 inches. Two identical FSS's were fabricated by Precision Prototypes of NJ, and returned to JPL and the NRAO, Green Bank, respectively. Measurements were then made of the frequency response of the FSS by both JPL and NRAO. JPL used an indoor range, had the FSS sheet taped to a Rohacell foam backing, and used dielectric lenses mounted on the apertures of the test horns to focus the beam within the borders of the FSS, which was placed somewhere between the two test horns. JPL's indoor range allowed for swept frequency response measurements. NRAO used an outdoor range, with the FSS mounted within a wooden frame which was designed to stretch the FSS surface taut, and the wooden frame was bracketed approximately 10 inches in front of the receiving horn. The backup foam was placed behind the FSS to give more rigidity to the panel, but was not adhered to the FSS surface. For 7-12.5 GHz measurements, a circular corrugated X-band horn was used to receive, and for 13-16 GHz measurements, a pyramidal Ku-band horn was used. The NRAO does not have swept-frequency measurement capability, so data was taken repeatedly at discrete frequencies with a phase-locked receiver.

The test procedure was to measure the power received with nothing between the test horns. The FSS is then placed between the horns and the power measured for every desired incident angle typically 0°,15°,30° and 40°. The FSS is removed and the power again measured with nothing between the two test horns. The resulting difference between power received without and with the FSS is the insertion loss of the FSS.

The measurement results are summarized in Figures ***- *** below, with plots of NRAO and JPL measurements of FSS insertion loss versus frequency, as a function of incident angle and polarization. WORDS about the plots , bandwidths, and various correspondences.

The results of the test of the first FSS, given below, did not meet our initial specifications. Actually, the specification was written rather simply, requiring better than 0.1 or 0.2 dB loss for certain frequency ranges, *for all angles of incidence and states of incident polarization.* Actually, we can tolerate losses at certain frequencies, angles, and polarization in excess of the levels given in the specification. What we really require, at minimum, is less than 0.1 dB loss in reflection (Ku-band), and less than 0.2 dB loss in transmission, for *the actual transmit-receive conditions that the earth station must handle.*

With the FSS placed in the near-field of a corrugated horn with circular polarization, many angles and a combination of TE and TM polarization are present at once. However, the total loss can be calculated by integrating the expected incident electric field, including amplitude, incident angle, and polarization, against the corresponding transmission or reflection loss function of the FSS. This has been done, using a program called FSSEFF written in FORTRAN on a SUN workstation. The results of this program, which uses actual measured FSS data, are shown in Fig. 2 for X-band, and Fig. 3 for Ku-band. Clearly, the loss exceeds 0.2 dB for some frequencies between 7.2 GHz and 8.5 GHz; and exceeds 0.1 dB for some frequencies between 14.2 GHz and 15.3 GHz. Also, it seems that although the overall efficiency can be improved by decreasing the angle of FSS tilt, the bandwidth of the response, particularly at X-band, will not be enough to meet either the original specification or the overall efficiency specification.

However, there is a third, "fall-back" option, which would require the FSS only to diplex Radiastron downlink signals with high efficiency. This would require a mechanical structure on the antenna to be added so that the FSS can be remotely stowed for VSOP transmission. The FSS would then be optimized for 8.47 GHz and 15.0625 GHz, and approximately 1 dB of transmission loss through the FSS would be tolerated at 7.2 GHz.

At present, the results of the overall efficiency study shown in Figures 2 and 3 indicate that this third option has already been met. If the design is scaled, the centers of the transmission and reflection bands can be placed at 8.5 GHz and at 14.85 GHz. Significantly, this might achieve less than 0.1 dB loss at 14.2 GHz and at 15.3 GHz. Thus, the only operational frequency at which the initial specification would not be met is at 7.2 GHz.

The loss calculations that we performed were done with certain assumptions that should be held in mind. First, transmission-only data was used. This means that the reflection loss was calculated assuming that all of the energy which was not *measured* in transmission was assumed to be reflected in the appropriate direction. Thus, we ignored the possible added loss of specular reflection and material loss.

We are presently trying to improve the design by using a layered teflon sandwich FSS. The main objective is to reduce the significant spectral spread in the resonant response at Ku-band as a function of angle, which was particularly bad for the first FSS with TM incident electric field. The tentative new design, also done by Wu of JPL, is shown in Figure 4.

The second design incorporates two layers of 35-mil thick Teflon, bonded together with a 0.5 oz (.7 mil)

TE Incidence		
Angle	1.0 dB Transmission Band	20 dB Reflection Bandwidth
Predicted Performance from Computer Simulation		
0	6.5-9.8, lowest loss-8.3	14.1-15.4, lowest loss 14.75
15	6.6-9.8, 8.3	14.0-15.3, 14.6
30	6.9-9.75, 8.5	13.75-15.0, 14.4
40	7.2-9.7, 8.5	13.6-14.75, 14.2
NRAO measurement		
0	6.7-10	13.9-15.35, 14.7
15	6.7-9.3	14.0-15.30, 14.5
30	6.7-9.2	13.75-15.0, 14.2
40	6.7-9.2	13.6-14.75, 14.1
JPL measurement		
0	7.2-8.6,8.15	13.8-15.5, 14.6
15	7-8.65,8.15	13.75-15.3, 14.5
30	7-9.35,8.1	13.5-15, 14.25
40	7-9.35,8.1	13.4-14.7, 14.0
TM Incidence		
Angle	1.0 dB Transmission Band	20 dB Reflection Bandwidth
Predicted Performance from Computer Simulation		
0	6.5-9.8, 8.3	14.1-15.4, 14.75
15	6.5-9.8, 8.3	14.0-15.2, 14.5
30	6.5-10, 8.4	13.6-14.5, 14.0
40	6.4-10, 8.4	13.25-14.2, 13.75
NRAO measurement		
0	6.7-10	14.0-15.6, 14.6
15	6.7-9.0	14.0-15.2, 14.5
30	6.5-9.3	13.2-14.5, 14.0
40	6.5-9.3	13.25-14.2, 13.75
JPL measurement		
0	7-8.7,8.1	13.8-15.5, 14.6
15	7-9.35,8.15	13.75-15.1, 14.4
30	7-9.4,8.1	13.3-14.5, 13.9
40	7-9.5,8.1	13.1-14.05, 13.5

Table 1: Transmission and reflection bandwidths for Gridded Square Loop FSS of Figure 1

copper pattern between the layers. There are many manufacturers of Teflon microwave substrates, among them are Taconic, Crane, Arlon, Rogers, and Norplex Oak. The product varies according to sheet size, dielectric constant and loss tangent, dielectric thickness, single or double sided copper, and mechanical properties. Very good electrical and mechanical properties such as low loss tangent, low linear thermal expansion, and low thermal coefficient of dielectric constant, can be obtained for a higher price. Crane is the only manufacturer that sells pure Teflon, which has very low loss tangent. For prototyping, we are not so much concerned with these properties, so a lower cost substrate was purchased from Norplex Oak. In addition to the Teflon, an adhesive agent is needed for the thermal compression bonding of the substrates. Ideally, this should have the same dielectric constant as the substrate and be low loss. A 25 foot by 12 inch roll of bonding film was purchased from Norplex Oak for this purpose.

For the second prototype FSS, in which two layers of Teflon substrate are sandwiched around the copper pattern, additional steps are required. Either two copper clad Teflon substrates are used, or one clad-substrate and one unclad. In any case, the copper is totally removed from one substrate. The second substrate is then carefully fabricated exactly as was the single layer Kapton FSS. Because the elements are to be embedded between dielectric layers, they must be smaller than the elements on the Kapton substrate, which makes the etching tolerance more critical. For this reason, 0.5 oz copper was specified rather than 1 oz. copper.

After etching, the substrates are prepared for bonding by quickly dipping them in a sodium etch solution, which roughs up the Teflon surface, enabling good adhesion. With electrodeposited copper, this step can be omitted, but the results may not be as good as with the sodium etch. In any case, bonding must be done imediately after the copper etch in a clean environment. The bonding film is then placed between the panels, and they are pressed together with a specified temperature and pressure for a specified length of time. Many vendors do not have the equipment for this step, so it is necessary to find one that does.

7 Remaining Work

7.1 R

eflection Measurements Reflection Measurements are needed to determine if Ku-band losses are as low as they appear. A reflection test has been done and the results are shown in Figure 6. The angular alignment of the mirror-FSS was not precisely known, so the setup was swept through a range of angles. More realistic conditions can be simulated, of course, once the subreflector and ellipsoid are procured.

7.2 Implementation of New FSS simulation program

A major hindrance has been the lack of an available NRAO FSS simulation program. Lumped element models have been written and are accurate to within about 300 MHz, but do not predict reliably the polarization and angular effects. The OSU code should be secured, but it is taking longer than expected. Meanwhile, Wu has done an analysis for a new FSS which could be better optimized, and the best approach may be to use the lumped element model to conservatively tweak his design.

The latest computer design results from Wu are shown in Table 2.

TE Incidence		
Angle	0.1 dB Transmission Band	17 dB Reflection Bandwidth
0	7.3-8.2, 7.8	13.4-15.7, 14.55
30	7.6-8.25, 7.9	13.2-15.65, 14.4
40	7.6-8.1, 7.95	12.9-15.4, 14.15
TM Incidence		
Angle	0.1 dB Transmission Band	17 dB Reflection Bandwidth
0	7.3-8.2, 7.8	13.4-15.7, 14.55
30	7.5-8.25	13.35-15.20, 14.27
40	7.6-8.40, 8.0	13.3-14.7, 14.0

Table 2: Transmission and reflection bandwidths for Gridded Square Loop FSS - Layered Teflon Design er=2.5, t=30 mil

7.3 Measurement of new FSS

Given the fact that the milestone for deciding the optics has passed, we should spare no more time in fabricating and measuring the teflon-sandwich FSS.

7.4 Consideration of Cross-Polarization Effects

Cross-polarization effects are introduced in our type of optics by two factors. First, the FSS elements convert some energy between orthogonal polarizations. This should be a very small amount. Second, the offset ellipsoid and even a perfectly conducting flat plate introduce unwanted cross-polarization. These effects need to be quantified and expressed as a polarization loss.

7.5 Development of low-vibration frame

The two-way timing link can be defeated by an FSS that is not mechanically sound, due to path-length effects. Whether a sound frame is achievabale has not been investigated.

7.6 Optimization of Material

Environmental factors, particularly temperature variation, will alter the frequency response of the FSS. A more temperature-stable material will be needed in later versions of the FSS.