55241

Metal Mesh Fabrication and Testing for Infrared Astronomy and ISO Science Programs; ISO GO Data Analysis & LWS Instrument Team Activities

Grant NAG5-7705

Summary of Research

For the period 1 January 1999 through 30 June 2001

Principal Investigator:

Dr. Howard A. Smith

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Prepared for
National Aeronautics and Space Administration
Washington D.C.

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The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Dr. Ronald J. Oliversen, NASA Goddard Space Flight Center, Greenbelt MD 20771-0001

I. SUMMARY

This research program addresses astrophysics research with the Infrared Space Observatory's Long Wavelength Spectrometer (ISO - LWS), including efforts to supply ISO-LWS with superior metal mesh filters. This grant has, over the years, enabled Dr. Smith in his role as a Co-Investigator on the satellite, the PI on the Extragalactic Science Team, and a member of the Calibration and performance working groups. The emphasis of the budget in this proposal is in support of Dr. Smith's Infrared Space Observatory research.

This program began (under a different grant number) while Dr. Smith was at the Smithsonian's National Air & Space Museum, and was transferred to SAO with a change in number. While Dr. Smith was a visiting Discipline Scientist at NASA HQ the program was in abeyance, but it has resumed in full since his return to SAO.

The Infrared Space Observatory mission was launched in November, 1996, and since then has successfully completed its planned lifetime mission. Data are currently being calibrated to the 2% level.

II. REVIEW OF THE PROPOSAL GOALS

This proposal and its predecessors have had the following primary goals:

1. ISO Science program: Data reduction and analysis for the ISO, in particular for both team and individual proposals for use of the ISO open and guaranteed time, including the ISO Central Programme, and general instrument evaluation and analysis issues for the ISO-LWS.

2. Astronomy: Continuing Excellent astronomical research related to and in support of the ISO science mission goals. This includes some ground-based observations and other astronomical research.

3. Mid and FIR Metal Mesh Development: Continue to investigate and develop superior free-standing "inductive" type metal meshes using new photo-lithographic techniques and microelectronics technology, and investigate their applicability in infrared astronomy programs.

III. PROGRAM PERFORMANCE SUMMARY

The ISO satellite program was reviewed by an external NASA review panel, which called ISO science one of its highest priorities, and the "major infrared mission of this decade." This proposal's program goals (1) and (2) were implemented, as proposed, by means of the grant supporting in part the salary of Dr. Smith, covering key travel to ISO and other astronomy related meetings in the US and abroad, and purchasing key computer equipment (a Sun Ultra-10)

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as spelled out in the proposal program plans, as well as some PC software (MathCad, SigmaPlot, and Excel).

Table 1 lists the ISO observations carried out with Dr. Smith as the PI. The table includes the details of source name and location, and time requests. Figure 1 shows a nice summary plot of a sequence of galaxies measured by ISO as part of this program.

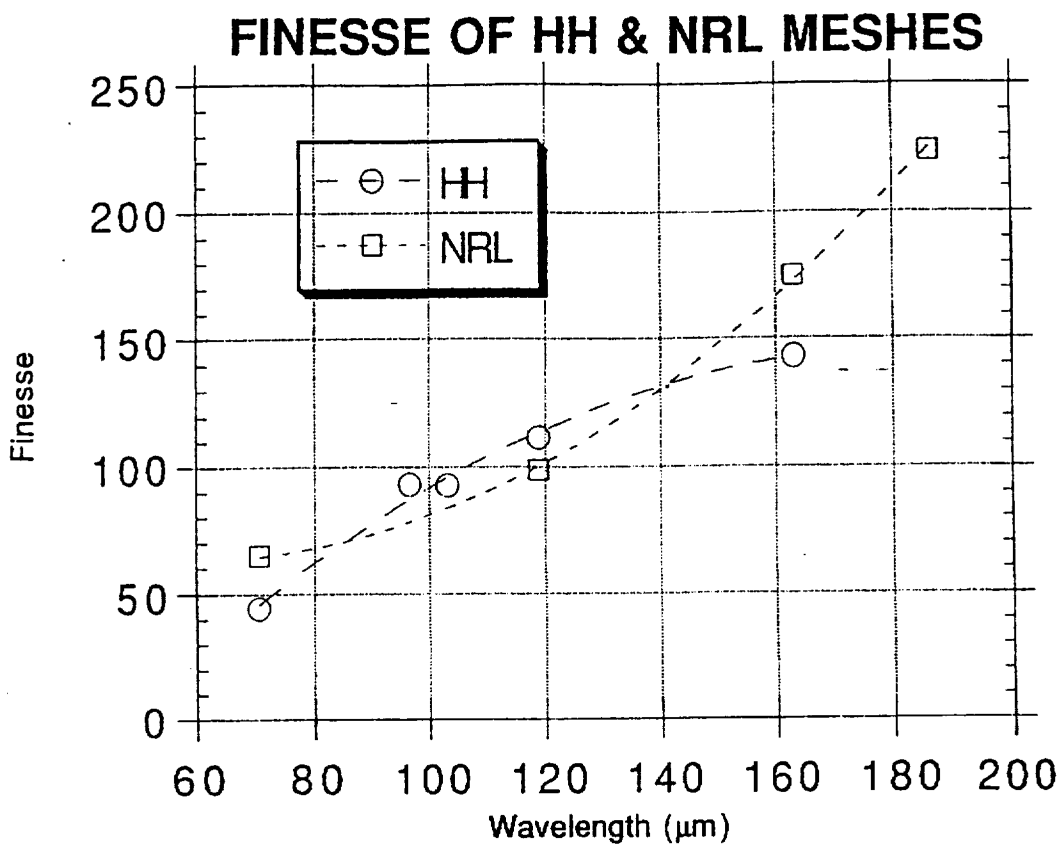
Table 2 is a list of all the publications supported in part by this program, since its inception. A total of 57 articles have appeared since the program began.

Education and Public Outreach are a minor but important part of this program. Appendix I contains the presentation of an invited talk given by Dr. Smith to the COSPAR meeting in Warsaw in 2000, and which discusses the popular attitudes towards space science. Appendix II contains the body of a proposal for a program called "Discovering the Cosmos", which brought an entire high-school to the Boston Museum of Science for a full day of astronomy-related talks and demonstrations.

Appendices III, IV and V are three papers published as a result of the metal mesh work in this program. These papers are in addition to those listed below in Table 2. As has been previously reported, and is shown in Figure 2, the metal meshes developed at NRL by the precursor of this program were superior to any other (e.g., Heidenhain - "HH") commercially available meshes, as confirmed by tests by the European Space Agency for ISO instrumentation.

IV. CONCLUSIONS

In its breadth and depth, this program has in our opinion been noteworthy and ambitious: seeking to do a range of high quality astronomy research, while developing new tools in instrumentation and research, and undertaking new E&PO projects. In all regards it has been a major success, as the Tables and Appendices can substantiate. Numerous refereed papers have been published (and frequently cited); the mesh techniques have made good progress; and the E&PO projects done well. All of these general areas have, in fact, been so successful that they have been able to transition to a new generation of supported research projects, whereby they continue to yield interesting and successful progress in our understanding of the Universe.


FINESSE OF HH & NRL MESHES
250
200
150
100
50
0
Finesse
HH
NRL
60
80
100
120
140
160
180
200
Wavelength (µm)

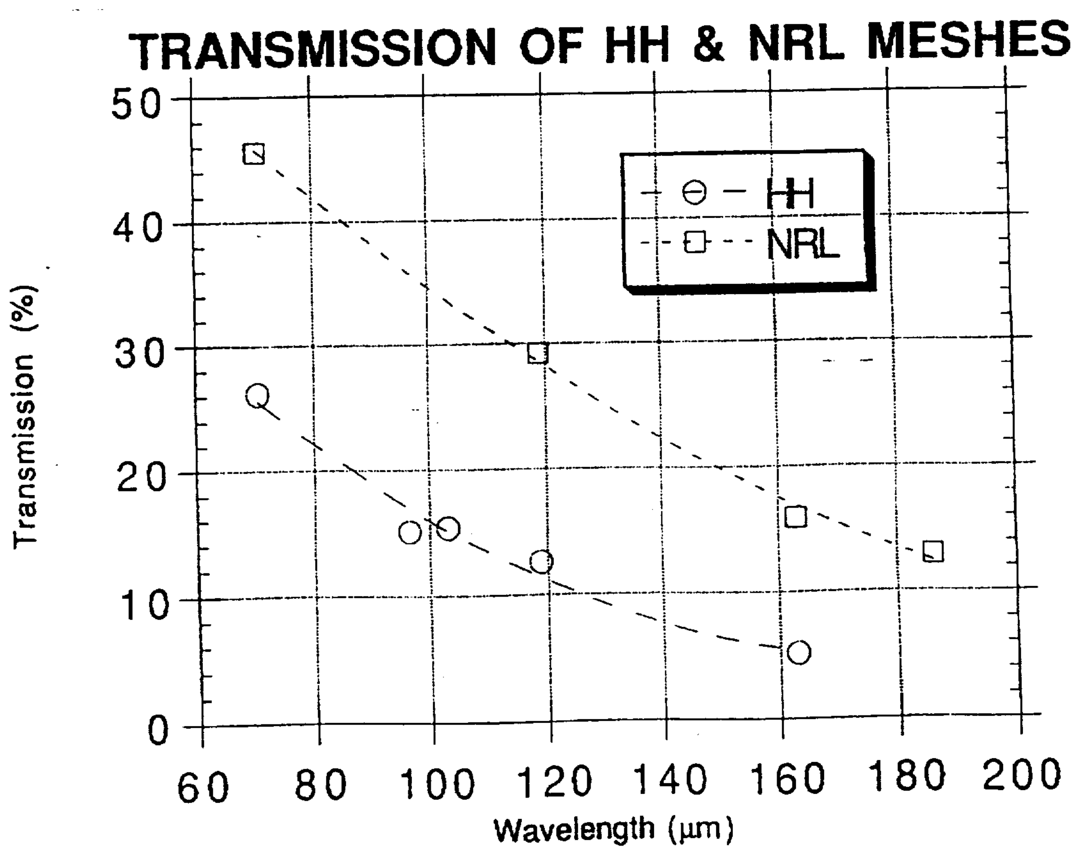

TRANSMISSION OF HH & NRL MESHES
50
40
30
20
10
0
Transmission (%)
HH
NRL
60
80
100
120
140
160
180
200
Wavelength (µm)

Fig. 1

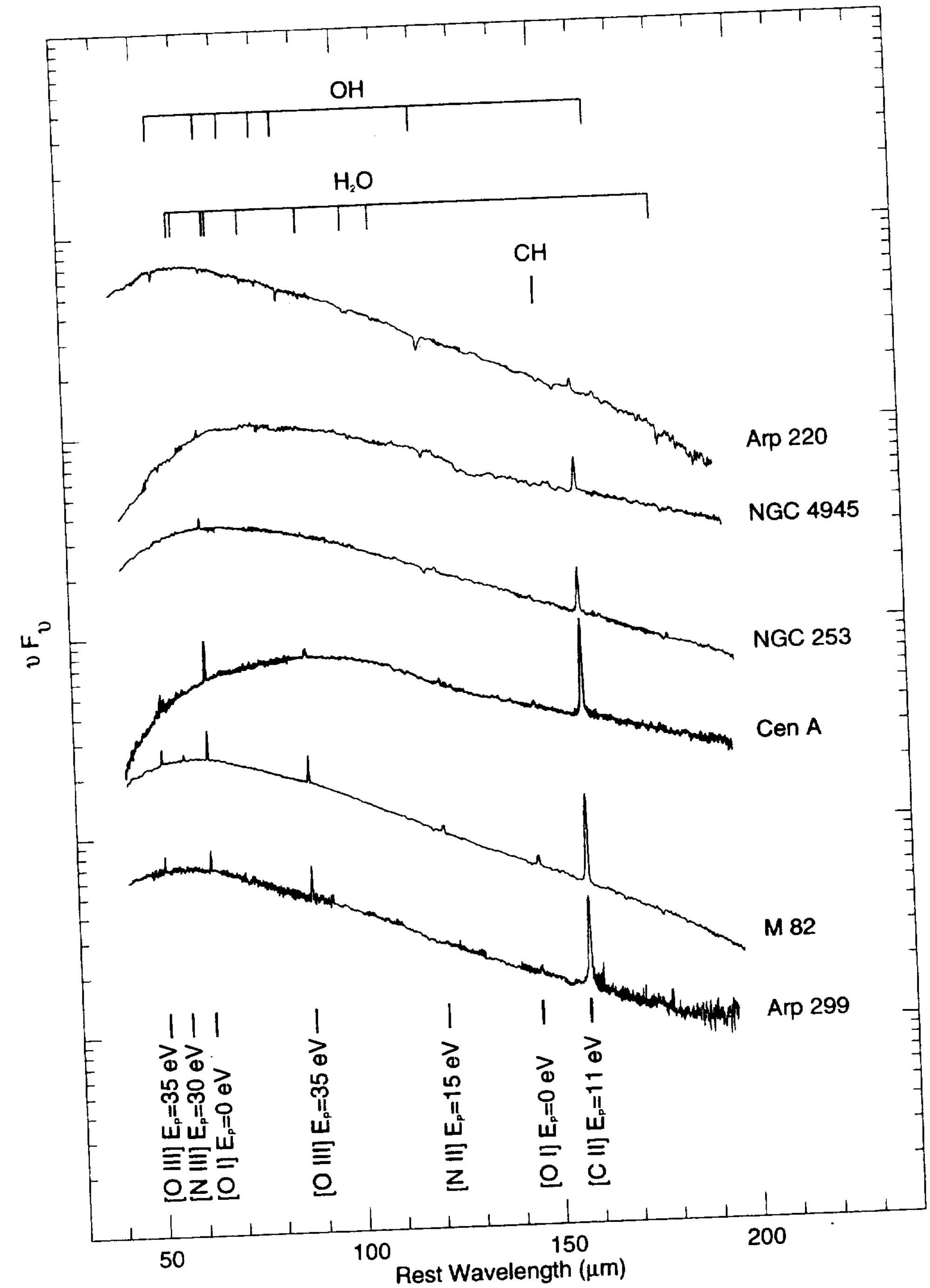


Figure 1. The full ISO Long Wavelength Spectrometer spectra of six IR-bright galaxies. The spectra have been shifted and ordered vertically according to apparent excitation (Fischer et al. 1999) and are not in order of relative luminosity or brightness.

Fig. 2

ISO Schedule Information

Specified Query Parameters

Type of Information:	ISO Schedule
Output Format:	Tabular Data
Maximum Records:	250
Target Name:	*
RA (J2000):	*
DEC (J2000):	*
Observer ID:	HSMITH
Proposal ID:	*
OSN:	*
Instrument:	*
On-Target Time:	*
Revolution Number:	*
Observation Status:	*
Scheduled Start Time:	*
Actual Start Time:	*
Actual End Time:	*
Sort Key-1:	None
Sort Key-2:	None
Sort Key-3:	None

Query Results

Last ISO Schedule Processing Date: 12 May 1998 11:06:14
Total Number of Records Found: 239

Observation Records Found

TARGET	RA (J2000)	DEC (J2000)	OBSERVER	PROPOSAL	ID
NGC 4945	13h 05m 26.2s	-49d 28' 15.5"	HSMITH	IRBGALS A	5
NGC 4945 OFF	13h 04m 35.8s	-49d 20' 31.5"	HSMITH	IRBGALS A	33
2132+01	21h 35m 10.6s	1d 39' 31.4"	HSMITH	AGN_A A	24
2237-06	22h 39m 53.6s	-5d 52' 20.3"	HSMITH	AGN_A A	51
Mkn 509	20h 44m 09.7s	-10d 43' 24.6"	HSMITH	AGN_A A	28
Mkn 509	20h 44m 09.7s	-10d 43' 24.6"	HSMITH	AGN_A A	25

Mkn 509	20h 44m 09.7s	-10d 43' 24.6"	HSMITH	AGN_A A	27
1700+64	17h 01m 00.4s	64d 12' 09.1"	HSMITH	AGN_A A	20
HB89 1821+643	18h 21m 57.2s	64d 20' 36.3"	HSMITH	AGN_A A	11
HB89 1821+643	18h 21m 57.2s	64d 20' 36.3"	HSMITH	AGN_A A	6
HB89 1821+643	18h 21m 57.2s	64d 20' 36.3"	HSMITH	AGN_A A	10
Fairall 9	1h 23m 45.7s	-58d 48' 20.4"	HSMITH	AGN_A A	39
1233+47	12h 35m 31.0s	47d 36' 05.0"	HSMITH	AGN_A A	17
M81	9h 55m 33.3s	69d 03' 55.6"	HSMITH	GALXISM A	5
M 82	9h 55m 52.3s	69d 40' 45.9"	HSMITH	IRBGALS A	1
M 82 OFF	9h 55m 53.1s	69d 57' 45.9"	HSMITH	IRBGALS A	29
IRAS10214+4724	10h 24m 34.5s	47d 09' 10.0"	HSMITH	IRBGALS A	54
NGC 3690	11h 28m 32.3s	58d 33' 43.4"	HSMITH	IRBGALS A	4
NGC 3690 OFF	11h 27m 25.1s	58d 41' 58.8"	HSMITH	IRBGALS A	32
1158+46	12h 00m 36.8s	46d 18' 46.0"	HSMITH	AGN_A A	98
MRK 231	12h 56m 14.2s	56d 52' 24.9"	HSMITH	IRBGALS A	6
Mrk 231 OFF	12h 54m 48.0s	56d 40' 02.4"	HSMITH	IRBGALS A	34
2235-03	22h 38m 22.3s	-2d 45' 52.6"	HSMITH	AGN_A A	42
Mrk 273	13h 44m 42.1s	55d 53' 13.1"	HSMITH	IRBGALS A	11
IRAS2249-1808	22h 51m 49.3s	-17d 52' 24.1"	HSMITH	IRBGALS A	19
M 82 map	9h 55m 52.3s	69d 40' 45.9"	HSMITH	IRBGALS A	10
M 82 map	9h 55m 52.3s	69d 40' 45.9"	HSMITH	IRBGALS A	15
M 82	9h 55m 52.3s	69d 40' 45.9"	HSMITH	IRBGALS A	38
M 82	9h 55m 52.3s	69d 40' 45.9"	HSMITH	IRBGALS A	52
M 82	9h 55m 52.3s	69d 40' 45.9"	HSMITH	IRBGALS A	56
M 82	9h 55m 52.3s	69d 40' 45.9"	HSMITH	IRBGALS A	57
M 82	9h 55m 52.3s	69d 40' 45.9"	HSMITH	IRBGALS A	58
I Zw 92	14h 40m 38.1s	53d 30' 15.8"	HSMITH	AGN_A A	4
NGC 4151	12h 10m 32.6s	39d 24' 20.3"	HSMITH	AGN_A A	2
NGC 4151 off-sou	12h 10m 53.4s	39d 24' 20.4"	HSMITH	AGN_A A	62
1247+34	12h 49m 42.0s	33d 49' 52.0"	HSMITH	AGN_A A	21
1335-04	12h 05m 23.0s	-4d 34' 03.1"	HSMITH	AGN_A A	16
1202-07	12h 05m 23.1s	-7d 42' 32.0"	HSMITH	AGN_A A	13
PG1211+143	12h 14m 17.6s	14d 03' 12.3"	HSMITH	AGN_A A	22
PG1211+143	12h 14m 17.6s	14d 03' 12.3"	HSMITH	AGN_A A	76
NGC 4039	12h 01m 54.3s	-18d 53' 02.3"	HSMITH	IRBGALS A	48
NGC 4039 OFF	12h 01m 53.3s	-18d 45' 30.3"	HSMITH	IRBGALS A	39
3C273	12h 29m 06.6s	2d 03' 08.6"	HSMITH	AGN_A A	7
3C273	12h 29m 06.7s	2d 03' 08.6"	HSMITH	AGN_A A	8
NGC 4039 Lines	12h 01m 53.3s	-18d 45' 30.3"	HSMITH	IRBGALS A	43
IRAS1207-0444	12h 09m 45.3s	-5d 01' 13.3"	HSMITH	IRBGALS A	21
NGC 253	0h 47m 33.2s	-25d 17' 18.2"	HSMITH	IRBGALS A	3
NGC 253 OFF	0h 47m 33.4s	-24d 52' 18.2"	HSMITH	IRBGALS A	31
NGC 253 map	0h 47m 33.2s	-25d 17' 18.2"	HSMITH	IRBGALS A	45
NGC 4038	12h 01m 53.0s	-18d 52' 05.1"	HSMITH	IRBGALS A	7
NGC 4038 OFF	12h 01m 53.3s	-18d 45' 30.3"	HSMITH	IRBGALS A	35
1302-14	13h 05m 25.2s	-14d 20' 41.0"	HSMITH	AGN_A A	52
1413+11	14h 15m 46.2s	11d 29' 43.5"	HSMITH	AGN_A A	18
ARP 220	15h 34m 57.2s	23d 30' 11.2"	HSMITH	IRBGALS A	2
Arp 220 OFF	15h 34m 57.2s	23d 37' 11.4"	HSMITH	IRBGALS A	30
NGC 6240	16h 52m 58.8s	2d 24' 04.3"	HSMITH	IRBGALS A	8
NGC 6240 OFF	16h 52m 58.7s	2d 31' 09.4"	HSMITH	IRBGALS A	36
NGC 4945	13h 05m 26.5s	-49d 27' 54.5"	HSMITH	IRBGALS A	40
NGC 4945 OFF	13h 04m 35.8s	-49d 20' 31.5"	HSMITH	IRBGALS A	47
NGC 4945 map cen	13h 05m 26.5s	-49d 27' 54.5"	HSMITH	IRBGALS A	46
NGC 4945 NE	13h 05m 36.9s	-49d 25' 45.2"	HSMITH	IRBGALS A	49
NGC 4945 SW	13h 05m 12.3s	-49d 30' 54.7"	HSMITH	IRBGALS A	50

Cen A Lines	13h 25m 30.2s	-43d 01' 20.6"	HSMITH	IRBGALS A	42
SAGA ql	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	25
SAGA on+20W	17h 45m 38.5s	-29d 00' 28.7"	HSMITH	GCENTER A	26
SAGA 20N	17h 45m 40.0s	-29d 00' 08.6"	HSMITH	GCENTER A	27
NGC 6764	19h 08m 16.3s	50d 55' 59.6"	HSMITH	GALXISM A	64
IRAS 1525+3609	15h 26m 59.3s	35d 58' 37.2"	HSMITH	IRBGALS A	60
M51 SW	13h 29m 44.4s	47d 10' 12.9"	HSMITH	GALXISM A	50
M51 Nucleus	13h 29m 53.2s	47d 11' 48.1"	HSMITH	GALXISM A	51
M51 NE	13h 29m 59.6s	47d 13' 58.3"	HSMITH	GALXISM A	49
NGC 4151 Repl 1	12h 10m 32.6s	39d 24' 20.3"	HSMITH	AGN_A A	63
NGC 4151 off Rep	12h 11m 08.9s	39d 24' 20.5"	HSMITH	AGN_A A	65
NGC 4151 Repl 3	12h 10m 32.6s	39d 24' 20.3"	HSMITH	AGN_A A	67
NGC 4151 Repl 4	12h 10m 32.6s	39d 24' 20.3"	HSMITH	AGN_A A	68
NGC 5195	13h 29m 59.4s	47d 15' 55.3"	HSMITH	GALXISM A	52
NGC 4151 Repl 5	12h 10m 32.6s	39d 24' 20.3"	HSMITH	AGN_A A	69
NGC 4151 off Rep	12h 11m 08.9s	39d 24' 20.5"	HSMITH	AGN_A A	81
NGC 4151 Repl 7	12h 10m 32.6s	39d 24' 20.3"	HSMITH	AGN_A A	85
UGC 11391	19h 01m 41.8s	40d 44' 52.1"	HSMITH	IRBGALS A	24
NGC 7592	23h 18m 22.2s	-4d 24' 57.2"	HSMITH	IRBGALS A	25
Cartwheel bright	0h 37m 40.1s	-33d 43' 27.0"	HSMITH	IRBGALS A	17
NGC 7714	23h 36m 14.7s	2d 09' 18.3"	HSMITH	GALXISM A	63
UGC 12699	23h 36m 14.1s	2d 09' 18.6"	HSMITH	IRBGALS A	26
Arp 256 South	0h 18m 50.8s	-10d 22' 36.7"	HSMITH	IRBGALS A	27
Arp 256 North	0h 18m 50.0s	-10d 21' 39.7"	HSMITH	IRBGALS A	53
I Zw 1	0h 53m 34.9s	12d 41' 36.3"	HSMITH	AGN_A A	78
I Zw 1	0h 53m 34.9s	12d 41' 36.3"	HSMITH	AGN_A A	32
UGC 00966	1h 24m 34.8s	3d 47' 30.0"	HSMITH	IRBGALS A	23
M83 Nucleus	13h 37m 00.3s	-29d 51' 51.3"	HSMITH	GALXISM A	55
M83 N01	13h 37m 00.3s	-29d 51' 51.3"	HSMITH	GALXISM A	74
IC 133	1h 33m 16.3s	30d 52' 51.9"	HSMITH	GALXISM A	72
NGC 604	1h 34m 32.8s	30d 47' 00.6"	HSMITH	GALXISM A	71
NGC 595	1h 33m 33.9s	30d 41' 30.3"	HSMITH	GALXISM A	70
CENTAURUS A	13h 25m 27.6s	-43d 01' 08.6"	HSMITH	IRBGALS A	9
Cen A OFF	13h 25m 27.4s	-42d 51' 08.6"	HSMITH	IRBGALS A	37
Cen A map	13h 25m 30.2s	-43d 01' 20.6"	HSMITH	IRBGALS A	51
M83 SE	13h 37m 06.4s	-29d 52' 39.2"	HSMITH	GALXISM A	54
SAGA 20N	17h 45m 40.0s	-29d 00' 08.6"	HSMITH	GCENTER A	27
SAGA L179	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	37
SAGA L63	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	34
SAGA L53	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	40
SAGA L185	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	41
SAGA R117A	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	42
SAGA R78	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	38
SAGA R110	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	30
SAGA L122	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	36
SAGA L88	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	35
SAGA R123	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	43
SAGA R159	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	46
SAGA R152	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	45
SAGA R145A	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	44
I Zw 92	14h 40m 38.1s	53d 30' 15.8"	HSMITH	AGN_A A	86
2235-03	22h 38m 22.3s	-2d 45' 52.6"	HSMITH	AGN_A A	30
2235-03	22h 38m 22.3s	-2d 45' 52.6"	HSMITH	AGN_A A	35
Fairall 9	1h 23m 45.7s	-58d 48' 20.4"	HSMITH	AGN_A A	36
I Zw 92	14h 40m 38.1s	53d 30' 15.8"	HSMITH	AGN_A A	5
0100+13	1h 03m 11.3s	13d 16' 17.0"	HSMITH	AGN_A A	12

0100+13	1h 03m 11.3s	13d 16' 17.0"	HSMITH	AGN_A A	92
Mkn 573	1h 43m 57.7s	2d 20' 59.7"	HSMITH	AGN_A A	90
Mkn 463	13h 56m 02.9s	18d 22' 18.0"	HSMITH	AGN_A A	89
MRK 231 OH	12h 56m 14.2s	56d 52' 24.9"	HSMITH	IRBGALS A	41
NGC 1068 Rep1	2h 42m 40.7s	-0d 00' 47.7"	HSMITH	AGN_A A	1
NGC 1068 off-rep	2h 42m 40.8s	0d 05' 12.3"	HSMITH	AGN_A A	41
NGC 1068 off-rep	2h 42m 40.8s	0d 05' 12.3"	HSMITH	AGN_A A	61
NGC 1068 Rep2	2h 42m 40.7s	-0d 00' 47.7"	HSMITH	AGN_A A	83
MRK273	13h 44m 41.6s	55d 53' 18.7"	HSMITH	OHMEGA A	4
ARP 220 lines	15h 34m 57.2s	23d 30' 11.2"	HSMITH	IRBGALS A	59
NGC891 NE	2h 22m 37.5s	42d 22' 50.4"	HSMITH	GALXISM A	57
NGC891 Nucleuss	2h 22m 33.0s	42d 20' 55.6"	HSMITH	GALXISM A	56
NGC891 SW1	2h 22m 28.6s	42d 19' 00.8"	HSMITH	GALXISM A	58
MRK273	13h 44m 41.6s	55d 53' 18.7"	HSMITH	OHMEGA A	5
NGC891 Z	2h 22m 33.0s	42d 20' 55.6"	HSMITH	GALXISM A	60
IC 4329A	13h 49m 19.3s	-30d 18' 34.2"	HSMITH	AGN_A A	93
CENTAURUS A	13h 25m 27.6s	-43d 01' 08.6"	HSMITH	IRBGALS A	64
HB89 1821+643	18h 21m 57.2s	64d 20' 36.3"	HSMITH	AGN_A A	11
HB89 1821+643	18h 21m 57.2s	64d 20' 36.3"	HSMITH	AGN_A A	6
HB89 1821+643	18h 21m 57.2s	64d 20' 36.3"	HSMITH	AGN_A A	10
1700+64	17h 01m 00.4s	64d 12' 09.1"	HSMITH	AGN_A_2 A	20
1700+64	17h 01m 00.4s	64d 12' 09.1"	HSMITH	AGN_A_2 A	26
M83 NW	13h 36m 57.9s	-29d 50' 47.4"	HSMITH	GALXISM A	53
IC342 MAP	3h 46m 49.7s	68d 05' 45.0"	HSMITH	GALXISM A	2
NGC 1068 HR1	2h 42m 40.7s	-0d 00' 47.7"	HSMITH	AGN_A A	54
NGC 1068 HR2	2h 42m 40.7s	-0d 00' 47.7"	HSMITH	AGN_A A	91
NGC 1068 HR1	2h 42m 40.7s	-0d 00' 47.7"	HSMITH	AGN_A_2 A	1
IRAS17208-0014	17h 23m 21.9s	-0d 17' 01.1"	HSMITH	OHMEGA A	8
IRAS17208-0014	17h 23m 21.9s	-0d 17' 01.1"	HSMITH	OHMEGA A	7
Mkn 6	6h 52m 12.4s	74d 25' 37.5"	HSMITH	AGN_A A	62
Mrk 3	6h 15m 36.4s	71d 02' 15.2"	HSMITH	AGN_A A	64
IRAS1520+3342	15h 22m 38.1s	33d 31' 33.3"	HSMITH	IRBGALS A	22
ARP 220 CII	15h 34m 57.2s	23d 30' 11.2"	HSMITH	IRBGALS A	65
ARP 220 CII	15h 34m 57.2s	23d 30' 11.2"	HSMITH	IRBGALS A	66
ARP 220 CII	15h 34m 57.2s	23d 30' 11.2"	HSMITH	IRBGALS A	67
II Zw40	5h 55m 42.6s	3d 23' 31.5"	HSMITH	GALXISM A	99
GCENT PISTOL	17h 46m 09.4s	-28d 48' 07.4"	HSMITH	GCENTER A	2
SAGAW	17h 45m 40.0s	-29d 00' 28.6"	HSMITH	GCENTER A	10
NGC 2146	6h 18m 38.7s	78d 21' 23.9"	HSMITH	GALXISM A	65
Mkn 3	6h 15m 36.4s	71d 02' 15.2"	HSMITH	AGN_A A	87
Mkn 6	6h 52m 12.4s	74d 25' 37.5"	HSMITH	AGN_A A	77
NGC7469	23h 03m 15.4s	8d 52' 25.4"	HSMITH	OHMEGA A	14
NGC7469	23h 03m 15.4s	8d 52' 25.4"	HSMITH	OHMEGA A	13
0050-25	0h 52m 44.7s	-25d 06' 53.0"	HSMITH	AGN_A_2 A	38
0050-25	0h 52m 44.7s	-25d 06' 53.0"	HSMITH	AGN_A_2 A	42
III Zw 107	23h 30m 09.9s	25d 31' 59.9"	HSMITH	GALXISM A	19
NGC1566-25.9	4h 20m 00.6s	-54d 56' 17.2"	HSMITH	AGN_A_2 A	13
Mkn 573	1h 43m 57.8s	2d 20' 59.7"	HSMITH	AGN_A A	73
NGC1316CII	3h 22m 41.5s	-37d 12' 33.6"	HSMITH	IRBGALS A	83
NGC1316-88	3h 22m 41.5s	-37d 12' 33.6"	HSMITH	IRBGALS A	84
NGC1316-88	3h 22m 41.5s	-37d 12' 33.6"	HSMITH	IRBGALS A	85
NGC1316-63	3h 22m 41.5s	-37d 12' 33.6"	HSMITH	IRBGALS A	88
NGC1316-63	3h 22m 41.5s	-37d 12' 33.6"	HSMITH	IRBGALS A	87
NGC1316-63	3h 22m 41.5s	-37d 12' 33.6"	HSMITH	IRBGALS A	86
NGC 592	1h 33m 11.7s	30d 38' 43.0"	HSMITH	GALXISM A	69
IC 142	1h 33m 55.2s	30d 45' 23.7"	HSMITH	GALXISM A	73

NGC 588	1h	32m	45.6s	30d	38'	53.7"	HSMITH	GALXISM	A	68
M33 Nucleus	1h	33m	50.9s	30d	39'	36.8"	HSMITH	GALXISM	A	67
NGC891 SW2	2h	22m	21.5s	42d	15'	57.1"	HSMITH	GALXISM	A	59
3C 120	4h	33m	11.1s	5d	21'	15.9"	HSMITH	AGN_A	A	88
3C 120	4h	33m	11.1s	5d	21'	15.9"	HSMITH	AGN_A	A	2
NGC6240-57	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	71
NGC6240-57	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	72
NGC6240-57	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	73
NGC6240-57	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	74
NGC 1097-74-3	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	66
NGC6240-57	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	75
NGC6240-52	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	77
NGC6240-57	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	76
NGC6240-52	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	79
NGC6240-52	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	80
NGC6240-52	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	81
NGC6240-52	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	82
NGC6240-52	16h	52m	58.8s	2d	24'	04.3"	HSMITH	IRBGALS	A	78
MKN 1073-25.9	3h	15m	01.4s	42d	02'	09.2"	HSMITH	AGN_A_2	A	17
NGC 1097-FS3	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	63
NGC 1097-74-1	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	64
NGC 1097-79-1	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	68
NGC 1097-163-2	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	73
NGC 1097-79-2	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	69
NGC 1097-79-3	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	70
NGC 1097-79-4	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	71
NGC 1097-74-4	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	67
NGC 1097-74-2	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	65
NGC 1097-FS2	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	62
NGC 1097-163-1	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	72
NGC 1097-FS1	2h	46m	18.7s	-30d	16'	32.2"	HSMITH	AGN_A_2	A	61
MKN 1073-7.6	3h	15m	01.4s	42d	02'	09.2"	HSMITH	AGN_A_2	A	14
MKN 1073-24.3	3h	15m	01.4s	42d	02'	09.2"	HSMITH	AGN_A_2	A	16
MKN 1073-14.3	3h	15m	01.4s	42d	02'	09.2"	HSMITH	AGN_A_2	A	15
SAGA R148	17h	45m	40.0s	-29d	00'	28.6"	HSMITH	GCENTER	A	48
ION NEW	17h	45m	44.1s	-28d	56'	55.3"	HSMITH	GCENTER	A	12
SAGA R84	17h	45m	40.0s	-29d	00'	28.6"	HSMITH	GCENTER	A	39
SAGA R145A	17h	45m	40.0s	-29d	00'	28.6"	HSMITH	GCENTER	A	47
SAGA R1555	17h	45m	40.0s	-29d	00'	28.6"	HSMITH	GCENTER	A	50
Q0307-49	3h	07m	22.9s	-49d	45'	47.7"	HSMITH	AGN_A_2	A	27
Q0307-49	3h	07m	22.9s	-49d	45'	47.7"	HSMITH	AGN_A_2	A	28
NGC1614	4h	33m	59.8s	-8d	34'	29.7"	HSMITH	OHMEGA	A	10
NGC1614	4h	33m	59.8s	-8d	34'	29.7"	HSMITH	OHMEGA	A	9
IRAS 19297-0406	19h	32m	22.1s	-4d	00'	02.2"	HSMITH	IRBGALS2	A	11
IRAS 20100-4156	20h	13m	29.7s	-41d	47'	35.0"	HSMITH	IRBGALS2	A	13
FSC05189-2524-7	5h	21m	01.4s	-25d	21'	45.0"	HSMITH	AGN_A_2	A	19
NGC1808	5h	07m	42.2s	-37d	30'	48.6"	HSMITH	IRBGALS2	A	10
IRAS 20087-0308	20h	11m	23.2s	-2d	59'	54.3"	HSMITH	IRBGALS2	A	12
SAGA R151	17h	45m	40.0s	-29d	00'	28.6"	HSMITH	GCENTER	A	49
NGC6328	17h	23m	41.0s	-65d	00'	36.6"	HSMITH	AGN_A_2	A	2
NGC6328	17h	23m	41.0s	-65d	00'	36.6"	HSMITH	AGN_A_2	A	3
NGC 7469-88	23h	03m	15.6s	8d	52'	26.4"	HSMITH	AGN_A_2	A	4
NGC 1566-63	4h	20m	00.6s	-54d	56'	17.2"	HSMITH	AGN_A_2	A	5
NGC 1566-88	4h	20m	00.6s	-54d	56'	17.2"	HSMITH	AGN_A_2	A	6
NGC 1566-158	4h	20m	00.6s	-54d	56'	17.2"	HSMITH	AGN_A_2	A	7
NGC 1566-7.6	4h	20m	00.6s	-54d	56'	17.2"	HSMITH	AGN_A_2	A	8

NGC 1566-12.8	4h 20m 00.6s	-54d 56' 17.2"	HSMITH	AGN_A_2 A	9
NGC1566-14.3	4h 20m 00.6s	-54d 56' 17.2"	HSMITH	AGN_A_2 A	10
NGC1566-15.6	4h 20m 00.6s	-54d 56' 17.2"	HSMITH	AGN_A_2 A	11
NGC1566-24.3	4h 20m 00.6s	-54d 56' 17.2"	HSMITH	AGN_A_2 A	12
FSC05189-2524-24	5h 21m 01.4s	-25d 21' 45.0"	HSMITH	AGN_A_2 A	22
IIIZW35	1h 44m 30.7s	17d 06' 09.5"	HSMITH	OHMEGA A	2
NGC6240	16h 52m 58.7s	2d 24' 03.8"	HSMITH	OHMEGA A	11
IIIZw35	1h 44m 30.7s	17d 06' 09.5"	HSMITH	OHMEGA A	1
IIIZW35	1h 44m 30.7s	17d 06' 09.5"	HSMITH	OHMEGA A	6

INS	NR	TDT	REV	STATUS	SCHEDULED START TIME	ACTUAL START TIME
LWS	1	1173	81	Observed	6 Feb 1996 19:43:52	6 Feb 1996 19:43:5
LWS	1	1013	81	Observed	6 Feb 1996 20:00:53	6 Feb 1996 20:00:5
PHT	32	1722	170	Observed	4 May 1996 23:22:40	4 May 1996 23:22:4
PHT	32	1722	170	Observed	5 May 1996 02:15:44	5 May 1996 02:15:4
SWS	2	7663	170	Observed	5 May 1996 07:43:54	5 May 1996 07:43:5
LWS	1	10327	170	Observed	5 May 1996 09:48:48	5 May 1996 09:48:4

SWS	1	6758	170	Observed	5 May 1996 12:40:46	5 May 1996 12:40:47
PHT	32	1722	178	Observed	13 May 1996 08:57:44	13 May 1996 08:57:44
LWS	1	10487	178	Aborted	13 May 1996 10:25:03	13 May 1996 10:25:04
SWS	1	6598	178	Aborted	13 May 1996 13:17:01	13 May 1996 13:17:02
PHT	22	1045	178	Failed	13 May 1996 15:06:50	
SWS	1	6758	179	Observed	14 May 1996 11:06:44	14 May 1996 11:06:45
PHT	32	1722	180	Observed	15 May 1996 01:25:22	15 May 1996 01:25:22
LWS	1	1311	180	Observed	15 May 1996 01:55:52	15 May 1996 01:55:52
LWS	1	2181	180	Observed	15 May 1996 02:15:25	15 May 1996 02:15:26
LWS	2	561	180	Observed	15 May 1996 02:49:18	15 May 1996 02:49:18
LWS	2	6597	180	Observed	15 May 1996 03:02:22	15 May 1996 03:02:22
LWS	1	3485	180	Observed	15 May 1996 04:52:17	15 May 1996 04:52:18
LWS	2	673	180	Observed	15 May 1996 05:47:50	15 May 1996 05:47:50
PHT	32	1722	180	Observed	15 May 1996 10:37:01	15 May 1996 10:37:02
LWS	1	3041	180	Observed	15 May 1996 11:05:32	15 May 1996 11:05:32
LWS	2	631	180	Observed	15 May 1996 11:53:45	15 May 1996 11:53:46
PHT	32	1722	181	Observed	16 May 1996 02:48:03	16 May 1996 02:48:03
LWS	2	665	184	Observed	19 May 1996 15:13:03	19 May 1996 15:13:03
LWS	2	763	186	Observed	21 May 1996 02:26:45	21 May 1996 02:26:45
LWS	2	1781	194	Observed	29 May 1996 02:26:07	29 May 1996 02:26:08
LWS	2	1781	194	Observed	29 May 1996 02:53:09	29 May 1996 02:53:10
LWS	1	2181	194	Observed	29 May 1996 03:20:09	29 May 1996 03:20:10
LWS	4	2093	194	Observed	29 May 1996 03:53:41	29 May 1996 03:53:42
LWS	4	2093	194	Observed	29 May 1996 04:25:45	29 May 1996 04:25:46
LWS	4	2445	194	Observed	29 May 1996 04:57:49	29 May 1996 04:57:50
LWS	4	1917	194	Observed	29 May 1996 06:15:23	29 May 1996 06:15:24
SWS	1	6750	195	Observed	30 May 1996 09:54:57	30 May 1996 09:54:57
LWS	1	10487	197	Failed	1 Jun 1996 07:05:07	
LWS	1	10327	197	Failed	1 Jun 1996 09:57:15	
PHT	32	1722	198	Observed	2 Jun 1996 04:40:13	2 Jun 1996 04:40:14
PHT	32	1722	211	Observed	14 Jun 1996 22:04:05	14 Jun 1996 22:04:05
PHT	32	1722	211	Observed	15 Jun 1996 00:10:57	15 Jun 1996 00:10:57
PHT	22	1205	238	Observed	11 Jul 1996 19:07:37	11 Jul 1996 19:07:37
LWS	1	10337	238	Observed	11 Jul 1996 19:24:53	11 Jul 1996 19:24:53
LWS	1	1479	240	Observed	14 Jul 1996 08:31:09	14 Jul 1996 08:31:10
LWS	2	515	240	Observed	14 Jul 1996 08:53:14	14 Jul 1996 08:53:14
PHT	22	1141	241	Observed	14 Jul 1996 23:49:28	14 Jul 1996 23:49:29
LWS	1	10337	241	Observed	15 Jul 1996 00:05:40	15 Jul 1996 00:05:41
LWS	2	12201	242	Failed	16 Jul 1996 03:56:58	
LWS	2	2211	246	Observed	19 Jul 1996 21:46:50	19 Jul 1996 21:46:50
LWS	1	4135	247	Observed	21 Jul 1996 04:36:34	21 Jul 1996 04:36:34
LWS	2	745	247	Observed	21 Jul 1996 05:43:13	21 Jul 1996 05:43:14
LWS	2	1623	247	Observed	21 Jul 1996 05:56:02	21 Jul 1996 05:56:02
LWS	1	4355	253	Observed	27 Jul 1996 01:07:58	27 Jul 1996 01:07:58
LWS	2	885	253	Observed	27 Jul 1996 02:18:04	27 Jul 1996 02:18:04
PHT	32	1722	257	Observed	31 Jul 1996 01:56:11	31 Jul 1996 01:56:11
PHT	32	1722	270	Observed	13 Aug 1996 04:44:31	13 Aug 1996 04:44:32
LWS	1	12973	278	Observed	20 Aug 1996 16:36:25	20 Aug 1996 16:36:25
LWS	2	1513	278	Observed	20 Aug 1996 20:10:02	20 Aug 1996 20:10:03
LWS	1	4355	278	Observed	21 Aug 1996 02:09:16	21 Aug 1996 02:09:16
LWS	2	885	278	Observed	21 Aug 1996 03:19:16	21 Aug 1996 03:19:16
LWS	1	2191	280	Observed	22 Aug 1996 16:59:55	22 Aug 1996 16:59:55
LWS	2	571	280	Observed	22 Aug 1996 17:33:53	22 Aug 1996 17:33:54
LWS	2	1225	280	Observed	22 Aug 1996 17:43:31	22 Aug 1996 17:43:32
LWS	2	1225	280	Observed	22 Aug 1996 18:03:56	22 Aug 1996 18:03:56
LWS	2	1225	280	Observed	22 Aug 1996 18:24:25	22 Aug 1996 18:24:26

LWS	2	1435	280	Observed	23 Aug 1996 06:26:07	23 Aug 1996 06:26:08
LWS	1	1029	287	Observed	30 Aug 1996 03:05:26	30 Aug 1996 03:05:26
LWS	1	11859	290	Observed	2 Sep 1996 01:28:06	2 Sep 1996 01:28:07
LWS	1	11859	301	Failed	12 Sep 1996 18:14:20	
LWS	1	2131	302	Observed	13 Sep 1996 23:29:15	13 Sep 1996 23:29:15
LWS	2	675	309	Observed	20 Sep 1996 23:17:54	20 Sep 1996 23:17:54
LWS	2	1987	351	Observed	1 Nov 1996 15:08:09	1 Nov 1996 15:08:09
LWS	1	1727	351	Observed	1 Nov 1996 16:51:14	1 Nov 1996 16:51:15
LWS	2	2153	351	Observed	1 Nov 1996 17:17:22	1 Nov 1996 17:17:23
LWS	1	3219	353	Observed	3 Nov 1996 12:31:57	3 Nov 1996 12:31:57
LWS	1	3219	353	Observed	3 Nov 1996 13:23:00	3 Nov 1996 13:23:01
LWS	1	3219	354	Observed	4 Nov 1996 12:29:08	4 Nov 1996 12:29:08
LWS	1	2781	354	Observed	4 Nov 1996 13:19:58	4 Nov 1996 13:19:58
LWS	2	1417	354	Observed	4 Nov 1996 17:49:53	4 Nov 1996 17:49:53
LWS	1	2781	357	Observed	7 Nov 1996 12:20:25	7 Nov 1996 12:20:26
LWS	1	2781	357	Observed	7 Nov 1996 13:04:10	7 Nov 1996 13:04:10
LWS	1	2781	358	Observed	8 Nov 1996 12:17:25	8 Nov 1996 12:17:25
SWS	2	3203	361	Observed	12 Nov 1996 04:06:52	12 Nov 1996 04:06:53
SWS	2	1793	365	Observed	15 Nov 1996 18:58:17	15 Nov 1996 18:58:17
LWS	2	8745	371	Observed	22 Nov 1996 00:03:53	22 Nov 1996 00:03:54
LWS	1	1301	375	Observed	26 Nov 1996 01:28:40	26 Nov 1996 01:28:41
SWS	2	1589	378	Observed	28 Nov 1996 13:29:04	28 Nov 1996 13:29:04
SWS	2	2263	380	Observed	30 Nov 1996 16:42:24	30 Nov 1996 16:42:24
SWS	2	2103	380	Observed	30 Nov 1996 17:17:24	30 Nov 1996 17:17:24
PHT	22	1205	395	Observed	15 Dec 1996 21:43:09	15 Dec 1996 21:43:10
SWS	2	24488	403	Observed	23 Dec 1996 18:55:36	23 Dec 1996 18:55:37
SWS	2	1119	409	Observed	30 Dec 1996 02:22:38	30 Dec 1996 02:22:38
LWS	2	941	447	Observed	5 Feb 1997 10:34:19	5 Feb 1997 10:34:19
LWS	1	1191	447	Observed	5 Feb 1997 10:47:11	5 Feb 1997 10:47:11
LWS	2	1023	451	Observed	9 Feb 1997 21:02:54	9 Feb 1997 21:02:54
LWS	2	1023	451	Observed	9 Feb 1997 21:17:35	9 Feb 1997 21:17:36
LWS	2	1023	451	Observed	9 Feb 1997 21:32:07	9 Feb 1997 21:32:08
LWS	1	1529	454	Observed	12 Feb 1997 07:20:10	12 Feb 1997 07:20:11
LWS	2	565	454	Observed	12 Feb 1997 07:43:06	12 Feb 1997 07:43:07
LWS	2	1785	454	Observed	12 Feb 1997 07:52:38	12 Feb 1997 07:52:39
LWS	2	6191	454	Observed	12 Feb 1997 08:24:54	12 Feb 1997 08:24:55
LWS	1	9724	464	Observed	22 Feb 1997 18:17:29	22 Feb 1997 18:17:30
LWS	4	2151	469	Observed	27 Feb 1997 13:32:20	27 Feb 1997 13:32:21
LWS	4	3019	469	Observed	27 Feb 1997 15:04:31	27 Feb 1997 15:04:31
LWS	4	7537	469	Observed	27 Feb 1997 18:29:02	27 Feb 1997 18:29:02
LWS	4	1519	469	Observed	27 Feb 1997 20:31:50	27 Feb 1997 20:31:50
LWS	3	8055	476	Observed	6 Mar 1997 10:50:06	6 Mar 1997 10:50:07
LWS	3	9927	507	Observed	6 Apr 1997 04:13:50	6 Apr 1997 04:13:50
LWS	3	6555	507	Observed	6 Apr 1997 08:45:17	6 Apr 1997 08:45:17
LWS	4	2959	507	Observed	6 Apr 1997 17:48:39	6 Apr 1997 17:48:39
LWS	4	1171	507	Observed	6 Apr 1997 19:44:56	6 Apr 1997 19:44:57
LWS	3	5529	508	Observed	7 Apr 1997 04:10:02	7 Apr 1997 04:10:02
LWS	3	5765	508	Observed	7 Apr 1997 18:23:59	7 Apr 1997 18:24:00
LWS	3	11811	509	Observed	8 Apr 1997 04:06:10	8 Apr 1997 04:06:11
LWS	3	10651	509	Observed	8 Apr 1997 12:49:08	8 Apr 1997 12:49:09
LWS	2	4383	543	Observed	12 May 1997 07:12:18	12 May 1997 07:12:18
PHT	22	942	545	Observed	14 May 1997 08:13:49	14 May 1997 08:13:49
PHT	22	782	545	Observed	14 May 1997 08:26:49	14 May 1997 08:26:49
PHT	22	2668	553	Observed	22 May 1997 10:22:56	22 May 1997 10:22:56
SWS	2	6823	561	Observed	30 May 1997 06:21:33	30 May 1997 06:21:33
PHT	22	942	577	Observed	15 Jun 1997 00:58:02	15 Jun 1997 00:58:03

PHT	22	782	577	Observed	15 Jun 1997 01:11:02	15 Jun 1997 01:11:03
LWS	2	4387	586	Observed	24 Jun 1997 11:53:03	24 Jun 1997 11:53:03
LWS	2	3567	602	Observed	10 Jul 1997 05:11:03	10 Jul 1997 05:11:04
LWS	1	4205	603	Observed	11 Jul 1997 00:47:57	11 Jul 1997 00:47:57
LWS	1	7865	605	Observed	13 Jul 1997 01:33:00	13 Jul 1997 01:33:01
LWS	2	1695	605	Observed	13 Jul 1997 03:41:28	13 Jul 1997 03:41:28
LWS	2	1695	605	Observed	13 Jul 1997 08:05:37	13 Jul 1997 08:05:38
LWS	1	7865	605	Observed	13 Jul 1997 08:31:15	13 Jul 1997 08:31:16
SWS	6	2224	610	Observed	18 Jul 1997 04:18:51	18 Jul 1997 04:18:52
LWS	2	6355	610	Observed	18 Jul 1997 10:18:14	18 Jul 1997 10:18:14
LWS	2	1887	611	Observed	18 Jul 1997 22:11:21	18 Jul 1997 22:11:22
LWS	1	1793	611	Observed	18 Jul 1997 22:40:05	18 Jul 1997 22:40:06
LWS	2	1887	611	Observed	18 Jul 1997 23:07:15	18 Jul 1997 23:07:16
LWS	1	4205	614	Observed	22 Jul 1997 06:48:49	22 Jul 1997 06:48:50
LWS	2	2199	614	Observed	22 Jul 1997 10:17:17	22 Jul 1997 10:17:18
LWS	2	2975	630	Observed	7 Aug 1997 03:50:24	7 Aug 1997 03:50:25
LWS	1	2801	634	Observed	11 Aug 1997 02:02:01	11 Aug 1997 02:02:01
LWS	1	9749	635	Observed	12 Aug 1997 08:27:13	12 Aug 1997 08:27:13
SWS	1	6590	635	Observed	12 Aug 1997 11:06:53	12 Aug 1997 11:06:53
PHT	22	1045	635	Observed	12 Aug 1997 12:56:34	12 Aug 1997 12:56:35
PHT	22	942	638	Observed	15 Aug 1997 05:29:42	15 Aug 1997 05:29:42
PHT	22	782	638	Observed	15 Aug 1997 05:42:42	15 Aug 1997 05:42:42
LWS	2	8047	642	Observed	18 Aug 1997 20:26:40	18 Aug 1997 20:26:40
LWS	1	9653	646	Observed	23 Aug 1997 00:36:31	23 Aug 1997 00:36:32
LWS	3	7561	649	Observed	26 Aug 1997 05:13:05	26 Aug 1997 05:13:06
LWS	3	7561	649	Observed	26 Aug 1997 07:16:17	26 Aug 1997 07:16:18
LWS	3	7561	649	Observed	26 Aug 1997 09:19:29	26 Aug 1997 09:19:30
LWS	1	2327	650	Observed	26 Aug 1997 23:20:00	26 Aug 1997 23:20:01
SWS	6	1280	650	Observed	26 Aug 1997 23:55:58	26 Aug 1997 23:55:59
SWS	2	6921	658	Observed	4 Sep 1997 01:11:10	4 Sep 1997 01:11:10
SWS	2	13133	658	Observed	4 Sep 1997 04:17:58	4 Sep 1997 04:17:58
LWS	2	1823	660	Observed	5 Sep 1997 19:54:23	5 Sep 1997 19:54:24
LWS	3	3265	667	Observed	12 Sep 1997 18:57:04	12 Sep 1997 18:57:04
LWS	3	3265	667	Observed	12 Sep 1997 19:48:40	12 Sep 1997 19:48:40
LWS	3	3265	667	Observed	12 Sep 1997 20:40:16	12 Sep 1997 20:40:16
LWS	1	2081	667	Observed	13 Sep 1997 05:15:48	13 Sep 1997 05:15:48
LWS	1	7535	677	Observed	22 Sep 1997 23:04:01	22 Sep 1997 23:04:01
LWS	1	1517	677	Observed	23 Sep 1997 01:56:41	23 Sep 1997 01:56:42
LWS	1	1361	679	Observed	24 Sep 1997 18:12:40	24 Sep 1997 18:12:41
LWS	2	4295	705	Observed	21 Oct 1997 02:51:58	21 Oct 1997 02:51:58
LWS	2	3511	705	Observed	21 Oct 1997 04:02:05	21 Oct 1997 04:02:06
LWS	1	3173	736	Observed	21 Nov 1997 00:39:08	21 Nov 1997 00:39:08
SWS	6	1244	736	Observed	21 Nov 1997 01:29:12	21 Nov 1997 01:29:12
PHT	22	942	744	Observed	28 Nov 1997 14:31:57	28 Nov 1997 14:31:58
PHT	22	782	744	Observed	28 Nov 1997 14:44:57	28 Nov 1997 14:44:58
LWS	1	4967	758	Observed	12 Dec 1997 19:25:51	12 Dec 1997 19:25:51
SWS	2	1262	791	Observed	14 Jan 1998 19:47:57	14 Jan 1998 19:47:57
SWS	2	6420	803	Observed	26 Jan 1998 10:34:58	26 Jan 1998 10:34:58
LWS	2	1363	803	Observed	26 Jan 1998 17:09:04	26 Jan 1998 17:09:04
LWS	2	1409	803	Observed	26 Jan 1998 17:28:58	26 Jan 1998 17:28:59
LWS	2	1409	803	Observed	26 Jan 1998 17:49:38	26 Jan 1998 17:49:39
LWS	2	1611	803	Observed	26 Jan 1998 18:10:18	26 Jan 1998 18:10:19
LWS	2	1611	803	Observed	26 Jan 1998 18:34:20	26 Jan 1998 18:34:21
LWS	2	1611	803	Observed	26 Jan 1998 18:58:22	26 Jan 1998 18:58:23
LWS	2	1023	805	Observed	28 Jan 1998 18:46:32	28 Jan 1998 18:46:33
LWS	2	1023	805	Observed	28 Jan 1998 19:01:03	28 Jan 1998 19:01:03

LWS	2	1023	808	Observed	31	Jan	1998	10:23:09	31	Jan	1998	10:23:1(
LWS	2	1023	808	Observed	31	Jan	1998	10:37:42	31	Jan	1998	10:37:4:
LWS	2	1775	808	Observed	31	Jan	1998	15:33:20	31	Jan	1998	15:33:2(
LWS	2	5051	809	Observed	2	Feb	1998	00:03:09	2	Feb	1998	00:03:1(
SWS	2	6415	809	Observed	2	Feb	1998	01:24:31	2	Feb	1998	01:24:3:
LWS	2	1451	810	Observed	2	Feb	1998	13:03:25	2	Feb	1998	13:03:2(
LWS	2	1451	810	Observed	2	Feb	1998	13:24:47	2	Feb	1998	13:24:4{
LWS	2	1451	810	Observed	2	Feb	1998	13:46:09	2	Feb	1998	13:46:1(
LWS	2	1451	810	Observed	2	Feb	1998	14:07:31	2	Feb	1998	14:07:3:
LWS	2	1115	813	Observed	5	Feb	1998	18:31:16	5	Feb	1998	18:31:1(
LWS	2	1451	816	Observed	8	Feb	1998	11:36:33	8	Feb	1998	11:36:3:
LWS	2	1151	816	Observed	8	Feb	1998	11:57:55	8	Feb	1998	11:57:5!
LWS	2	1451	816	Observed	8	Feb	1998	12:14:17	8	Feb	1998	12:14:1:
LWS	2	1151	816	Observed	8	Feb	1998	12:35:39	8	Feb	1998	12:35:3!
LWS	2	1151	816	Observed	8	Feb	1998	12:52:01	8	Feb	1998	12:52:01
LWS	2	1151	816	Observed	8	Feb	1998	13:08:23	8	Feb	1998	13:08:2:
LWS	2	1151	816	Observed	8	Feb	1998	13:24:45	8	Feb	1998	13:24:4!
LWS	2	1151	816	Observed	8	Feb	1998	13:41:07	8	Feb	1998	13:41:0:
SWS	2	1732	816	Observed	9	Feb	1998	02:06:46	9	Feb	1998	02:06:4:
LWS	1	1841	819	Observed	11	Feb	1998	09:45:21	11	Feb	1998	09:45:2:
LWS	2	1115	819	Observed	11	Feb	1998	10:13:13	11	Feb	1998	10:13:1:
LWS	2	1115	819	Observed	11	Feb	1998	11:43:59	11	Feb	1998	11:44:0(
LWS	2	911	819	Observed	11	Feb	1998	11:59:45	11	Feb	1998	11:59:4(
LWS	2	1115	819	Observed	11	Feb	1998	12:12:07	11	Feb	1998	12:12:0{
LWS	2	1115	819	Observed	11	Feb	1998	12:27:53	11	Feb	1998	12:27:5:
LWS	2	1115	819	Observed	11	Feb	1998	12:43:39	11	Feb	1998	12:43:4(
LWS	2	1115	819	Observed	11	Feb	1998	12:59:25	11	Feb	1998	12:59:2(
LWS	2	1115	819	Observed	11	Feb	1998	13:15:11	11	Feb	1998	13:15:1:
LWS	1	1841	819	Observed	11	Feb	1998	13:30:57	11	Feb	1998	13:30:5{
LWS	2	911	819	Observed	11	Feb	1998	13:58:49	11	Feb	1998	13:58:5(
LWS	1	1841	820	Observed	12	Feb	1998	09:42:12	12	Feb	1998	09:42:1:
SWS	2	1262	840	Observed	4	Mar	1998	20:37:21	4	Mar	1998	20:37:2:
SWS	2	1262	840	Observed	4	Mar	1998	20:55:34	4	Mar	1998	20:55:3:
SWS	2	1732	840	Observed	4	Mar	1998	21:13:47	4	Mar	1998	21:13:4{
LWS	3	5727	849	Observed	13	Mar	1998	10:00:40	13	Mar	1998	10:00:41
LWS	1	1517	849	Observed	13	Mar	1998	12:09:09	13	Mar	1998	12:09:0!
LWS	3	6567	850	Observed	14	Mar	1998	08:06:16	14	Mar	1998	08:06:1(
LWS	3	5665	850	Observed	14	Mar	1998	09:52:54	14	Mar	1998	09:52:5:
LWS	3	5619	850	Observed	14	Mar	1998	11:24:30	14	Mar	1998	11:24:3(
PHT	22	942	855	Observed	19	Mar	1998	09:25:24	19	Mar	1998	09:25:2:
PHT	22	782	855	Observed	19	Mar	1998	09:38:24	19	Mar	1998	09:38:2:
LWS	1	2625	855	Observed	19	Mar	1998	17:25:45	19	Mar	1998	17:25:4(
SWS	6	1244	855	Observed	19	Mar	1998	18:06:41	19	Mar	1998	18:06:4:
LWS	2	3165	857	Observed	21	Mar	1998	08:46:28	21	Mar	1998	08:46:2{
LWS	2	9899	859	Observed	23	Mar	1998	16:50:06	23	Mar	1998	16:50:0(
SWS	2	1497	870	Observed	3	Apr	1998	15:08:47	3	Apr	1998	15:08:4{
LWS	1	6347	999	Pending								
LWS	2	5523	999	Pending								
LWS	3	7031	999	Pending								
LWS	2	2195	999	Pending								
SWS	2	15178	999	Pending/Blocked								
LWS	2	1339	999	Pending								
LWS	2	1253	999	Pending								
LWS	2	1223	999	Pending								
LWS	2	987	999	Pending								
SWS	2	1262	999	Pending								

Table 2: PUBLICATIONS

Over 26 refereed papers have been published so far by Dr. Smith as part of this overall program, and another 31 papers have been presented at conference proceedings. Over 300 citations to these papers have been registered so far - note that many papers have only been published in the past two years. This represents a significant and important contribution, and we believe this grant -- on this basis alone – has been an unqualified success.

Publications supported in part by this Program, both in its current phase, and under its earlier grant numbers, are listed below (identifying numbers refer to running table of HAS publications):

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120. "The Rich Far Infrared Spectrum of Water Vapor in W Hya", Barlow, M.,.mand the LWS Consortium, Smith, H.A., *et al.*, *Astr. Ap.*, **315,** L241, 1996.

121. "The ISO LWS Grating Spectrum of NGC 7027", Liu,X.-W.,.and the LWS Consortium, Smith, H.A.,.*et al.*, . *Astr.Ap.*, **315,** L257, 1996.

122. "Extended Fine Structure and Continuum Emission from S140/L1204", Emery, R., and the LWS Consortium, Smith, H.A., *et al.*, *Astr. Ap.*, **315,** L 285, 1996

123. "LWS Observations of the Bright Rimmed Globule IC1396 N", Saraceno, P., and the LWS Consortium, Smith, H.A....*et al.*, Astr.Ap., **315,** L293, 1996.

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"[And] though I know that the speculations of a philosopher are far removed from the judgment of the multitude - for his aim is to seek truth in all things as far as God has permitted human reason so to do -- yet I hold that opinions which are quite erroneous should be avoided."

--Nicholaus Copernicus, *De Revolutionibus*, from the preface to Pope Paul III
(as cited in Theories of the Universe by Milton K. Munitz, 1957)

I. THE "JUDGMENT OF THE MULTITUDE"

Contrary to the sentiment Copernicus expressed to Pope Paul III circa 1542, today the "judgment of the multitude" is not far removed from the research of space science, or from its other activities for that matter. The pubic pays for them, and pays attention to them. The Federal government provides billions of dollars to the space science enterprise; state and private contributors also provide substantial funding. Progress in space science therefore depends upon public dollars, although continued financial support is only one reason -- perhaps not even the most important one -- why the space science community should be attentive to popular perceptions. In this article I will review our knowledge of the US public's attitudes, and will argue that vigorous and innovative education and outreach programs are important, and can be made even more effective.

In the US, space science enjoys broad popular support. People generally like it, and indeed say that they follow it with interest. Later in this article I will discuss some specific survey results (Sections II - V), and the somewhat paradoxical result that, despite being interested and supportive, people are often ignorant about the basic facts (Section V). The 1985 study by the Royal Society of Britain entitled, "The Public Understanding of Science" (Royal Society, 1985) is a landmark document in addressing the topic, and in the US, the NSF's series "Science and Engineering Indicators" (*S&EI*; National Science Board, 2000) is an ongoing, statistical study of public attitudes from which I draw many examples. Although these studies and their datasets have come under various levels of legitimate criticism (e.g., Irwin and Wynne, 1996; Section VI), I will argue that they provide useful and relatively self-consistent statistics from which to consider the state of the public's consciousness.

Why should we as scientists care about these social analyses, or the statistical subtleties of the public's knowledge, interest, or "understanding", especially when the methodology of such studies is under attack? First, despite their limitations, such surveys show that we (i.e., the space science community) can do better at public education – in none of the important measures of public response are the results close to "saturation." And secondly, they highlight disconcerting but redeemable public attributes, prompting me to suggest we ought to do better -- not in order to increase budgets, but because a scientifically literate society (not proficient, just literate) is essential to rational discourse and judgment in a millennium dominated by science and technology which to many people increasingly resembles sorcery. Space science, popular as it is according to all studies, is one of the most potent areas of inquiry which science has at its disposal to teach the facts and methods of modern scientific research. In Section VII, I look at basic research and the reasons for pursuing it, and note that there are intangible benefits to space research. In Section VIII, I will mention some outreach challenges, and two innovative programs.

The term "space science" encompasses a much wider arena of topics than simply astronomy or satellite-based research. The popular conception of the topic includes rockets and the technologies needed for rocket and shuttle launches, their control and tracking, and also the technologies for new instruments; the results of the National Air and Space Museum survey (see below) confirm this. The term rightly includes the manned aspects of space exploration, from the Apollo-to-the-Moon missions to future manned missions to Mars, as well as earth-orbiting space stations. Some of the surveys I will discuss make explicit distinctions between these various areas, but most often they do not.

II. ALL THE SURVEYS SAY THAT PEOPLE ARE INTERESTED

For over fifteen years the National Science Board of the National Science Foundation has taken "science indicator surveys" of the US public's relationships with science (National Science Board, 2000), asking people about their attitudes towards a wide range of science topics, including in particular space exploration but also medicine, nuclear power, environment, and technology. While this limited breakdown of science topics constrains some of our conclusions (and see below), it is adequate for most of the discussion. There have been ups and downs in the numbers over time, reflecting, for example, concerns after the explosion of the space shuttle Challenger, or budget deficits, but the general conclusions have been roughly the same: a huge number of Americans -- 77% in 1997 -- say they are very interested or moderately interested in space exploration. A majority of people also say they are interested in "new scientific discoveries"-- 91% -- so space science is not unique in its appeal, but it is remarkable in that it does not involve the immediate practical concerns of the other queried science topics like heath, the environment, or nuclear power. Indeed the second highest "not interested" response was to "space exploration" – 22% in 1997 (agricultural and farm issues was the highest at 26%). The largest difference in responses between male and female respondents, 30%, was for space exploration. Also noteworthy is the fact that expressed interest is about 50% greater in people with graduate degrees than in those who have not completed a high school education. By comparison, the 1998 survey done by the European Space Agency of the 14 ESA countries found that about 42% of the public said they were interested or very interested in space exploration.

During the time I was chairman of the astronomy program at the Smithsonian Institution's National Air and Space Museum (NASM) in Washington, D.C., the museum undertook a survey of its approximately 8 million annual visitors in an effort to understand why they came, and what they liked. It is useful to this article because it broke down the broad category of "space science" into subtopics. Most people came to the museum to see a bit of everything, but of those who came particularly to see an artifact or gallery (and excluding the IMAX theater) 45% came for aviation-related subjects and 35% came for the spacecraft, or astronomy galleries, or the planetarium shows. Those people who came with no specific special interest in mind were asked upon leaving what they had found the "most interesting." Forty-three percent said they found space science topics (spacecraft/astronomy/planetarium) "the most interesting", with the spacecraft artifacts being by far the most popular of these, by about 3:1. Forty-four percent said they found the aviation exhibits most interesting. The NASM artifacts are spectacular and inspirational, so it is perhaps not surprising that people want to see them; we will see below that space technology and manned exploration bring excitement to the whole space science endeavor. What is interesting from the study is the very strong showing of non-artifact based space science.

III. SPACE SCIENCE NEWS IS GENERALLY GOOD NEWS

The Pew Research Center for the People and the Press (quoted in *S&EI-2000*) has for over 15 years tracked the most closely followed news stories in the US. There were 689 of them, with 39 having some connection to science (including medicine, weather, and natural phenomena.) To an overwhelming degree these 39 science stories were bad news -- earthquakes or other calamities of nature, nuclear power, AIDS, or medical controversies. But virtually every *good news* science story was about space science: John Glenn's shuttle flight, the deployment of the Hubble, the Mars Pathfinder mission, and the cosmic microwave background. (The only positive, *non*-space, science news story was on Viagra, while only the negative space stories were the explosion of the Shuttle Challenger, and troubles with the Mir space station.)

Five Reasons for the Appeal of Space Science

Space science, as these news items suggest, makes people feel good about themselves; no doubt this is one reason why people say they like it. There are at least four other reasons which I believe are unique to astronomy and space science, and which set the field apart from others in science like physics, chemistry or biology. They are worth explicitly listing because effective education and outreach efforts can build on their inherent appeal (see section VIII). (1) Universal access to the skies: everyone can look up in wonder at the heavens. Creation myths, developed by many diverse cultures, make the sky a simple yet nearly universal natural reference frame, while those people who have more interest can easily become familiar with the constellations or planets using only their eyes. Reports of the latest discoveries, for example, protoplanetary disks in the Orion nebula, can be made more immediate to people by pointing out their positions in the sky. (2) Issues of personal meaning: the religious/spiritual implications of space. Questions about the universe lead naturally to questions of origins -- the creation of the universe, and the creation of life. These matters, far from being esoteric philosophical debates about matters that happened perhaps 13 billion years ago, are taken personally. They directly affect the spiritual perspectives of at least the Western religions. But even for nonreligious people these are matters of spirit and meaning, and so they are both important as well as interesting. The vigorous and sometimes acrimonious debate in the US over Darwinian evolution is a biological echo of these spiritual sensitivities. (3) Ease of understanding: the profound questions are simply put. As a physicist by training, I am excited by developments in physics today - in quantum mechanics, the nature of elementary particles, and progress towards a "theory of everything". I am not a biologist, but I recognize the revolutionary advances underway in understanding the genome, for example. But, in terms of easily communicating these discoveries to the public, there is no comparison with astronomy's advantage: the pressing, current questions of astronomy are easy to describe. How did planets form? When and how did the universe begin? Are stars born, and how do they die? Furthermore, often the answers can usually be understood without resorting to complex jargon. These are powerful edges over other scientific disciplines. Added to this, of course, and not to be underestimated, is space science's ability to talk about modern research with spectacular, inspirational imagery. (4) Excitement and drama: the human adventure. Finally the exciting, dramatic and often dangerous *human* exploration of space is a powerful stimulant for interest in space science, as broadly defined. Despite the controversies over the international space station, or the costs of a manned mission to Mars, the human element of space helps keeps NASA funding percolating at a high level (although exactly how this funding ends up benefitting space science is a much less straightforward calculation).

IV. SPACE SCIENCE IS INTERESTING AND APPEALING – AND PEOPLE SUPPORT IT

Space science is the beneficiary of considerable public largesse in the US. Federal funding of astronomy alone, via NASA and NSF, was about $800M in 1997. NASA's share, in 1997 dollars, has increased from $380M in 1981 as more and more space missions are undertaken; NSF's share is about steady at $100M.

Additional Federal funding for space science comes through other agencies including the Defense Departmem (for example, the recent Air Force MSX mission, or the Naval Observatory programs), and is significant but harder to quantify. Finally there is substantial public support in the form of local (state) funds for university telescopes, and/or from private foundations. It is worth noting, as does the recent National Academy report on astronomy funding, that of ten new generation telescopes being built with US support whose apertures are over 5 meters in diameter, only five get some Federal funding. Clearly the US public is willing to fund space science at productive levels.

Public support for space science, as measured by the perceptions of its cost-to-benefit ratio, has also been high in the US. Nearly half of all adults sampled -- 48% in 1997 -- said the benefits of "space exploration" far outweighed or slightly outweighed the costs. This figure has been relatively stable over the past ten years. We note that support for scientific research in general, including medical research, is even higher -- averaging about 70% over the past ten years, although for some disciplines the support is less: genetic engineering, for example, received endorsement from only 42% of adults in 1997.

The *Science and Engineering Indicators* survey asked people whether they viewed themselves as attentive to the various fields of science, generally interested, or neither. (To be attentive in this study the respondent had to indicate he or she was very interested, very well informed, and regularly read about the material.) When one compares the responses to being attentive to that of *support* for science, it becomes clear that the attentive public is the most supportive, both in terms of the strict cost benefit ratio, and also insofar as the perceived advantages (leading to better lives, more interesting work, more opportunities, etc.) outweigh the perceived disadvantages (its effects can be harmful, change our way of life too fast, or reduce the dependence on faith, etc.) Among the attentive population, two and one-half times as many think of science as positive and promising as compared to those whose attitudes are critical or pessimistic. Among the public who are neither attentive nor particularly interested, this ratio is only one and one-half -- so, about 43% of them are quite pessimistic. When formal education is taken into account, it clearly appears that the more educated the population, the more likely it is to be optimistic and supportive -- about twice as much for college graduates as for those without a high school diploma, and even more so for those with post graduate education. However, increased education (and knowledge, too, we infer) does <u>not</u> always lead to a more supportive community. In the example of nuclear power, the survey showed that support leveled off as more informed people also become more critical. No such tendency was found in the space science sample.

An interesting point arises regarding the group of people who thought of themselves as "very well informed": they were significantly more likely to say they participated in public policy disputes than those who had doubts about their level of understanding. Increasing the knowledge of the public will, if these trends are related, also increase the number who participate in the policy development. It is also true that some of the more knowledgeable public were aware of their limits and did not consider themselves "very well informed," and so to some extent increased knowledge might lead to a group declining to participate; however, better teaching will also educate those who do participate while not being particularly well informed. Overall, then, better education about space science -- and we show below that there is considerable room for improved education -- should result not only in a better informed citizenry, but one more likely to participate intelligently the public discourse, and one more optimistic about -- and supportive of -- space science.

V. BUT THE PUBLIC'S KNOWLEDGE OF SPACE SCIENCE IS SURPRISINGLY LIMITEL

Just the Facts

The NSF *Science and Engineering Indicators* surveys also sampled the public's knowledge of scientific facts by asking 20 questions, three of which were astronomy or space science related: (1) "True or false -- The Universe began with a huge explosion?" (2) "Does the earth go around the Sun or does the sun go around the earth?" (3) "How long does it take for the earth to go around the sun: one day, one month or one year?" The results are disconcerting, if not completely new. Only 32% of all adults answered true to number 1, including fewer than half of those who considered themselves as "attentive" to science topics. Some good news: nearly three-quarters -- 73% -- did know the earth went around the sun, although fewer than half of those without a high school education knew this to be the case. Perhaps most surprisingly, fewer than half of all adults, 48%, knew that the earth circles the sun in one year -- and 28% of those adults with graduate/professional degrees, the most knowledgeable category, did not know this fact.

It is important to place all this in context. For comparison, 93% of all adults in the survey knew that "cigarette smoking causes lung cancer" -- this was the best response to any of the factual questions . Not too far behind, about 83% of the adult public knew that "the oxygen we breathe comes from plants" and that "the center of the earth is very hot." I conclude that is it reasonable to hope that effective education programs might teach something to the 68% of adults unfamiliar with the Big Bang, or the 52% unsure of what a "year" is. The survey also discovered that only 11% of adults (only 28% of college graduates!) could in their own words describe "What is a molecule?" from which I conclude that, just as the level of general knowledge about space science could be better, it could also be worse. This is important to recognize because there may be a tendency to throw up one's hands in despair, given the tremendous, post-sputnik science education efforts under which many of those in the survey were schooled. These efforts were not obviously failures, but we can do better.

A further conclusion can be derived about the *attentive* public – it was (not surprisingly) also the most knowledgeable. In every science topic the respective attentive public was better informed than the "interested" public, which in turn was much better informed than the general public. Thus there is a clear link between the attentive and interested public, and the knowledgeable public.

Beyond the Facts: the Belief in Astrology and Pseudoscience

It's not only what people don't know that can hurt them. In a recent survey undertaken by York University in Toronto, 53% of first year students in both the arts and the sciences, after hearing a definition of astrology, said they "somewhat" or "completely" subscribed to its principles (an increase of 16 percentage points for science students since the first survey was done in 1991). The students also replied that "astronomers can predict one's character and future by studying the heavens." The *S&EI-2000* study is only a little more sanguine: it found 36% of adults agreeing that astrology is "very scientific" or "sort of scientific," and notes that a roughly comparable percentage believes in UFOs and that aliens have landed on Earth – so, more people than know about the Big Bang. And about half of the people surveyed believe in extra-sensory perception -- more than know that Earth goes around the sun in a year. The *S&EI-2000* study speculates that the dominant role of the media (especially the entertainment industry) in people's awareness has resulted in an increasing inability to discriminate between fiction and reality. People can forget what they learned in high school, while the media, insofar as they do contribute to the "dumbing down" of America, provide a steady stream of images; public education efforts need to be persistent and competitive as well.

VI. MIGHT THE SURVEYS BE WRONG OR MISLEADING?

In their book Misunderstanding Science? The Public Reconstruction of Science and Technology, Irwin and Wynne (1996), and the other contributors to the volume, attack the Royal Society's methodology and Report (and by inference other similar studies) for its implicit presumptions about the nature of science and the scientific methods (for example, that science is "a value-free and neutral activity"), and for its presumptions as well about the citizenry (for example, the "assumption of 'public ignorance' " and that "science is an important force for human improvement.") They emphasize that "in all these areas, social as well as technical judgments must be made -- the 'facts' cannot stand apart from wider social, economic and moral questions." It is perhaps easy to understand their criticisms of surveys of attitudes towards medicine, or nuclear power, where the impact on the individual or the state is more direct than it is for space science. Their underlying proposition however -- "the *socially negotiated* [their emphasis] nature of science" -- applies across the board, and is a much more controversial one. As for the data themselves, they point out that the surveys, as a result of these presumptions, are of questionable value. For example, in the context of the public's knowledge of the facts, they cite studies that show "ignorance [can be] a deliberate choice – and that [it] will represent a reflection of the power relation between people and science." The ESA survey, for example, rather clearly indicated it was sponsored with the aim of ascertaining public support for ESA's programs. Without necessarily agreeing on all these counts, we can still appreciate the legitimate limits of these surveys. As Bauer, Petkova and Boyadjieva (2000) suggest, there are other ways of gauging knowledge. In our case, for instance, the fact so many people answered incorrectly to the survey's query about the earth's revolution may not really be so damning a statistic; it may not even prove that people really do not know the meaning of a "year." Despite their possible limitations, there is nevertheless an internal consistency to these studies. I believe they demonstrate, at least insofar as "knowledge" is concerned, that things could be worse -- but also that they could be better.

VII. WHY DO SPACE SCIENCE RESEARCH?

Copernicus expressed the opinion that the philosopher's "aim is to seek truth in all things." Certainly many researchers today would echo this high-minded sentiment. However Copernicus does not say why a practical-minded public should support that effort, and so it is interesting to attempt an understanding of public attitudes towards basic research itself.

Copernicus, Newton, Bacon, and Jefferson

Gerald Holton (1998, 1999) has put forward a model in which basic scientific research falls into three general categories, each associated with an historical figure who represented that mode of inquiry. The "Newtonian mode," also the Copernican model, is the one in which scholars work for the sake of knowledge itself. Francis Bacon, on the other hand, urged the use of science "not only for 'knowledge of causes, and secret motion of things,' but also in the service of *omnipotence*, 'the enlarging of the bounds of the human empire, to the effecting of all things possible." According to Holton's analysis, this applied, "mission-oriented" approach to research is today the one most often used to justify public support of science. He proposes that there is actually a third way to view research, as exemplified by Thomas Jefferson's arguments to Congress for funding the Lewis and Clark expedition, namely, the "dual-purpose style of research" in which basic new knowledge is gained but where there is also a potential for commercial or other practical benefit.

The positive public attitudes towards science and space science in part reflect the opinion that basic scien research ultimately does drive a successful economy and lifestyle. Since 1992 the *S&EI* studies have tried to quantify these attitudes by asking people whether they thought science (in general, and not space science in particular) was beneficial by making our lives "healthier and easier," "better for the average person," would make work "more interesting," and provide "more opportunities for the next generation." In 1999 over 70% of all adults agreed with all of these assertions. But at the same time more than half of the respondents (to another survey) agreed that "science and technology have caused some of the problems we face as a society." Progress is a mixed bag. More to the point, a dramatic 82% of adults in the 1999 *S&EI* study agreed that, "Even if it brings no immediate benefits, scientific research that advances the frontiers of human knowledge is necessary and should be supported by the Federal Government." Space science research benefits from this general support, but in a more limited way. While 37% of adults thought "too little" money was being spent by the government on "scientific research," only 15% thought so regarding "exploring space,"while 46% thought "too much" was being spent on it (by far the highest percent of the three science disciplines queried: exploring space, pollution and health.)

The Kennedy Model

It is clear basic research -- the search for "truth" -- is supported by the public, especially if there might be some practical outcome. While heath and profit are obvious inducements to the support of medical, environmental, or applied research, the practical benefit of having more *astronomy* truths is harder to identify. I argue, however, that in fact there are unique, even practical benefits to space science research, based on two of the "appeals of space science" presented above, namely, the implications for spiritual and personal meaning, and (not unrelated) satisfying a love of adventure and exploration. Following in the example of Holton, I call this perspective on research the "Kennedy Mode." Said President Kennedy, referring to the Apollo program to land on the moon, "No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish . . . in a very real sense, it will not be one man going to the moon if we make this judgment affirmatively, it will be an entire nation (May 25, 1961)." "We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard (Sept. 12, 1962)." While understanding that Kennedy had many political, economic and defense concerns enmeshed in his proposals – all justifications for government research admittedly have complex subtexts associated with them – it is nonetheless significant that he chose to frame a justification for the space program, as exemplified by these quotes, in the clear language of spirit and of challenge. Space is a grand human adventure, not done purely for the sake of curiosity, nor for the sake of economic benefit either, whether strategic or serendipitous. This underlying sense of the important intangibles of space science is quite pervasive. For example, the recent National Academy of Science Committee on Science, Engineering and Public Policy (COSEPUP) report, "Evaluating Federal Research Programs: Research and the Government Performance and Results Act (1999)", states, "Knowledge advancement furthermore leads to better awareness and understanding of the world and the universe around us *and our place therein* [my emphasis]... " Our place in the universe is not a reference to astrometric studies of the stellar reference frame and the location of the sun and earth in space, but to personal meaning.

VIII. SUCCESSFUL COMMUNICATION – IT TAKES EFFORT FROM BOTH SIDES

There are an incredible number of popular books on space science. A search of Amazon.com finds 2395 books in print on the topic of "cosmology," about 800 of them (!) published since 1996. Many are not for the general public, but most are, yet even the popular ones are often not very good. The best example is Stephen Hawking's phenomenal success, "A Brief History of Time". (Hawking, 1988). A movie with the same name, about his life and touching on this material, was made in the early 1990's, and which I had the pleasure of introducing at its Washington, D.C. premier at the Museum. I fielded questions from the audie... afterwards, and took the opportunity to pose a few of my own to those assembled, which, like most NASM audiences, was literate and self-selected. When I asked the sellout crowd of over 500 people how many had read the book, virtually every person raised his or her hand. Then I dared to ask how many people understood the book -- and almost no one raised his hand, or the few who did, did so with visible temerity. Despite the talents of this great physicist and communicator, this book was a failure as an effort to teach. Indeed I spent most of the next hour trying to persuade people that they were not stupid, and that most of the material in the book was possible for *even* a layman to understand, though it might take a bit more effort on both the part of the reader and the writer. I noted, since the majority of them had said they were lawyers, that even though I have a Ph.D. I did not expect to understand the details of real estate law after reading a 200 page book, or seeing a movie. Motivation and expectations are important ingredients of learning.

A Scientific Understanding of the Public

Irwin and Wynne (1996) urge that scholars consider "not just the 'public understanding of science' but also the scientific understanding of the public and the manner in which that latter understanding might be enhanced [because] without such a reflexive dimension scientific approaches to the 'public understanding' issue will only encourage public ambivalence or even alienation." The surveys help towards this goal because they clarify what is meant by "the public understanding," provide context, and can measure trends. To rise to the challenge of increasing the public's understanding of space science, we must be able to evaluate success or failure, using studies including the *S&EI*, yet often the community has felt that simply trying hard was good enough. The statistics suggest we have so far been able to maintain steady levels of "understanding", but made little progress. In the new millennium there are hurdles which will require new approaches. The five "appeals" of space science listed above (Section III) can facilitate creative new programming, while involving adults, children, and people of all cultures and backgrounds.

Some Challenges Facing the Space Science and Museum Communities

There are some specific difficulties, as well advantages, for space science education efforts. For one thing, the pace of discovery in astronomy is very rapid. There are about 65% more US astronomers today than in 1985 (as measured by the total membership in the American Astronomical Society), and more papers are being published, about 80% more, for example, in *The Astrophysical Journal*. Furthermore very large amounts of data are now being collected thanks in part to the sensitive, large format detector arrays. In 1969, for instance, the Infrared Sky Survey found about 6000 objects, whereas the 2MASS infrared sky survey now underway has over 300 million point sources, and will produce over 2 TB of data. Not least, the topics are increasingly complex. The power spectrum of the cosmic microwave background is a more difficult concept to explain than is the recession velocity of galaxies. Finally, television, computers and increased mobility mean that there are new populations of people, with varying educations, backgrounds, and perspectives, who are gaining access to modern space science information. All of these challenges should be viewed as opportunities as well, chances to incorporate exciting new results and alternative perspectives for what, in agreement with Irwin and Wynne, I think must be a more reflexive educational approach. There will be a temptation to use hyperbole to emphasize discoveries whose scientific importance may be hard to explain. These temptations should be resisted, because, as survey critics have noted, people may be smarter than polls suggest.

Family and Community-Based Outreach: Two Examples

The astronomy department at the National Air and Space Museum produced two award-winning educational programs under the leadership of Dr. Jeff Goldstein, which continue under his guidance today at the Challenger Center for Space Science Education. They capture some of the unique strengths offered by space science, in particular the wide popularity of the subject matter, and directly address some of the criticisms mentioned above. The programs are premised on the idea that "learning is a family experience," not limited to kids or students, and that modern astronomy research is both interesting and comparatively to explain to *all* age groups. Developed and run in close collaboration with teachers and communit representatives, they aim to attract entire families and multi-cultural groups to a museum (or other environment) to experience together artifacts, lectures, demonstrations, a movie, and/or other astronomy or space science features. The programs highlight the excitement of space exploration while studying the cosmos, and as an added benefit simultaneously promote better communications between groups (e.g., parents and teachers, parents and their children). They also include pre-visit teacher training, and post-visit follow-ups.

The first of the programs, called "Learning is a Family Experience - Science Nights," is an evening event in which parents and teachers, students and their siblings, participate together. It succeeded in part because parents were willing to take an evening of their time to visit a popular attraction like the National Air and Space Museum; museums should use the appeal of their collections to attract people in this way. The second program is based on an outdoor exhibition now under development. "Voyage - A Scale Model Solar System" is a nearly exact scale model of the solar system, on the 1:ten billion scale, stretching along a 600-meter walking path, with the sun a sphere 13.9 cm in diameter at one end. "Voyage" maintains the scales both of the distances between objects and their sizes, with the small solar system bodies mounted in glass to be (barely) seen or touched. A visitor to the exhibit becomes a space voyager, traveling to the solar system, sailing along its length, seeing its varied planets and moons, and -- importantly -- sensing in its sweep the immense distances and relative sizes. Recall that only 48% of adults responded that the Earth circles the Sun in one year. This exhibition, sponsored in part by NASA, is designed to be an opportunity for people to place many seemingly diverse facts into striking, and hopefully memorable, context.

IX. "NOTHING... [CAN] BE MOVED WITHOUT PRODUCING CONFUSION"

"Thus...I have at last discovered that, if the motions of the rest of the planets be brought into relation with the circulation of the Earth and be reckoned in proportion to the orbit of each planet, not only do the phenomena presently ensue, but the orders and magnitudes of all stars and spheres, nay the heavens themselves, become so bound together that nothing in any part thereof could be moved from its place without producing confusion of all other parts and of the Universe as a whole."

-- Nicolaus Copernicus, *De Revolutionibus* (preface)

Copernicus observed that his model worked well, and furthermore, that like a jigsaw or clockwork, it seemed to fit together so perfectly that the simple notion of the earth circling the sun led to an entire universe with internal order and beauty. I make, by analogy, the same point as regards the public's understanding of space science. A population which can comprehend that the earth revolves around the sun in one year -- one of those simple facts -- is one which may also comprehend that the scientific method offers a rational, consistent and objective approach to life. And, contrariwise, a public which does not have a grasp of the basics is likely to be one which is susceptible to "confusion", doubting these facts and perhaps the methods used for their discovery as well. Does it matter that only 48% of adults, not 58%, know the period of the earth's revolution? Perhaps not. But the statistics provide strong evidence that improvement is possible, and likewise that degeneration is possible with increasing numbers of people vulnerable to astrology, belief in alien invaders, or the hope that their lucky numbers will win at the lottery. I have shown that space science is a very popular kind of science, particularly accessible and interesting. These indicators should spur on the space science community to continue, and enhance, its public programming in order to attract and inform new and larger audiences.

The consequences of an improved understanding of space science on attitudes towards space scie… not clear. Increased knowledge may be accompanied by increased scepticism about particular mission… experiments, as polls show can happen. Nevertheless it seems likely, to first order, that research programming will benefit from increased civic knowledge. While felicitous, this should not in itself be the reason for improving our educational efforts, for like Copernicus, I believe our "aim is to seek truth in all things as far as God has permitted human reason so to do," and in this enterprise the multitude, our sponsors, are also our partners.

ACKNOWLEDGMENTS

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Discovering the Cosmos — An Integrated Curriculum Astronomy Event

ABSTRACT

DISCOVERING THE COSMOS is a program designed to use astronomy and space science as a thematic focus for high schools, with two goals: (1) teach astronomy concepts; and, (2) dramatically illustrate the many ways that space science inspires a variety of human activity. We want to make astronomy accessible and interesting to students – whatever their interests. In this program all aspects of a high school curriculum, from art to zoology, English to music, math to Bible studies, will be directed towards projects with an astronomy/space science theme.

The New Jewish High School of Greater Boston will be the initial school participating, and will help with formative evaluation of the concept. The highlight of the program is an all-day, all-school "Discovering the Cosmos" focus day event, which will be held at Boston's Museum of Science (MOS) and Charles Hayden Planetarium. Students with particularly exceptional projects (musical compositions, short stories, computer programs, etc.) will present their projects to other students, parents and/or guests at this day-long event. Throughout the day, faculty and special guests will be lecturing in classrooms about "Discovering the Cosmos" in science, art and the humanities. The event includes an astronomy lecture by a professional astronomer, a planetarium show, and an evening highlight: a star-party on the roof of the museum. The program includes funding for assessment and the dissemination of results.

Notes:

This Education/Public Outreach proposal is the companion effort to Howard Smith's proposal entitled "Infrared Spectroscopy of Star Formation in Galactic and Extragalactic Regions," SAO proposal # P5031-10-00. We understand that this proposed E/PO effort may be awarded as an add-on to the grant based on P5031-10-00, which we expect to receive shortly.

The 2001 program will be held on 24 January; very long lead times are needed to schedule the events. Since we anticipate that any grant award based on this proposal may not be funded until after this date, we request NASA approval to use those funds for this event.

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I. INTRODUCTION

The idea of "focus topics" for high schools is familiar: It is a way to involve students normally interested in very different disciplines in a single unifying theme, so that they can all share their skills with each other, gain mutual respect for the differing talents of classmates, and of course learn some new material. This proposal, for a "Discovering the Cosmos" (DTC) activity, uses astronomy and space science as the thematic focus. There are three aspects of this program that we think are innovative and exciting.

The first is our partnership, a combination of the Smithsonian Astrophysical Observatory (SAO), The New Jewish High School (NJHS) of Greater Boston, and the Museum of Science (MOS), Boston, which is home to the Charles Hayden Planetarium. SAO brings well-known professional expertise in astronomy. The NJHS, with its approximately 200 students (Grades 9-12), is unusual in that its curriculum emphasizes innovative approaches to education and also includes intensive Bible and Judaic studies. The NJHS will bring an enthusiasm to implement this program in an optimal way and also provide an opportunity to have students address with some level of sophistication the relationships between astronomy and matters of human spirit. The MOS is an outstanding venue for highlighting astronomy, has a staff expert in education, and is well-connected to other schools and museums who may subsequently want to adopt aspects of the program. While we think our team is a particularly good one, we plan to use the results of this pilot study to prepare a generalized program that would be suitable for other high school/museum partnerships to adopt.

The second important feature of this program is its aim not simply to spend a day teaching astronomy to students, but rather to encourage longer-term student projects across a wide range of disciplines – and to bring these people and their ideas together on the focus day. This is not a passive activity for students, but an active one, which we hope will capture students' imaginations and require thoughtful creativity. As an aside, we hope this approach will facilitate communications between students whose differing interests do not normally bring them together. We can learn from each other.

Finally, we see as important our program goal of involving the parents and siblings of students in the MOS's day of activities. It is a way to illustrate to everyone that "learning can be a family experience," to lend parental support to students' academic achievements, and to provide a forum for the professional staff and parent body to meet and talk about science education. Like a prototype program initiated by the National Air and Space Museum (for which Dr. Howard Smith was a Co-Investigator), this program uses the drama and glamour of a leading museum – in this case the MOS – to persuade parents to give up one of their free evenings to learn astronomy with their kids, and to see some innovative school projects. We plan both a planetarium show and a "star-party" on the roof.

II. ACTION PLAN AND RESPONSIBILITIES

<u>At the New Jewish High School</u>: Mr. Brian Rogan, Head of the Science Department at NJHS and a teacher of astronomy, and Mr. Eric Grossman, Director of the Bible Studies Program and coordinator of the school's DTC Focus Day activities, will lead the school's programming efforts. They will work with the faculty of the school to help them encourage students and advise them on astronomy-based projects, and will coordinate the faculty's MOS lectures (see below). They are responsible for most of the logistical arrangements with the MOS. They will also, with the school's main

office, prepare communications with parents and friends of the school.

At the Smithsonian Astrophysical Observatory: Dr. Howard Smith, Senior Astrophysicist at the Harvard-Smithsonian Center for Astrophysics and Principal Investigator on several NASA grants, will help Brian Rogan in advising the school's teachers and students in an ongoing way. He will also present a keynote lecture at the MOS on astronomy. For this event the topic will be modern concepts in astronomy and cosmology and the relationship to Jewish and Biblical concepts. Dr. Smith will be responsible for coordinating the project report, the program evaluation, and materials for general dissemination. He is responsible for the program budget.

At the Boston Museum of Science: Dr. Cary Sneider, Vice President for Programs, and Ms. Marianne Dunne, Ms. Lynn Baum, and Ms. Sharon Horgan will be responsible for helping to coordinate the school's visit and its day-long activities.

Dr. Sneider is an experienced science educator who served on the National Research Council committee to develop *National Science Education Standards* (NRC, 1996). Dr. Sneider's research has focused on helping children unravel misconceptions in astronomy and develop fundamental inquiry skills.

III. SCHEDULE OF THE "DISCOVER THE COSMOS" FOCUS DAY

The logistics of the DTC Focus Day are complex. We will have 200 students, plus faculty, parents, and guests, at the MOS from about 10AM until about 8 PM.

9:45 ~~10:00~~	Talk in Cahners Auditorium for entire school, given by Dr. Smith: "Sacred Space: Concepts in Modern Astronomy and Cosmology"
11:00	Students tour exhibit halls with focusing activities
12:00	First lunch shift picnic-style in the Atrium or buy in the MOS Cafe
12:30	Second lunch shift
1:00	1st seminar period
2:00	2nd seminar period
3:00	OmniMAX film (nominally "Cosmic Voyage")
4:00	3rd seminar period
5:00	"Galileo" in the Planetarium
6:00	Reception with parents in the MOS Galaxy cafe Star party on the roof of the MOS, weather permitting
8:00	Conclude

The day will begin with a multi-media opening lecture by Dr. Smith on modern astronomy and its relationships to non-scientific concepts about the Universe. The title, "Sacred Space," refers to the fact that the heavens can be appreciated for more than their mathematical or physical properties: for the way they have inspired poets, artists, and religious thinkers. Following a Q&A period, the remainder of the morning will allow students to tour the MOS exhibit halls, with staff on hand to provide focus and explanations.

After lunch there we will hold a series of seven simultaneous lecture/presentations around the Museum on the topic of "Discovering the Cosmos" in different disciplines. Each event will be led by a member of the NJHS faculty; during the sessions students whose projects were deemed by their faculty advisors to be especially meritorious will have an opportunity to present their music/poem/calculation/etc. to the audience. The topical materials will be repeated three times during the afternoon, enabling students to visit and hear any three of the seven topics being presented. A detailed schedule will be distributed at the opening session.

At the end of the afternoon, and as part of the programming designed to bring the day's activities to a focus, students will attend two events. The first is a showing of an IMAX film (tentatively "Cosmic Voyage"). We note that currently the MOS is not showing this Academy Award nominee. Therefore we will incur a cost of $500 (plus shipping expenses) to rent the film for the evening. The teachers at the NJHS, as well as the other Co-Investigators of this project, feel this film is singularly well adapted to all of the themes being presented in DTC, teaching astronomy concepts in an exciting, multi-disciplinary way, and we are requesting support for this rental in this proposal. Following the film, which presents a review of the scale of the Universe in powers of ten, both in *space* and in *time* (starting from the Big Bang), the students will see a dramatic presentation/planetarium show, "Galileo's Odyssey." This exciting new MOS program features a live actor playing Galileo, who – echoing the cross-disciplinary theme of this DTC proposal – brings concepts of both theater and religion to make astronomy exciting and relevant.

Some parents might be able to attend on-and-off during the day, but near the end of the afternoon and early evening, when most parents and guests are expected to arrive, the DTC program and the museum will host a modest buffet reception at which key student projects will be honored. Total evening attendance is estimated to be about 300. At this time we plan to hand out questionnaires to parents as part of the program evaluation (students will receive their forms at school).

A key part of the evening programming is an on-going "star-party." To this end the NJHS under the direction of Brian Rogan, Chairman of the of Science Department, will set up a small telescope on the roof of the MOS. In addition we plan to invite members of the Boston Amateur Telescope Makers to assist in the viewing. Everyone in the project believes in the importance of having this opportunity to experience the night sky directly – not only through slides and shows. This telescope, and some associated naked-eye viewing, will help make the excitement of all the day's ideas, and all of the prior weeks of planning, come alive. The telescope itself will also be used by students pursuing an astronomy-science focus. Following the evening the telescope will become an ongoing part of the school's astronomy curriculum. In particular subsequent star parties, at the NJHS location, will be planned to accommodate all of the interest that has developed.

We have requested a budget for two years, in order to give us one opportunity for a second iteration to improve the results. Working with the MOS and SAO, we hope to be able to include other high schools in subsequent years, but a lot depends on how well the first programs go.

IV. EVALUATION

The program evaluation will be a collaboration of all three partners. The Principal Investigator and all Co-Investigators will meet to develop questionnaires for all students, parents, and teachers involved in the project. The questionnaires will ask participants to rate their satisfaction with each program component, as well as the entire unit, including its culmination at the Museum of Science, and to make suggestions for improvement.

To minimize costs the questionnaires will be administered after Astronomy Day activities in Year 1, and again in Year 2. Questionnaires will be administered and collected by NJHS personnel, then summarized by MOS staff. Approximately one month after each Astronomy Day the Co-Investigators will meet to discuss the results of the questionnaires and decide on improvements for the future.

The Principal Investigator will prepare a final report, summarizing the results of the evaluation study and lessons learned. He will also make recommendations for future implementation of programs that may be offered by the Museum of Science or other museums. We hope that many of the student projects will be available to enrich and enliven this report. The report will be made available for other partnerships of schools, science centers, and research institutions.

V. BUDGET NARRATIVE

This E/PO proposal is a companion effort to Howard Smith's proposal entitled "Infrared Spectroscopy of Star Formation in Galactic and Extragalactic Regions," SAO proposal # P5031-10-00. We expect that this proposed E/PO effort will be awarded as an add-on to the grant based on P5031-10-00. Because Dr. Smith's time spent on E/PO activities will be charged to that grant, his salary costs are not included here.

The MOS has agreed to a reduced cost basis for use of its facilities and shows.

The major remaining costs are presented in the Estimate of Cost and in Attachment A.

The 2001 program will be held on 24 January; very long lead times are needed to schedule the events. Since we anticipate that any grant award based on this proposal may not be funded until after this date, we request NASA approval to use those funds for this event.

VI. CONTRACTUAL AND COST INFORMATION INCLUDING CERTIFICATIONS

The Smithsonian Institution, an independent trust establishment was created by an act of the Congress of 1846 to carry out the terms of the will of James Smithson of England, who had bequeathed his entire estate to the United States of America "to found at Washington, under the name of the Smithsonian Institution, an establishment for the increase and diffusion of knowledge among men." After accepting the trust property for the United States, Congress vested responsibility for administering the trust in a Smithsonian Board of Regents.

The Smithsonian performs research, educational and other special projects supported by grants and contracts awarded under the cost principles of the Federal Acquisition Regulation, Subpart

Nanotechnology Fabrication of Polysilicon Film/Metal Grid Infrared Filters

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Naval Research Laboratory

Howard A. Smith
Smithsonian Astrophysical Observatory

Peter Ade, Rashme Sudiwala
Queen Mary and Westfield College

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NASA Goddard Space Flight Center

1. Program Overview

We have initiated a new program to perfect and test innovative new nano-fabrication technology for producing low cost, high transmission, multilayer filters for use at infrared wavelengths longward of approximately 20 μm. The fundamental design issues have been resolved in the past decade, and applied successfully to long wavelength filters (> 100μm). At shorter wavelengths (10 microns – 100 μm) the key issues remaining are ones of control of the substrate thickness, transparency, layering, and granulation.

This program will develop the process by first characterizing substrates, and then perfecting the fabrication processes. We have identified as the most promising candidates silicon, polysilicon produced by chemical vapor deposition (CVD), diamond CVD, polyimide (using improved liquid deposition techniques), and polystyrene. To produce a filter, we fabricate onto each substrate layer a metal mesh grid. Our interdisciplinary team has perfected this grid technology while developing free-standing (so-called "inductive") metal mesh reflectors used in Fabry-Perot interferometers for systems below 100 microns. These layers are then stacked with precise spacing.

Our effort is a collaboration of the Smithsonian Astrophysical Observatory, the Naval Research Laboratory Remote Sensing Division, Queen Mary and Westfield College (QMW), and NASA Goddard Research Center. Fabrication will be done at the Nanoelectronics Facility at the Naval Research Laboratory using new photolithographic, plating, microstructuring, and CVD techniques.

2. Current Status of FIR Filters

Far-infrared (FIR) filters are needed for a wide range of NASA missions, both pending and planned, including the Stratospheric Observatory for Far Infrared Astronomy (SOFIA), long duration balloon systems for both astrophysics and atmospheric research, and satellite projects such as SIRTF, FIRST, Planck, NGST and others. Each instrumental program has different filter design requirements, but all of them are looking for mid-IR to FIR filters with high, flat transmissions, sharply defined and precise spectral shapes, and excellent out of band rejection.

Narrow bandpass, cut-on, or cut-off FIR filters are made in a method analogous to making optical dielectric filter layers: by precisely stacking and spacing materials of different indices – in our case, inductive and capacitive resonant metal mesh grids. "Inductive" meshes are metal grids, with a square or cross pattern of narrow wires, which can be free-standing or deposited on a substrate; "capacitive" meshes are the geometric inverse of inductive meshes, and must be supported by a substrate material such as polypropylene or polyethylene film. This terminology derives from the electrical circuit analog of their transmission properties.

Substrate support, and precise spacing of the grid layers, involves two critical features which are the emphases of this current filter program. The first is the selection of the optimum substrate material to minimize even small absorptions that become amplified when a resonant grid structure is laid on its surface, and then the precise and reproducible fabrication of the substrate thickness – to within a few tenths of a micron. Fabrication of the actual filter then requires the mounting and stacking of four or more inductive and capacitive layers to achieve the desired spectral characteristics. The desired requirements for high out-of-band blocking are often satisfied by combining the interferometric performance of the multiple layers with substrate materials having specific absorption bands.

3. Metal Mesh Grids

We have successfully fabricated, using our patented photolithography and plating processes, nickel and gold metal free-standing mesh grids, with line widths as small as $2\mu m$, periodicities as small as $8\mu m$, and diameters of 50 mm. The grids were provided as reflectors for the Infrared Space Observatory (ISO) Fabry-Perots, operating from $45\mu m$ – $180\mu m$ in the Long Wavelength Spectrometer (LWS), and were measured by the European Space Agency to have as much as ten times the transmission of commercially available devices, while having reflectance limited finesses up to 50% higher.

The NRL – SAO meshes were able to obtain this high performance because of at least three fabrication considerations: (1) mask masters designed specifically for the performance requirements, with optimum geometries (including thickness, sharp cornering, and wall steepness) maintained throughout the process; (2) a patented nanoelectronic silicon technique, involving over 12 carefully controlled steps, using photolithography, plating, and etching to convert the pattern into a free-standing mesh; (3) precisely deposited metals on optically polished silicon surfaces which give the mesh high tensile strength, high conductivity, low impurity contamination, and very low absorption losses. These and other nanofabrication experiences are being applied to the problem of obtaining useful yields of high performance, precisely controlled filters.

4. Substrate Characterization

The mid-IR and FIR filters consist of resonant-pattern grids of gold photolithographically patterned onto each substrate layer. The geometry of a typical "resonant-cross" pattern operating at $150\mu m$ is shown in Figure 2. The presence of this resonant grid on the surface of the substrate material increases the effective path length of the electric field at the resonant frequency, thereby also increasing the detrimental effects of any small absorptions of the substrate material at the resonant frequency of the filter.

Our investigation of potential substrate materials has concentrated on identifying the lowest loss materials. For each potential substrate we lay down a resonant grid geometry designed to measure small substrate absorptions at the filter wavelengths of interest.

Prior to fabrication of a test sample, we determine a profile of the expected transmittance using adaptations of tools developed for our metal mesh program. By modeling the grid as a shunt impedance on a transmission line, the impedance is derived analytically, and the response can be calculated as a function of wavelength. When necessary, the resonant frequency can be adjusted empirically.

Current submillimeter wavelength filters produced by QMW typically use polypropylene as a substrate material, but at the much shorter wavelengths we are working at this material is no longer optimum. We are pursuing four additional possibilities: (1) thin crystalline silicon, (2) polysilicon CVD films, (3) liquid polyimide films, and (4) diamond CVD films. We determine their performance by depositing a resonant grid filter pattern and measuring the transmission both warm and at cryogenic temperatures using FIR FTS spectrometers at Goddard and QMW. Our results to date have shown that crystalline silicon, both in its high and normal resistivity forms, has small absorptions in the $10 - 100\mu m$ regions which result in the filter's peak transmission falling below 60%, and therefore below our design goals.

We are actively studying the properties of polysilicon films. These are produced by a high temperature CVD process capable of precise thickness control. The polysilicon is fabricated on a silicon wafer substrate to enable ease of handling in the assembly and testing process. Subsequently, the polysilicon is separated from the silicon by etching away a thin "lift-off" layer of SiO_2.

5. Fabrication of Polysilicon Test Samples

The semiconductor processes needed to produce these samples were designed and executed by the same team at NRL responsible for our highly successful freestanding metal mesh program. Summarized in Figure 3, this procedure was repeated for various thicknesses of SiO_2 and polysilicon.

We decided to construct our samples one layer at a time, allowing our colleagues at Goddard to perform Fourier Transform Spectrometer (FTS) scans after each successive layer was applied. These tests not only provided valuable data on polysilicon, our first candidate spacer for grids, but also on SiO_2. In addition to using SiO_2 as a "lift-off" material for separating our CVD silicon substrates, we are also studying its properties for use as a filter substrate.

6. Future Plans

We continue to characterize the polysilicon CVD process, and have begun to characterize other potential substrate materials. We are concurrently revising and improving our modeling programs to incorporate the absorption results obtained so far, and to include more detailed EM wave theory calculations.

References:

[1]Rebbert, M., et al. 1994, Applied Optics, 33, 1286

Acknowledgments:

We thank Dr. John Miles (Lockheed-Martin) for his assistance early-on in this program's modeling and development efforts. We gratefully acknowledge partial support from NASA's Infrared, Submillimeter and Radio Astronomy Research and Analysis Program, from the Office of Naval Research, and from the Smithsonian Institution.

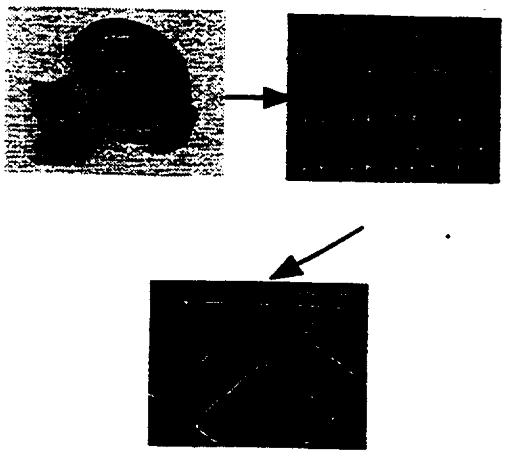
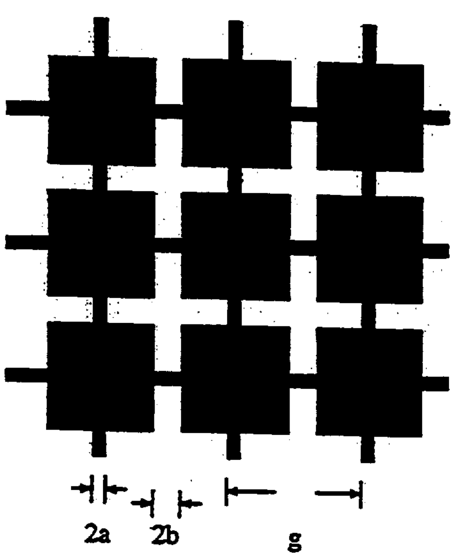


Figure 1
Typical Inductive Metal Mesh Grid



g=70um, a/g = 0.06, b/g = 0.09

Figure 2 - Resonant Grid Geometry

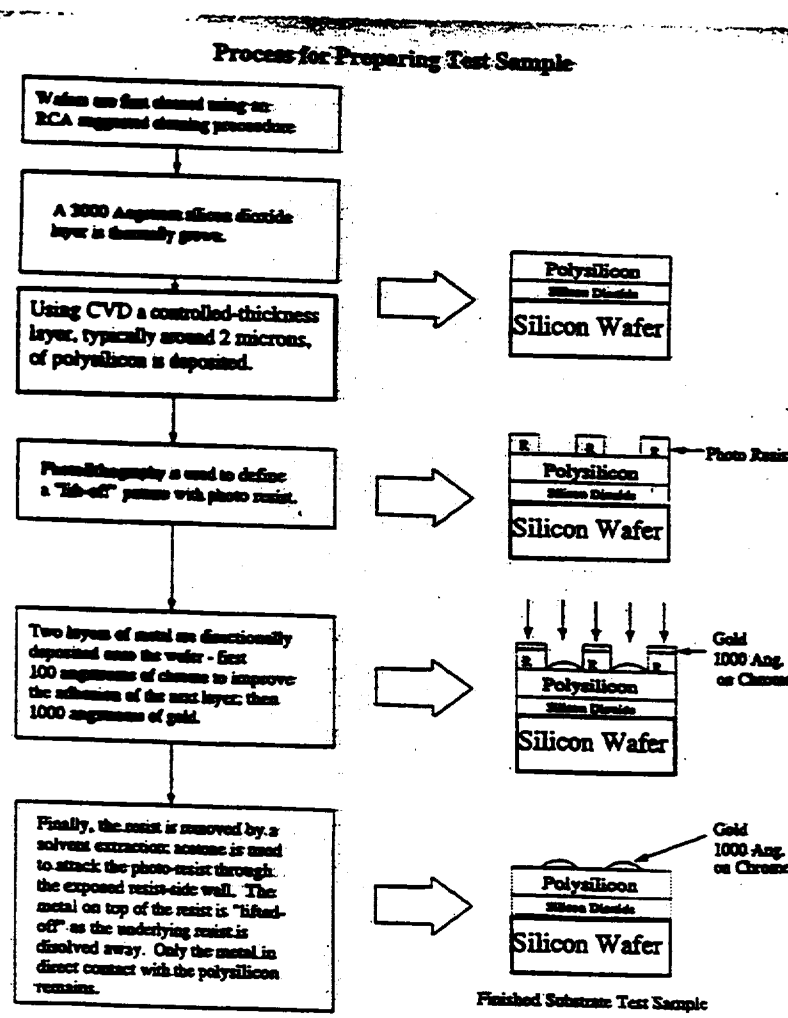


Figure 3 - Sample Fabrication Process

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Thin and thick cross shaped metal grids

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Abstract

Thin cross shaped metal grids have been studied in the infrared for wavelengths smaller and larger than the periodicity constant. Resonance frequencies of thin grids, calculated using rigorous computational methods, agree well with experimental data and empirical formulas. Resonance wavelength and the Wood anomaly of metal meshes on silicon substrates show frequency shifts to longer wavelength, with shifts smaller than the refractive index for the resonance and equal to the refractive index for the Wood anomaly. An empirical formula for the wavelength of the "thickness" peak of free standing thick cross shaped grids is shown and agrees very well with experimental and computational results.

Keywords: Metal grid; Infrared; Silicon substrate

1. Introduction

Free standing metal meshes and their complementary structures were studied in the far infrared in the 1960s [1–3]. The metal meshes were commercially available and manufactured by electroforming processes using Ni, Cu, and Au. The periodicity constants varied from 25 microns to a few thousand microns. The width of the wires was about 1/5 of the periodicity constant and the thickness in the range of 2 to 5 microns.

In Fig. 1a we show the transmission of a metal mesh with periodicity constant $g = 50$ microns [1], as function of the normalized wavelength λ/g were λ is the wavelength.

Such metal meshes could be used as a mask to produce the complementary structure, either by evaporation of a metal onto a substrate or in a lithographic process.

In Fig. 1b we show the transmission as function of the normalized wavelength of a complementary structure with $g = 49$ microns on a quartz substrate, see Ref. [2].

Ulrich [4] used transmission line theory for the design and description of transmission filters with many layers, and called the metal mesh of Fig. 1a an inductive grid, the complementary structure, Fig. 1b, a capacitive grid. A superposition of an inductive grid with its complementary structure results in a cross shaped pattern, see Fig. 1c. Ulrich used such a superposition as a mask and produced capacitive

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grids consisting of metal crosses on a mylar substrate. The transmission of a capacitive cross shaped grid with Ni crosses having center to center distance $g = 102$ microns is shown in Fig. 1d. A strong resonance is observed at wavelength $\lambda = 152$ microns ($66\ cm^{-1}$). This resonance has a wavelength larger than the periodicity constant, a feature appearing when the wavelength is equal to the periodicity constant is referred to as the ''Wood anomaly''.

Since the resonance wavelength of the grid in Fig. 1d is about twice as large as one arm of a cross, one assumes a dipole interaction of the incident light with the cross array.

For thin grids one observes for complementary grids a complementary pattern [2], in agreement with Babinet's principle in electromagnetics [5]. One observes for capacitive cross shaped grids, see Fig. 1d, a transmission minimum, whereas for inductive cross shaped grids one expects a transmission maximum

2. Thin free standing cross shaped grids and the shape of the crosses

Free standing cross shaped grids and grids on thin substrates have been produced in the long wave-

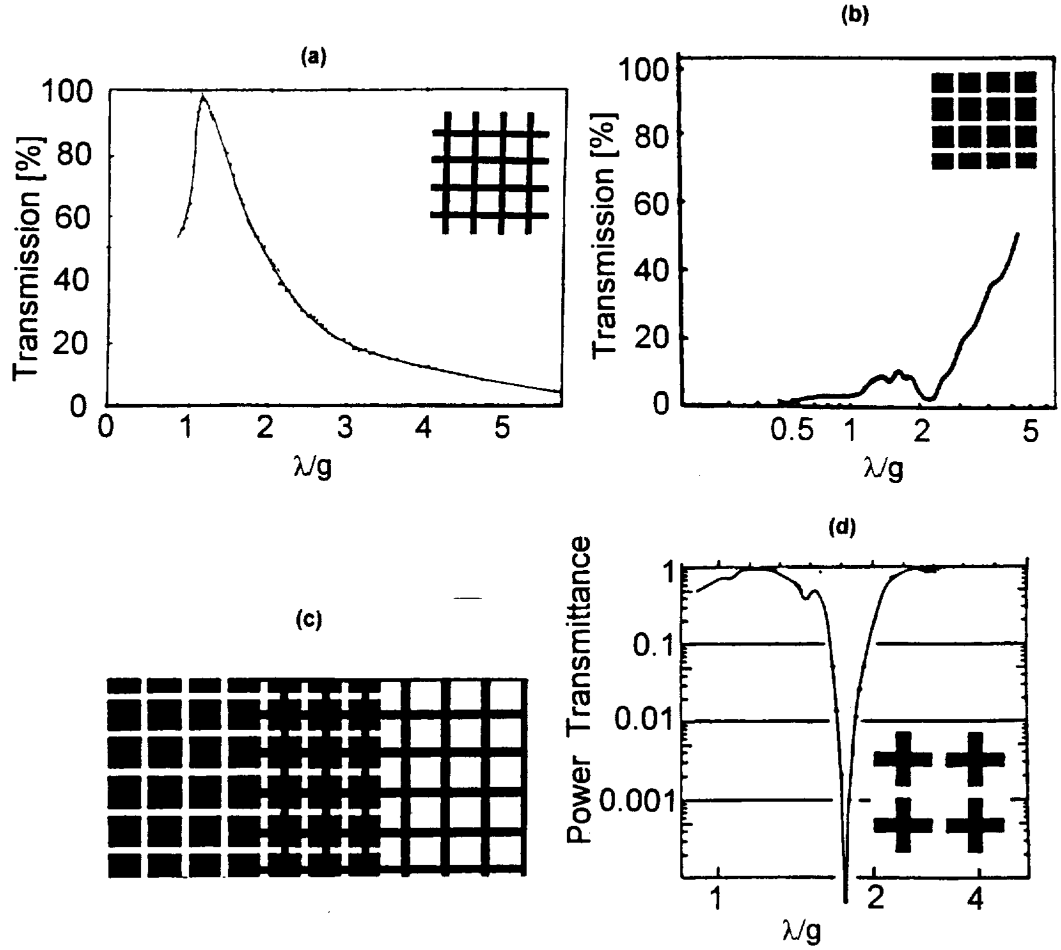

Fig. 1. Metal meshes. (a) Transmission depending on λ/g of a free standing inductive metal grid with $g = 50$ microns [1]. (b) Transmission depending on λ/g of a capacitive grid, aluminum on quartz substrate, $g = 49$ microns [2]. (c) Production of cross shaped pattern by superposition of a capacitive and an inductive grid. (d) Power transmittance depending on λ/g of a capacitive cross shaped grid on a mylar substrate with periodicity constant $g = 102$ microns. Resonance at 152 microns ($66\ cm^{-1}$) [4].

length region. The free standing cross shaped grids of thickness of a few microns were manufactured using an electroforming process. Photolithography was used to deposit thin grids of thickness of a few thousand angstrom on mylar films of about 2.5 microns. The transmission of these grids shows a broad maximum at a peak wavelength larger than the periodicity constant. The use of thin mylar substrates did not effect much the transmission maximum.

Chase and Joseph [6] produced inductive cross shaped grids with six different cross shapes and studied their transmission in the long wavelength region. In Fig. 2a the shapes of the crosses are shown for different types, labeled #1 to #6. The transmission depending on λ/g of grids #1 to #3, having periodicity constant $g = 410$ microns, is shown in Fig. 2b, and in Fig. 2c for grids of #4 to #6 with $g = 375$ microns. The resonance wavelength, observed at peak transmission, is larger than the periodicity constant and not the same for the six grids. The peak transmission is in the 90% or higher range, and for grids with crosses having large cross arms, the width of the transmission curve is wider than for grids with small cross arms. All grids show a minimum around $\lambda = g$.

An empirical formula for the resonance wavelength, Eq. (1a), was given by Chase and Joseph [6]. It was derived by a least square fit calculation to

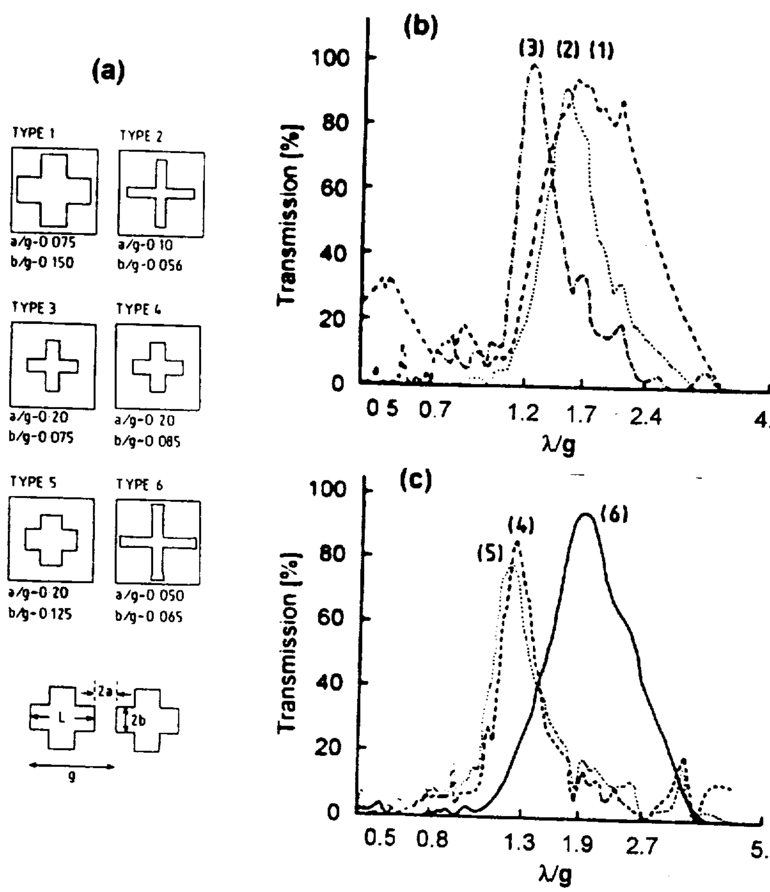

Fig. 2. Effect of the shape of crosses on the transmission of inductive grids. (a) Definition of the shapes of six crosses. (b) Observed transmission depending on λ/g of thin grids of type #1 to #3 with $g = 410$ microns. (c) Observed transmission depending on λ/g of thin grids of type #4 to #6 with $g = 375$ microns.

determine the coefficients of an expression depending on g, a, and b, using the six observed values of the resonance wavelengths.

$$\lambda_R = 2.1g - 4.2a + 2.1b \tag{1a}$$

$$\lambda_R = 2g - 4a - 2b \tag{1b}$$

$$\lambda_R = 2g - 3.6a - 2.7b \tag{1c}$$

$$\lambda_R = 2.6g - 4.3a - 3.9b \tag{1d}$$

An empirical formula on the basis of dipole interaction was derived by Möller et al. [7], shown in Eq. (1b).

For the calculation of the transmission of the six grids shown in Fig. 2, we have used the Golden program [8]. This program may only be used for thin grids and needs as input data the geometry of the crosses and the surface conductivity (Ω cm). We assumed for our calculations infinite conductivity, and show the transmission of the grids of type #1 to #6 as function of normalized wavelength λ/g, see Fig. 3a. There is good agreement with the experimental findings for the values of the position of the maxima, depending on the different types of crosses, and a minimum is observed at $\lambda = g$ for all grids. A least square fit calculation was performed for the resonance wavelengths and the resulting formula is listed as Eq. (1c).

We also conducted computations of the transmission of the six grids shown in Fig. 2 in the near infrared spectral region, The calculations were performed with the Fourier Modal Method [9]. This rigorous method relies on a Fourier decomposition of the electromagnetic field inside the grating region. Symmetry considerations were exploited to reduce the number of Fourier orders, and to guarantee the exactness of the computed data, absolute error smaller than 0.01. The calculations were performed in the near infrared for a nickel film surrounded by air with a periodicity constant of $g = 2.14$ microns. The real and imaginary part of the refractive index of nickel were interpolated from tabulated data [10]. The transmission for the six cross shaped grids is shown in Fig. 3b. A least square fit calculation for the resonance wavelength resulted in a formula shown in Eq. (1d). In comparing this formula with Eq. (1c) one has to take into account that the formula in Eq. (1c) has been derived for the case of infinite conductivity of the metal, whereas for the calculations leading to the formula shown in Eq. (1d) one has the case of finite conductivity.

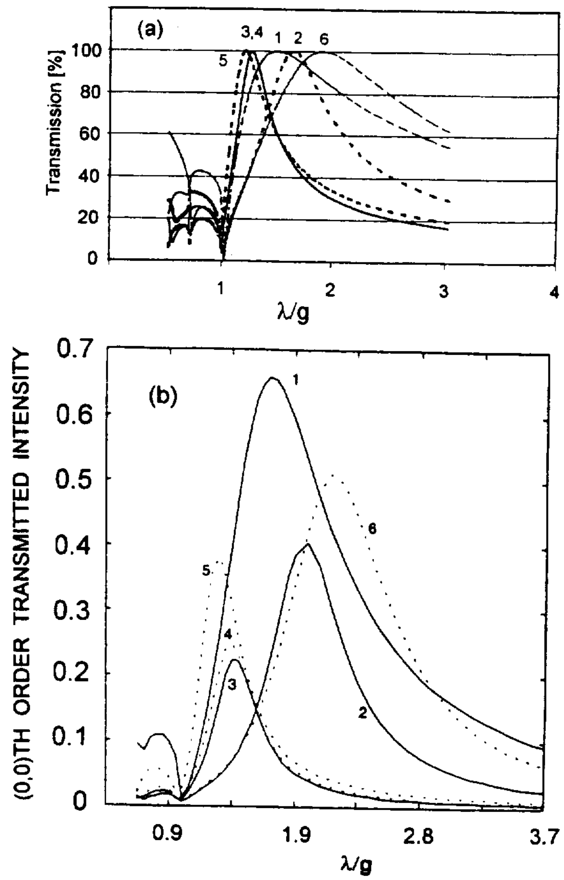

Fig. 3. Calculated transmission of the six cross shaped grids shown in Fig. 2. (a) Results of the calculations of the transmission depending on λ/g of the six grids shown in Fig. 2, using the "Golden Program" for thin grids, assuming infinite conductivity. (b) Calculation of the (0,0)th order transmitted intensity for thin grids of the six types shown in Fig. 2. for the near infrared region of the spectrum (0.5 to 8 microns). For the computation, we assume nickel as the metal and grid of 0.2 microns.

3. Thin cross shaped grids on a silicon substrate

Inductive grids with $g = 12.5$, 20 and 70 microns and values of $a/g = 0.06$, $b/g = 0.09$ were pro-

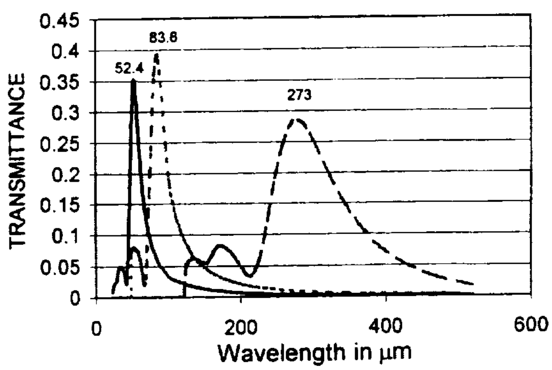

Fig. 4. Transmission depending on wavelength of thin inductive grids on a silicon substrate. The grids with periodicity constants $g = 12.5$, 20, 70 and $t = 0.1$ microns have resonance wavelengths at $\lambda_R = 52.4$, 83.6 and 273 microns and minima at $\lambda_W = 41.5$, 66.5 and 216 microns, respectively. All grids have the same ratios of $a/g = 0.06$ and $b/g = 0.09$.

duced on a silicon substrate by Hicks et al. [11]. The grids were made of a Au layer of 1000 Å on Cr. The metal layers were deposited on a polysilicon film on a silicon wafer with resistivity of 10 Ω cm. The transmission depending on wavelength of these grids is shown in Fig. 4 with maximum transmission in the 40% range. The grid with $g = 12.5$, 20, and 70 microns show maxima at $\lambda_R = 52.4$, 83.6, and 273 microns, and minima at $\lambda_W = 41.5$, 66.5, and 216 microns, respectively. In Table 1 we have compiled these values, and for comparison, we have calculated the corresponding values for the free standing metal grids, using the empirical formula shown in Eq. (1b).

We have manufactured inductive grids on a silicon substrate having $g = 16.4$, $2a = 2.5$, $2b = 4.8$. and $t = 0.2$ microns, and $g = 26.4$, $2a = 3.2$, $2b = 4.8$, and $t = 0.2$ microns. The resulting transmission

Table 1
Thin grids on a silicon substrate

	g	λ_R	λ_W	Free standing: Cal. Eq. (1b)		Ratios	
				$\lambda_R(g)$	$\lambda_W(g)$	$\lambda_R/\lambda_R(g)$	$\lambda_W/\lambda_W(g)$
Far infrared							
Inductive grid		On silicon: experiment					
	12.5	52.4	41.5	19.74	12.5	2.65	3.32
	20	83.6	66.5	31.6	20	2.65	3.33
	70	273	216	110	70	2.48	3.09
		On silicon: experiment					
	16.4	61	45.8	22.9	16.4	2.66	2.79
	26.4	115.2	91	41.6	26.4	2.77	3.45
		On silicon: simulation					
	16.4	67.2	55.3	22.9	16.4	2.93	3.37
	26.4	124.9	89.7	41.6	26.4	3.00	3.40
Capacitive grid		On silicon: experiment					
	16.4	62.5	56	22.9	16.4	2.73	3.41
	16.7	70	54	26.4	16.7	2.65	3.23
		On silicon: simulation					
	16.4	68.1	55.2	22.9	16.4	2.97	3.37
	16.7	79.4	58.2	26.4	16.7	3.01	3.49
					Averages	2.77	3.49[b]
					Ratio:	0.79	
Near infrared							
	i	n(i)	λ_R(i)	λ_W(i)	$\lambda_R(i)/\lambda_R(1)$	Ratio[a]	$\lambda_W(i)/\lambda_W(1)$
	1	1	4.15	2.22	1		1
	2	1.5	4.95	3.33	1.18	0.80	1.5
	3	2	6	4.3	1.45	0.72	1.93

[a] Ratio is $\lambda_R(i)/(\lambda_R(1)/n(i))$.
[b] This is equal to the refractive index n.

as a function of wavelength is shown in Fig. 5a. One observes maxima at $\lambda_R = 61$ and 115.2 microns, minima at $\lambda_W = 45.8$ and $\lambda_W = 91$ microns, respectively. The resistivity of the silicon wafer was 15 Ω cm.

We have calculated the transmission for these inductive grids using the Sonnet Microstrip program [12], see Fig. 5b. One obtains maxima at $\lambda_R = 67.2$ and 124.9 microns, minima at $\lambda_W = 55.3$ and $\lambda_W = 89.7$ microns, respectively. All data for λ_R and λ_W are listed in Table 1, and for comparison, the corresponding values for the free standing grids are also tabulated, calculated from the empirical formula (1b).

We have produced two capacitive grids on silicon substrates and show the transmission as function of wavelength in Fig. 6a. The grid with $g = 16.4$, $2a = 2.5$, $2b = 4.8$, and $t = 0.2$ microns shows a resonance minimum at $\lambda_R = 62.5$ microns and a maximum at $\lambda_W = 56$ microns, and the grid with $g = 16.7$, $2a = 2$, $2b = 3$, and $t = 0.2$ microns shows a resonance minimum $\lambda_R = 70$ microns and a maximum at $\lambda_W = 54$ microns.

We have also calculated the transmission of these capacitive grids using the Sonnet Microstrip program [12], see Fig. 6b. Minima are observed at $\lambda_R = 68.1$ and 79.4 microns, maxima at $\lambda_W = 55.2$ and $\lambda_W = 58.2$ microns, respectively.

The Sonnet Micro-strip program [12] solves Maxwell's equations for a proposed structure and

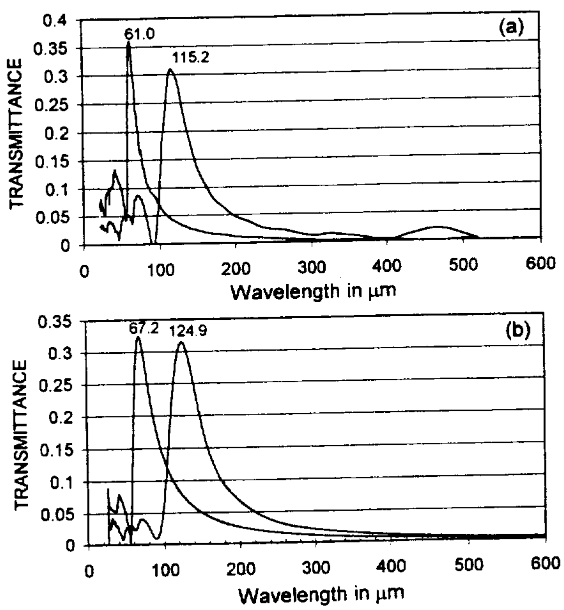

Fig. 5. Transmittance of thin inductive grids on a silicon substrate depending on wavelength. (a) Experimental. The grid with geometrical parameters $g = 16.4$, $2a = 2.5$, $2b = 4.8$, and $t = 0.2$ microns, has resonance wavelength at 61 microns and minimum at $\lambda_W = 45.8$ microns. The grid with geometrical parameters $g = 26.4$, $2a = 3.2$, $2b = 4.8$, and $t = 0.2$ microns has resonance wavelength at $\lambda_R = 115.2$ microns and minimum at $\lambda_W = 91$ microns. (b) Sonnet Program Simulation. The grid with geometrical parameters $g = 16.4$, $2a = 2.5$, $2b = 4.8$, and $t = 0.2$ microns has resonance wavelength at $\lambda_R = 67.2$ microns and minimum at $\lambda_W = 55.3$ microns. The grid with geometrical parameters $g = 26.4$, $2a = 3.2$, $2b = 4.8$, and $t = 0.2$ microns has resonance wavelength at $\lambda_R = 124.9$ microns and minimum at $\lambda_W = 89.7$ microns. All data are listed in Table 1.

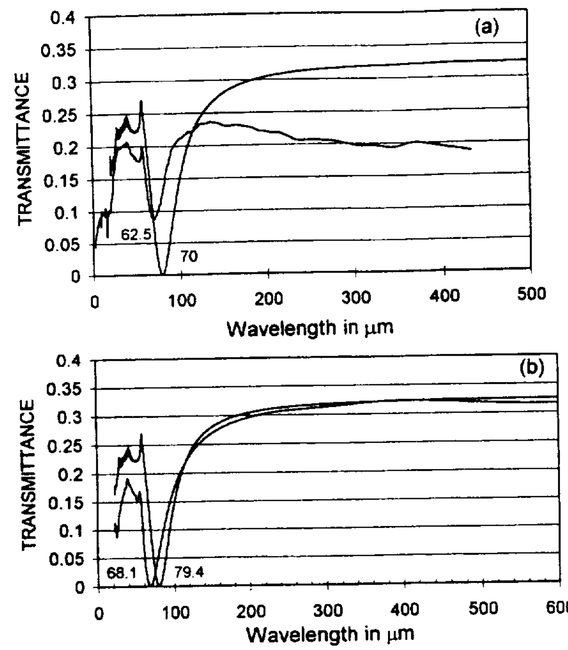

Fig. 6. Transmittance of thin capacitive grids on silicon substrate depending on wavelength. (a) Experimental. The grid with geometrical parameters $g = 16.4$, $2a = 2.5$, $2b = 4.8$, and $t = 0.2$ microns and the grid with geometrical parameters $g = 16.7$, $2a = 2$, $2b = 3$, and $t = 0.2$ microns have both resonance minima at $\lambda_R = 62.5$ and 70 microns, and maxima at $\lambda_W = 56$ and 54 microns, respectively. (b) Sonnet Program Simulation. The grid with geometrical parameters $g = 16.4$, $2a = 2.5$, $2b = 4.8$, and $t = 0.2$ microns has resonance minimum at 68.1 microns and maximum at 55.2 microns. The grid with geometrical parameters $g = 16.7$, $2a = 2$, $2b = 3$, and $t = 0.2$ microns has resonance minimum $\lambda_R =$ at 79.4 microns and maximum at $\lambda_W = 58.2$ microns. All data are listed in Table 1.

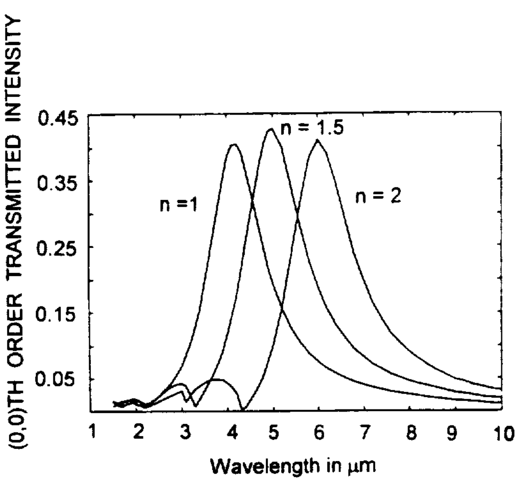

Fig. 7. Calculation of the (0,0)th order transmitted intensity using the Fourier Modal method. Transmission of three grids of type #2 (Fig. 2) on substrates with refractive indices $n = 1$, 1.5 and 2. For the three indices, maxima have been observed at 4.15, 4.95 and 6 microns, and minima and 2.22, 3.33, and 4.3 microns, listed in Table 1. The thickness of the grids are 0.2 microns.

needs as input data the geometrical parameters, the surface conductivity of the metal, and the refractive index of the dielectric substrate, if applicable. One sees that the agreement is good, considering that for the calculations the values for g, a, and b of the masks are used, and not the values of the finally manufactured grids, and that averages had to be taken to remove the interference fringes of the substrate. All data are listed in Table 1.

Comparison of the transmission of inductive and capacitive thin grids shows that one observes a complementary pattern for complementary grids. This is true for the resonance wavelength as well as for the Wood anomaly.

The ratios of the wavelength observed for a grid on silicon to the wavelength of a free standing grid, for both resonance wavelength and Wood anomaly, are listed in Table 1. For the free standing grids the resonance is calculated from the empirical formula, Eq. (1b). For the resonance, the ratio of the wavelength of the grid on silicon to the wavelength of the free standing grid is on the average 2.8, while for the Wood anomaly a similar ratio is about equal to the refractive index of silicon (3.4). Therefore the resonance wavelength shifts by about 80% of the refractive index while the Wood anomaly shifts by about the value of the refractive index. We note that for the free standing capacitive grids, which do not exist, we took the corresponding values from the free standing inductive grids, calculated from the empirical formula.

We have calculated, using the Fourier Modal method, the transmission of three grids of type #2 of Fig. 2, for substrates of refractive indices $n = 1$, $n = 1.5$, and $n = 2$, see Fig. 7, and results are tabu-

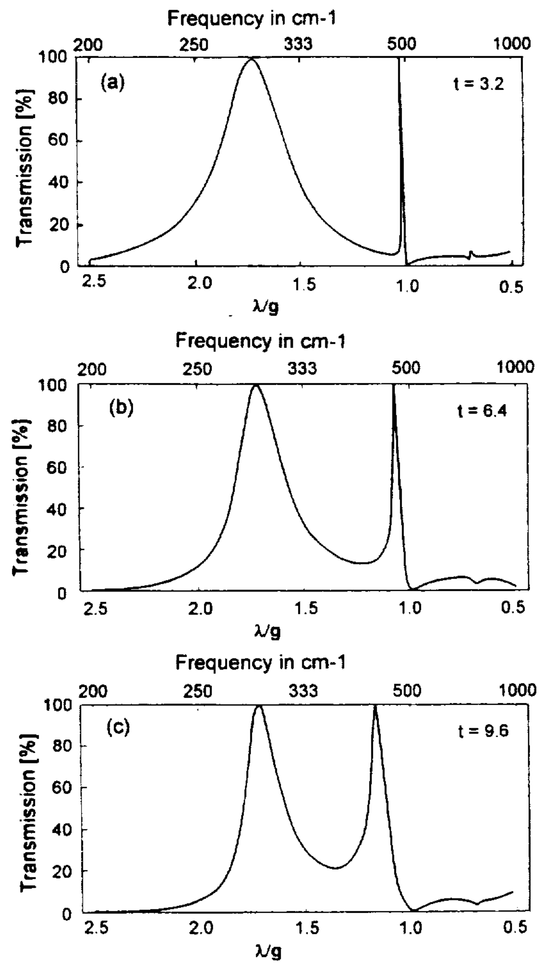

Fig. 8. Transmission of free standing thick grids depending on λ / g. Theoretical calculations taken from Ref. [14] with geometrical parameters $g = 20$, $2a = 2.4$, and $2b = 3.6$ microns. For (a) to (c) we have thickness $t = 3.2$, 6.4 and 9.6 microns, resonance peaks at 30.9, 29.8, 31.3 microns, and "thickness peaks" at 20.4, 21.2, and 22.6 microns, respectively. (The frequency is indicated in cm^{-1}, the wavelengths have been determined from the figures of the paper.)

lated in Table 1. The shift of the resonance wavelength of a grid on a substrate compared with the resonance wavelength of the free standing grid is also about 80% of the refractive index, similar to the case of silicon, and the Wood anomaly shifts just with the refractive index.

Dawes et al. [13] have theoretically studied the transmission of metal meshes on a substrate, and the above observations are in general agreement with their calculations.

4. Thick free standing cross shaped grids

Thick free standing cross shaped grids have been theoretically studied by Compton et al. [14] using the mode expansion method. The grids were assumed to have infinite conductivity, periodicity constant $g = 20$ microns, values of $2a = 2.4$, and $2b = 3.6$ microns and thickness of $t = 3.2$, 6.4 and 9.6 microns. The transmissions of these grids depending on λ/g are shown in Fig. 8. One observes for all three grids a resonance peak at about 30 microns and a second peak that depends on the thickness. This peak appears as a very narrow peak close to $\lambda = g$ for $t = 3.2$ microns, then broadens and shifts to longer wavelength with larger values of t. For $t = 3.2$, 6.4 and 9.6 microns the peaks appear at 20.4, 21.2, and 22.6 microns, respectively. A minimum is also observed at $\lambda_W \approx g$, corresponding to the Wood anomaly. All peaks are listed in Table 2.

Using the LIGA method, Ruprecht et al. [15] produced free standing cross shaped grids with geometrical parameters $g = 20$, $2a = 1.5$ and $2b = 3$ microns and thickness $t = 11$, 20 and 29 microns. The observed transmission of the grids showed no dependence on the metal used for the manufacturing, such as Cu, Ni or Au. The transmission of these grids depending on frequency in cm^{-1} is shown in Fig. 9. All grids show a resonance peak at around 35 microns, and for the grids of $t = 11$, 20 and 29 microns there are second peaks at 24.5, 28.2 and 31 microns, respectively. A third peak at 24.5 microns is observed for the grid with $t = 29$ microns. The wavelengths of all peaks are listed in Table 2.

Using the Fourier Modal method we have calculated the transmission of grids with thickness of $t = 0.2$, 0.4 and 0.8 microns, see Fig. 10. The calculations were performed in the near infrared for a type #2 grid, see Fig. 2a, with geometrical parameters of $g = 2.143$, $2a = 0.428$ and $2b = 0.24$ microns. In Fig. 10 one finds a small second peak for the grid of

Table 2
Thick free standing grids

		Resonance peak		Thickness peak (First)		Grid Parameters		
						g	$2a$	$2b$
Fig. 9	t	Cal. Eq. (1b)	obsv. (R14)	Cal. Eq. (2)	obsv. (R14)			
	11	34	35	24.5	24.5	20	1.5	3
	20	34	35	28.3	28.2			
	29	34	34	31	31			
	29			24.5[a]	24.5[a]			
Fig. 8	t	Cal. Eq. (1b)	data (R13)	(First) Cal. Eq. (2)	data (R13)			
	3.2	31.6	30.9	20.1	20.4	20	2.4	3.6
	6.4	31.6	29.8	22	21.2			
	9.6	31.6	31.3	23.8	22.6			
Fig. 10	t	Cal. Eq. (1b)	data	(First) Cal. Eq. (2)	data			
	0.2	3.19	4.0	2.06	non	2.143	0.428	0.24
	0.4	3.19	4.1	2.19	2.25			
	0.8	3.19	4.2	2.43	2.42			

[a](Second) calculated with Eq. (2) and $2g - t$ instead of t.

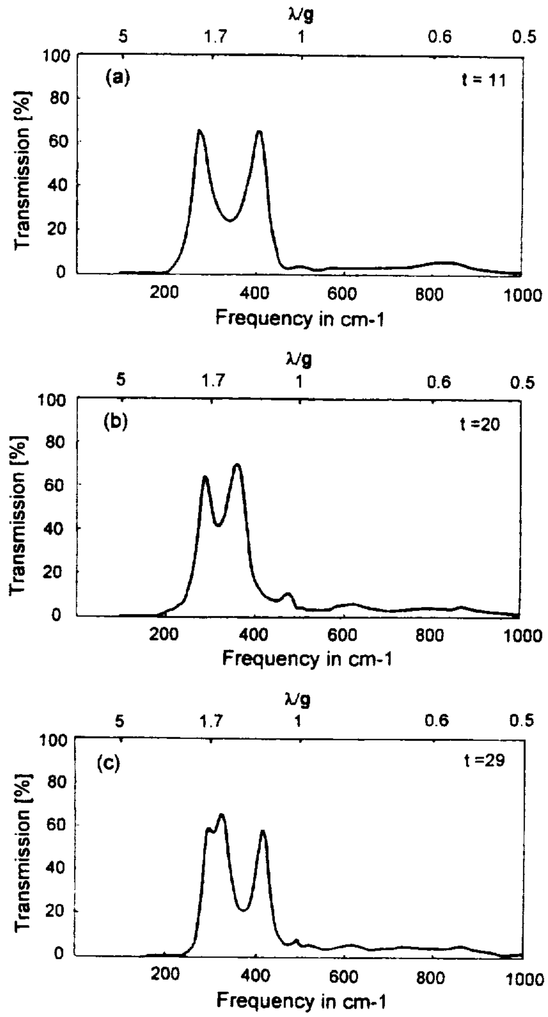

Fig. 9. Transmission of free standing thick grids depending on frequency in cm^{-1}. Experimental data taken from Ref. [15]. The geometrical parameters are $g = 20$, $2a = 1.5$, and $2b = 3$ microns. For (a) to (c) we have thickness $t = 11$, 20 and 29 microns, resonance peaks at 35 (287 cm^{-1}), 35 (287 cm^{-1}), and 34 (290 cm^{-1}) microns, and "thickness peaks" at 24.5 (409 cm^{-1}), 28.2 (355 cm^{-1}) and 31 (318 cm^{-1}) microns, respectively. The "second" peak in (a) at $\lambda = 24.5$ microns and the "third" peak in (c) have been reported at exactly the same frequency of 409 cm^{-1}. Values for λ / g are also indicated, and the values of all frequencies in cm^{-1} are reported in Ref. [15] and listed in Table 2.

thickness $t = 0.4$ microns, and to longer wavelength a larger peak for the grid with $t = 0.8$ microns.

The grids with transmissions shown in Figs. 8 and 9 have the same periodicity constant $g = 20$ microns, and the thickness of the grids has the values 3.2, 6.4, 9.6, 11, 20, and 29 microns. The a and b values of the grids in Fig. 8 [14] are slightly different from the grids shown in Fig. 9 [15]. The values of the main peaks around 31 and 35 microns, respectively, agree well with values calculated using the empirical formula, Eq. (1b), and are listed in Table 2. All grids of Figs. 8 and 9 show a second peak, depending on the thickness t and shifting to longer wavelength with larger values of t. To get an empirical formula for these second peaks, we recall that the "dipole interaction" results in a wavelength of $\lambda_R \approx 2g$ where the corresponding K_R vector has a value of $2\pi/2g$.

For the "side wall interaction" we use a wave vector K_S equal to $2\pi/(g+t)$ with a wavelength λ_S depending linearly on t and approaching g for $t = 0$. The wavelength λ_T of the "second peak" is calculated from the vector addition of K_R and K_S, assuming that they are perpendicular to one another. This results in

$$1/(\lambda_T)^2 = 1/(2g)^2 + 1/(g+t)^2 \qquad (2)$$

This empirical formula for λ_T uses only the periodicity constant g and the thickness t of the grids.

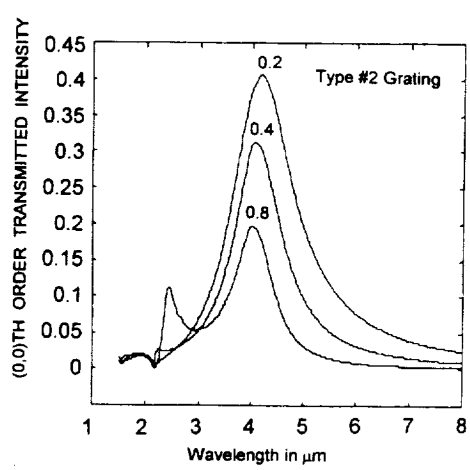

Fig. 10. Calculations using the Fourier Modal method for free standing thick grids of type #2. Calculation of the transmitted intensity of grids with $g = 2.143$ in the near infrared. The thickness of the grids were assumed to be 0.2, 0.4 and 0.8 microns, and for thickness of 0.4 and 0.8 microns one sees the development of a "thickness" peak. Resonance peaks occur at 4.0, 4.1, and 4.2 microns and "thickness" peaks at 2.25 and 2.42 for thickness of 0.4 and 0.8 microns, respectively. Data are listed in Table 1.

The calculated values using this formula are listed in Table 2, and agree very well with the data from Compton et al. [14] and the observed data from Ruprecht et al. [15]. A third peak, only observed for the grid in Fig. 9c with a t value larger than g, is observed at 409 cm^{-1}, exactly at the same wavenumber reported in Fig. 9a for the second peak of the grid with $t = 11$. If we assume that for values t' larger than g we have to use $2g - t'$, and insert it into Eq. (2) for t, we obtain the same value of 409 cm^{-1} for the third peak in Fig. 9c as was obtained for $t = 11$ for the second peak in Fig. 9a.

5. Comments and discussion

The empirical formula for resonance, Eq. (1b), has shown good agreement with experimental data in the mid and far infrared. The formula obtained by application of the A. Golden program to the case of infinite conductivity results in a similar formula. The coefficients are different when applying the Fourier Modal method, but one has to take into account that the calculations are done for much shorter wavelength, and by using the complex index of refraction, losses are taken into account.

For thin inductive and capacitive grids on a Silicon substrate, we have compared the experimental data for the resonance wavelength and Wood anomaly with the values calculated for "free standing" metal grids. We have chosen to calculate the resonance wavelength by using Eq. (1b), and use the periodicity constant g for the Wood anomaly. We have not used experimental values of "free standing" grids, because manufactured grids from the same mask have shown different resonance wavelengths, see Ref. [7].

The result of the comparison is shown in Table 1 and one has on average a factor of 2.77 for the shift of the resonance wavelength to longer wavelength when the grid is on the silicon substrate. A value close to the refractive index is obtained for the shift of the Wood anomaly. A similar result is obtained using the Fourier Modal method applied to three different refractive indices, see also Table 1.

Comparing the transmission of capacitive and inductive grids having the same geometrical parameters, we observe that complementary grids show complementary transmission, both for resonance and Wood anomaly. This is in agreement with the "electromagnetic" formulation of Babinet's principle.

Thick grids have metal surfaces located in planes perpendicular to the surface of the grid and show additional peaks. These peaks appear at wavelengths proportional to the thickness and between the resonance and the Wood anomaly. In the case where the thickness approaches zero, it seems that the wavelength converges to the periodicity constant g.

Using the Fourier Modal method we have calculated the transmission depending on the thickness and have also found a second peak between the Wood anomaly and the resonance wavelength.

The calculations performed with the Golden program, the Sonnet Microstrip program and the Fourier Modal method represent well the observed data.

The empirical formula of Eq. (1b) may be used to calculate the resonance wavelength for free standing thin and thick grids, and thin grids on a substrate, if the wavelength shift is taken into account.

The empirical formula of Eq. (2) calculates well the wavelength of the "thickness peaks" for all thickness' in the case without [14] and with losses [15], and for the near infrared. The formula uses only the periodicity constant g and the thickness t.

Acknowledgements

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INDUCTIVE CROSS SHAPED METAL MESHES AND DIELECTRICS.

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Abstract

Calculations of resonance wavelength and bandwidth of inductive cross shaped metal meshes, free standing or supported by dielectric layers, have been performed using the Micro-Stripes program. The dependence of the shift of the resonance wavelength on the thickness and refractive index of dielectric layers has been described by a "pair of coupled surface plasmons". The approximate width of the surface plasmons in direction normal to the surface has been obtained. The transmittance of two mesh filters with dielectric layers are calculated for specific alignment of the crosses of one mesh with respect to the other. A coupled oscillator model has been used for discussion of the interaction of the resonance wavelengths of the two meshes with one another and with the Fabry-Perot modes. Design procedures for two mesh filters are given.

1. Introduction

Electroformed metal meshes have been used in the 60s by Ulrich[1] as Fabry-Perot reflectors in the far infrared. These square shaped metal meshes, called by Ulrich[2] "inductive" grids, showed high reflectivity and low losses over a large spectral region and were used in the long wavelength region as band pass filters. The inverse structure, first published by Ressler and Möller[3], were called "capacitive" grids" and used as low pass filters.

Ulrich[4] introduced a combination pattern of grids and squares for the manufacturing of cross shaped grids and Chase and Joseph[5] studied in detail the resonance wavelength and the bandwidth. Two patterns are shown in Fig. 1: a mesh with the shape of crosses shown

in Fig. 1a has a large bandwidth of about 50% to 60%, while a mesh as shown in Fig. 1b has a smaller bandwidth of about 20%.
Ulrich[2] developed transmission line theory for monitoring multiple mesh filters and introduced the "damped oscillator" model. Timusk and Richards[6], following Ref. 7, used cascading matrices for transmission line calculations of multi-layer capacitive meshes on dielectric substrates.
Cross shaped metal meshes on Silicon substrate have been investigated experimentally by Hicks[8] and Möller et al[9] and the Micro-Stripes program[10] was successfully used to reproduce the experimental data.
We have used in a preceding paper[11] the Micro-Stripes program to calculate the near field effect of multi-layer cross shaped free standing metal meshes. In this paper we will use the Micro-Stripes program to study the resonance wavelength and bandwidth of a single metal mesh on dielectric layers. The input data are the geometrical parameters of the cross, the surface impedance of the metal mesh and the refractive index and thickness of the dielectric layers. In contrast, transmission line theory uses the resonance wavelength and bandwidth as input parameters for transmittance calculations of a single mesh.
The Micro-Stripes program calculates the transmittance of two metal meshes separated by a dielectric spacer, but gives very different results depending on whether the two meshes are lined up, or whether the second mesh is displaced a distance g/2, in the plane of the mesh, with respect to the first. Because of boundary condition symmetry requirements, these two configurations are the only ones that Micro-Stripes is able to calculate.
Transmission line theory may be used to calculate the transmittance of two metal meshes for a non-aligned configuration as one has for experimental two mesh filters. However, using as input data the Micro-Stripes results for a single mesh, the transmission line calculations do not account for the shift of the resonance wavelength of the meshes depending on the thickness of thin dielectric layers.

2. Transmission line theory.

In analogy to microwave theory, Ulrich developed transmission line theory for the calculation of reflectance and transmittance of metal meshes[2]. The theory uses geometrical and electrical parameters for the description of optical properties. A short description is given in Ref. 12.
The theory is semi-empirical and in its original formulation employs only three parameters related to a single mesh. These parameters are the resonance frequency ω_o, the bandwidth A1 and the loss parameter a1. The theory is limited to the wavelength region larger than the periodicity constant.
In the following we will list the essential formulas for the oscillators and the cascading matrices and the expressions for the transmitted and reflected intensities.

A. Oscillator Expressions.

We consider only thin grids, and the shunt impedance of inductive grids is taken as

$$Y(\lambda) = 1/[a1 - i(\omega\, A1)/\Omega(\lambda)] \quad (1)$$

where $\omega = \omega_o \sqrt{2/(n_1^2 + n_2^2)}$ (2)

and $$\Omega(\lambda) = g/\lambda\omega - \lambda\omega/g. \quad (3)$$

The resonance frequency of the mesh is ω_o and the corresponding wavelength may be obtained form an empirical formula for thin inductive cross shaped grids[5]. The loss parameter a1 is taken as 0.001, see Ref.13. The bandwidth parameter A1 may be calculated using the Micro-Stripes program or chosen from empirical data.

B. Cascading matrices

The waves on the left side of the impedance Y, see Fig 2, are related to the waves on the right side by a matrix M as

$$b_1 = m_{11}\, a_2 + m_{12}\, b_2$$
$$a_1 = m_{21}\, a_2 + m_{22}\, b_2 \quad (4)$$

For $a_2 = 0$ one has for the ratio of reflected wave b_1 to incident wave a_1

$$b_1/a_1 = m_{12}/m_{22} \quad (5)$$

and for the transmitted wave

$$b_2/a_1 = 1/m_{22}. \quad (6)$$

The cascading matrix M1 describes the impedance at the interface of a metal mesh with dielectrics of refractive index n_1 on the left and n_2 on the right and is given as

$$m1_{11} = [-Y + (n_1 + n_2)]/2n_1 \qquad m1_{12} = [-Y + (n_1 - n_2)]/2n_1$$
$$m1_{21} = [Y + (n_1 - n_2)]/2n_1 \qquad m1_{22} = [Y + (n_1 + n_2)]/2n_1 \quad (7)$$

The cascading matrix M2 describes the impedance at the interface of a dielectric with refractive index n_1 on the left and n_2 on the right and is given as

$$m2_{11} = (n_1 + n_2)/2n_1 \qquad m2_{12} = (n_1 - n_2)/2n_1$$
$$m2_{21} = (n_1 - n_2)/2n_1 \qquad m2_{22} = (n_1 + n_2)/2n_1 \qquad (8)$$

The matrix M3 describes a transmission line without losses of length d in the medium with refractive index n.

$$m3_{11} = \exp(-i2\pi dn)/\lambda \qquad m3_{12} = 0$$
$$m3_{21} = 0 \qquad m3_{22} = \exp(i2\pi dn)/\lambda \qquad (9)$$

Losses may be included in M1 to M3 by using a complex refractive index.
A combination of several matrices of the type M1, M2, and M3 will now be used for the calculation of the transmittance of various combinations of metal meshes with dielectric layers. Two metal meshes with a dielectric spacer will be described by the matrix product Mb =M1M3M1, and two metal meshes embedded in a dielectric by a seven matrix product Mf = M2M3M1M3M1M3M2. The refractive indices have to be specified appropriately in each matrix, and also the thickness in M3 type matrices.

3. Calculations based on Electromagnetic theory.

Many authors have used electromagnetic wave theory for the calculation of the transmittance of metal meshes. We like to cite only a few. Dawes et al[14] studied capacitive grids on substrates of various refractive indices and compared with transmission line calculations and experimental observations. Compton et al[15] studied free standing cross shaped inductive grids and predicted the "thickness" peaks. Porterfield et al[16] used Fourier expansions and the commercially available HFSS program[17] to study thin cross shaped grids.
The Micro-Stripes program has been used successfully by Möller et al.[9] to reproduce the transmittance of thin inductive and capacitive metal meshes on thick Silicon substrates. The agreement with the experimental data are excellent. Therefore we think that one can consider the Micro-Stripes program calculations equivalent to "experimental results".

4. Free standing single metal meshes.

A. Resonance wavelength.

The Micro-Stripes program needs as input data the geometrical parameters of the cross, the thickness of the metal mesh and the surface impedance. From the calculated transmittance one obtains the resonance wavelength and the bandwidth. The losses may be determined from the choice of the surface impedance. We have calculated the transmittance of thin cross shaped metal meshes with geometrical parameters $g = 24$ μm, $2a = 9.6$ μm, $2b = 3.6$ μm, metal thickness of 0.2 μm and surface impedance of 1.635 Ohm cm. The calculated transmittance is shown in Fig.3 with resonance wavelength $\lambda_R = 32.8$ μm.

The resonance wavelength agrees very well with the empirical formula[5]

$$\lambda_R = 2g - 4a + 2b \qquad (10)$$

Using the above values of g, a and b one obtains $\lambda_R = 32.4$ μm. The validity of this formula for slightly different values of a and b and a constant g may be seen from Table 1. The formula is not valid for a/g values around 0.2 and b/g values around 0.5 to 1.

B. Bandwidth of a single mesh.

We have studied the dependence of the bandwidth on the cross parameters 2a and 2b for a constant value of g. The transmittance is shown in Fig.3 for five different sets of a/g and b/g. The bandwidth BW is taken as the width at half height divided by the peak wavelength. The BW and peak intensity depending on the pair of values of a/g and b/g are listed in Tab.1

Table 1
Bandwidth depending on a/g and b/g

All g = 24 # in Fig.3	a/g	b/g	Peak WL 2g-4a+2b	Peak WL From Fig.3	BW	Intensity
1	0.233	0.008	26	31.5	0.07	0.86
2	0.217	0.042	29.2	32.8	0.13	0.97
3	0.200	0.075	32.4	32.8	0.18	0.98
4	0.183	0.108	35.6	33.7	0.26	0.99
5	0.133	0.208	45.2	33.2	0.63	1

One finds from Table 1 that a bandwidth of 13% to 18% with a theoretical transmittance close to 1 may be obtained for a/g values of about 0.2 and b/g values of about 0.05. This is in good agreement with the study by Chase and Joseph[5] on the bandwidth of cross shaped metal meshes.

5. Single metal mesh supported by dielectric layers.

A. The "pair of coupled surface plasmons" model.

Ulrich[18] and Popov[19] have given a general analysis of the modes of a 2D periodic metal mesh. The resonance wavelength λ_R, discussed above, corresponds to a resonance frequency of one of these modes. The incident light excites this mode, and the incident energy is transformed to the reflected and transmitted light waves.

A mode of the metal mesh consists of a pair of coupled surface plasmons. When a surface plasmon on one side of the mesh propagates in a dielectric layer, the resulting resonance wavelength of the metal mesh mode will shift to longer wavelength and even more when the metal mesh is embedded in a dielectric.

B. Transmission line theory and experimental data.

Transmission line theory cannot be used to calculate the resonance wavelength and bandwidth of a metal mesh. They are chosen as input parameters related to an electrical resonance circuit. Whitbourn and Compton[13] have analyzed the role the capacitance plays in the electrical circuit with respect to the resonance frequency. They conclude that the resonance frequency is shifted by a factor of $\sqrt{[2/(n_1^2 + n_2^2)]}$, where n_1 is the refractive index on one side of the mesh and n_2 on the other. We have investigated[9] experimentally a thin cross shaped mesh on a Silicon substrate of 500 μm thickness and found λ_R shifted by a factor of 2.48. From the square root expression one has a shift of 2.5 for a dielectric constants of $n_1 = 1$ on one side and $n_2 = 3.4$ (Silicon) on the other side.

C. Inductive metal mesh and dielectric layers.

The Micro-Stripes program has been applied to calculations of the transmittance of cross shaped metal meshes on a substrate or embedded in a dielectric. The parameters of the mesh are g = 20 μm, 2a = 1.5 μm, 2b = 3 μm, and t = 0.2 μm. Calculations were performed for a free standing mesh, a mesh on a substrate of refractive index n = 1.5 and thickness d = 7 μm and embedded in a dielectric, with thickness of 7 μm on each side. The results are shown in Fig.4. The shift of the resonance wavelength of the metal mesh on the substrate of refractive index n = 1.5 is 9.1 μm (22.8%), and for the embedded case 20.6 μm (51.6%).

D. Wavelength dependence of the resonance mode on the thickness of the dielectric layers and the extent of the surface plamons in the normal direction.

The amplitudes of the surface plasmons on both sides of the metal mesh surface have an exponential decrease in the z-direction, that is the direction perpendicular to the surface, see Ref.20. The resonance wavelength shifts depending on the thickness of the dielectric layer. At zero thickness the resonance wavelength is the same as for a free standing mesh. With increasing thickness the resonance wavelengths shifts to longer wavelength. After the thickness has reached a value corresponding to a sufficient decrease of the amplitude in z-direction, the resonance wavelength does not shift any more.
The Micro-Stripes program has been used to calculate the resonance wavelength depending on thickness of a dielectric substrate of refractive indices 1.5, 2.4 and 3.4, see Fig. 5. The parameters of the mesh are g = 20 μm, 2a = 1.5 μm, 2b = 3 μm, and t = 0.2 μm and substrate thickness of 0 to 18 μm. The resonance wavelength shifts to longer wavelength for all three refractive indices. The shift, after a first maximum, becomes smaller. This is attributed to interaction of the resonance modes with an internal

reflection mode of the plane parallel dielectric layer. In Fig.6 we compare the dependence of the resonance wavelength of a metal mesh on a dielectric substrate with a mesh embedded in a dielectric. One mesh is on a substrate of n = 1.5 and thickness d, the other supported on both sides by a dielectric layer of thickness d and again n = 1.5. The shift for the embedded mesh is always larger. It appears from Fig.5 that the extent of the surface plasmons into the z-dielectric is approximately 1/2 of the periodicity constant g divided by the refractive index.

6. Two metal meshes with dielectric spacer or embedded in a dielectric.

A. Micro-Stripes and Transmission line calculations.

The Micro-Stripes program was applied to transmittance calculations of two meshes separated by a dielectric spacer of thickness d, or embedded in a dielectric. The geometrical parameters of the meshes are g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and t = 0.2 μm. There are two configurations for the two meshes, one with the openings of the two meshes lined up (A) and the other with the openings of one mesh in the middle between the openings of the other mesh (B) (see Fig 7)
Transmission line theory does not assume any "line up" of the crosses of one mesh with respect to the other and is therefore much closer to experimental set-ups of the two cross shaped meshes. While transmission line calculations do not account for the shift of the resonance wavelength of the mesh depending on the thickness of the dielectric layers, one can qualitatively study the interaction of the modes of the two meshes. We call the modes of the meshes M-modes and for non-zero interaction of the two meshes one has two different resonance wavelengths. The difference gets smaller and smaller with increasing spacing and at a certain distance a new mode appears, and its peak wavelength shifts to longer and longer wavelengths for increasing thickness. We call this mode the FP-mode because of its similarity to the modes of a Fabry-Perot with two reflector plates at distance d.

B. Refractive index n =1.5.

a. Transmission line calculations for d = 2 to 16 μm.

We assume for this qualitative study that there is no dependence of the resonance wavelength on the thickness of the dielectric spacer or layers. The transmittance is calculated for two meshes with spacer and embedded in a dielectric for the range of d = 2 to 16 μm and d* = 10 μm, see Fig.8. The mesh parameters are a1 = .001, A1 = 0.1 and λ_o = 32.4 μm, corresponding to values of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm. The peak wavelengths of the lowest calculated peaks are plotted in Fig.8 for both, the case of a spacer (SP) and the embedded case (EM) and for spacers of 4 and 8 μm in Fig.9 to 12 (TLT). For the (SP) and (EM) configuration see Fig.7.

b. Micro-Stripes calculations for spacer of thickness 4 and 8μm.

The transmittance for two meshes, separated by a dielectric spacer of thickness of 4 μm is shown in Fig.9 and for 8 μm in Fig.10.
In Fig.9 we have for filter (A) and (B) 2 M-modes and one FP- mode and 2 M-modes for (TLT).
In Fig.10 we have for filter (A) and (B) 2 M-modes and one FP- mode and 2 M-modes for (TLT). The interaction of the 2 M-modes of (B) and (TLT) decreases, while the interaction of the 2 M-modes of (A) are zero.

c. Embedded with spacers of 4 and 8 μm and layers of 10 μm.

The transmittance for two meshes embedded in a dielectric with thickness d* of "outside dielectric layers" of 10 μm and spacer of thickness of 4 μm is shown in Fig.11 and for 8 μm in Fig.12.
- In Fig.11 we have 2 M-modes and one FP- mode for filter (B) and 2 M-modes for (TLT). The M-modes of filter (A) show decrease intensity.
In Fig.12 we have 2 M-modes and one FP- mode for filter (B) and 1 M-modes for (TLT). The interaction of the 2 M-modes of (B) and (TLT) decreases, while the interaction of the 2 M-modes of (A) are zero for increasing distance.

C. Refractive index n =3.4.

a. Transmission line theory of a two coupled oscillator model.

We have calculated the transmittance of two meshes with spacer and embedded in dielectric for d = 2 to 16 μm, d* = 5 μm, and mesh parameters a1 = 0.001, A1 = 0.1 and λ_o = 32.4 μm, corresponding to values of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm. Similarly as discussed above we ignore the thickness dependence of the spacer in this approximate calculations. The result of the peak wavelengths of the lowest calculated peaks are plotted in Fig.13 for both, the spacer and the embedded case and also for spacers of 4 and 8 μm in Fig.14 to 17 (TLT).

b. Dielectric spacer of thickness 4 and 8 μm.

The transmittance for two meshes, separated by a dielectric spacer of thickness of 4 μm is shown in Fig.14 and for 8 μm in Fig.15.
In Fig.14 we have 2 M-modes and one FP- mode for filter (A) and (B) and 2 M-modes for (TLT).
In Fig.15 we have 2 M-modes and 2 FP- modes for filter (A) and (B), and 2 M-modes and one FP-mode for (TLT). The interaction of the 2 M-modes of (A), (B) and (TLT) have decreased for larger spacing.

c. Embedded in dielectric with spacer of thickness 4 and 8 μm and layers of 5 μm.

The transmittance for two meshes embedded in a dielectric with thickness d* of "outside dielectric layers" of 5 μm and spacer of thickness of 4 μm is shown in Fig.16 and for 8 μm in Fig.17.
In Fig.16 we have 2 M-modes and one FP- mode for filter (A) and (B) and 2 M-modes for (TLT). The M-modes of filter (A) show decrease intensity.
In Fig.17 we have 2 M-modes and one FP- mode for filter (A) and (B) and 2 M-modes for (TLT). The interaction of the 2 M-modes of (B) and (TLT) have decreased, while the interaction of the 2 M-modes of (A) are zero.

D. Discussion.

From the qualitative study of the modes, see Fig.8 and 13, one expects that the interaction of the modes decreases from spacing of 4 μm to spacing of 8 μm and is smaller for the (EM) case than for the (SP) case. This is shown in Fig.9 to 12 for n = 1.5 and Fig. 14 to 17 for n = 3.4.
The λ/4 spacing of the two meshes without any dielectrics, that is for two free standing meshes is 8 μm. Fig. 8 and 13 show minimum interaction at that spacing, and less splitting is seen in Fig.9 to 12 and Fig. 14 to 17 for most peaks.
One has smaller interaction of all modes for low refractive index. For n = 1.5, comparing Fig.10 to Fig.12, one sees that the (TLT) modes reduces their interaction such that only one line appears, while for the (EM) case, the filter A configuration reduces the transmittance to a single line.

7. Filter design.

A. Single mesh filter.

a. Calculation of resonance wavelength and bandwidth.

The Micro-Stripes program calculates the resonance wavelength λ_R of a free standing metal mesh depending on g, a, b and metal thickness t. The calculated peak wavelength agrees very well with the empirical formula $\lambda_R = 2g - 4a + 2b$. The resonance wavelength of the metal shifts to longer wavelength when supported by dielectric films. The Micro-Stripes program calculates also the shifted resonance wavelength for given refractive index and thickness of dielectric layers on one side of the mesh or on both.
The dependence of the bandwidth of a single free standing mesh on the choice of the parameters g, a, and b suggest to use for a narrow bandwidth of 15% values of a/g around 0.2 and b/g around 0.05, see Table 1.

B. Two mesh filter.

a. Micro-Stripes calculations of resonance wavelength and bandwidth using the Micro-Stripes program for two mesh filter with dielectrics.

In order to reduce the bandwidth of a single mesh one uses two meshes mounted parallel at distance d. The experimental mounting results usually in a "non-aligned" configuration. The Micro-Stripes program can only calculate the aligned configurations A and B. The configuration A may be used for narrow band pass filters with high transmittance while the configuration B offers a high reduction of short wavelength light, but usually displays more than one resonance peak

b. Transmission line calculation of bandwidth using transmission line theory for two mesh filter with dielectrics.

Transmission line theory can calculate the transmission of two metal meshes with crosses in the "non-aligned" configuration, but it cannot correctly include the shift of the resonance wavelength originating from the dielectric spacer of thickness d and refractive index n. The percentage shift of the resonance wavelength of the free standing mesh is larger for high refractive index material than for low ones A choice of Silicon with n = 3.4 results in a large wavelength shift depending on thickness, while a low refractive index of n = 1.5 makes approximate methods useful

One obtains a small bandwidth when the interaction of the resonance wavelength of the two meshes is small, that is for meshes in free space at a spacing of $\lambda_R/4$. To minimize the interaction between the two meshes separated by a dielectric spacer, the distance between the two meshes should be $d_s = \lambda_F/4$, where λ_F is the resulting resonance wavelength of the mesh in contact with the dielectric layer For spacers with low refractive index we discuss the approximate case that the thickness of the spacer is so large that the shift of the resonance wavelength depends only on the refractive index of the spacer and not on the thickness. The shifted resonance wavelength of one mesh is then $\lambda_F = n\,\lambda_R$, and therefore $d_s = n\,\lambda_R/4$. The geometrical distance $d = d_s/n = n\lambda_R/4n = \lambda_R/4$. In this approximation we have for the thickness of the spacer the same value as one obtains for free standing meshes. This has been shown in Section 6 for two meshes with dielectric spacer, see Fig.8, 10 and 12 for n = 1.5

In Fig.18 we show the transmittance for two meshes with spacer of thickness 8 μm, for free standing meshes (F), spacer of refractive index n = 1.5 (SP) and embedded in dielectrics of n = 1.5 (EM), with outside layers of 10 μm. The bandwidth of (F) is 10%, of (EM) is 10% and of (SP) is 12%. One observes that the resonance wavelength is shifted when using dielectric layers, but that the bandwidth remains about the same. altered.

C. Results of Filter design

The resonance wavelength and bandwidth of a single mesh may be calculated from the geometrical parameters of the metal and the supporting films and the loss parameter of the metal and dielectrics.
The resonance wavelength and bandwidth of two metal meshes separated by a dielectric spacer can only be calculated by the Micro-Stripes program for two specific cases of alignment of the crosses of one mesh with respect to the other.
Transmission line theory cannot calculate the resonance wavelength and bandwidth of two metal meshes separated by a dielectric spacer because it does not account for the shift of the resonance wavelength depending on the thickness of the spacer.
An approximate procedure may be used for a dielectric spacer of low refractive index and thickness so large that the dependence on the thickness of the resonance wavelength may be disregarded.

8. Summary.

We have studied the resonance wavelength of cross shaped metal meshes in contact with dielectric layers. The resonance modes of the metal meshes were described by a pair of tightly bound surface plasmons. The dependence of the shift of the resonance wavelength on thickness and refractive index of the dielectric layer was used for an estimate of the width of the surface plasmons in direction perpendicular to the surface of the metal mesh. The resonance wavelength and bandwidth of a single mesh in contact with dielectric layers was calculated using as input data the geometrical parameters, the surface impedance of the metal and the refractive index of the layers.
Using Micro-Stripes calculations, the resonance wavelength of two metal meshes can only be obtained for two specific alignments of the crosses of the meshes with respect to one another. The resonance wavelength of two metal meshes with non-aligned crosses can be calculated approximately for low refractive index materials using transmission line theory.

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Figure Captions

Fig.1.
a. Inductive cross shaped mesh, black is metal, bandwidth 40% to 60%..
c. Inductive cross shaped mesh, black is metal, bandwidth 15% to 30%.
c. Geometrical parameters of crosses.

Fig.2.
Shunt impedance with incident and reflected waves on left side with refractive index n_1 and right side with refractive index n_2.

Fig.3.
Bandwidth of cross shaped meshes. The periodicity constant is g = 24 µm. The pairs of a and b values are: (1), a = 5.6 µm and b = 0.2 µm (2), a = 5.2 µm and b = 1.0 µm. (3), a = 4.8 µm and b = 1.2 µm. (4), a = 4.4 µm and b = 0.26 µm (5), a = 3.2 µm and b = 5 µm.

Fig.4.
Transmittance of inductive cross shaped metal meshes with g = 20 mµ, 2a = 1.5 mµ, 2b = 3 mµ and thickness 0.2 µm.
a. Free standing, resonance wavelength 39.9 µm
b. On substrate of thickness 7 µm and refractive index n 1.5, resonance wavelength 49 µm.
c. Embedded in dielectric, thickness of 7 µm on both sides and n = 1.5, resonance wavelength 60.5 µm.

Fig.5
Transmittance of inductive cross shaped metal meshes with g = 20 mµ, 2a = 1.5 mµ, 2b = 3 mµ and thickness 0.2 µm on dielectric substrate of various thickness' and refractive indices. Triangles: n = 3.4, squares n = 2.4, round dots n = 1.5

Fig.6.
Transmittance of inductive cross shaped metal meshes with g = 20 mµ, 2a = 1.5 mµ, 2b = 3 mµ and thickness 0.2 µm and dielectrics of refractive index n = 1.5.
Metal mesh on a substrate (d) and embedded in a dielectric (2d). The embedded metal mesh has a dielectric layer of thickness d on both sides

Fig.7.
Schematic arrangement of metal mesh and dielectrics. Black lines are metal meshes. Spacer configuration (Sp) with thickness d, Embedded configuration (EM) with d* thickness of layers on "outside" of meshes. In the filter configuration (A) the openings of both metal meshes are "lined up", in configuration (B) the openings of one mesh is in the middle between the openings of the other mesh.

Fig.8.
Transmission line calculations of peak wavelength of two meshes with dielectrics of n = 1.5 depending on thickness of spacer d = 2 to 16 μm. Transmission line parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001 corresponding to g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm The thickness of the outside layer for the embedded case is d* = 10 μm. Squares (SP): spacer only. Round dots (EM): embedded.

Fig.9. Two metal meshes with spacer of refractive index n = 1.5 and thickness d = 4 μm. Geometrical parameters of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm. Shaded line (A): Micro-Stripes calculation of filter. Solid line (B): Micro-Stripes calculation of filter. Broken line: Transmission line theory (TLT) using parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001.

Fig.10. Two metal meshes with spacer of refractive index n = 1.5 and thickness d = 8 μm. Geometrical parameters of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm. Shaded line (A): Micro-Stripes calculation of filter. Solid line (B): Micro-Stripes calculation of filter. Broken line: Transmission line theory (TLT) using parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001.

Fig.11. Two metal meshes embedded in a dielectric of refractive index n = 1.5, spacer thickness of d = 4 μm and outside layer of thickness d* = 10 μm. Geometrical parameters of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm. Shaded line (A): Micro-Stripes calculation of filter. Solid line (B): Micro-Stripes calculation of filter. Broken line: Transmission line theory (TLT) using parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001.

Fig.12. Two metal meshes embedded in a dielectric of refractive index n = 1.5, spacer thickness of d = 8 μm and outside layer of thickness d* = 10 μm. Geometrical parameters of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm. Shaded line (A): Micro-Stripes calculation of filter. Solid line (B): Micro-Stripes calculation of filter. Broken line: Transmission line theory (TLT) using parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001.

Fig.13.
Transmission line calculations of peak wavelength of two meshes with dielectrics of n = 3.4 depending on thickness of spacer d = 2 to 16 μm. Geometrical parameters of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm corresponding to transmission line parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001. The thickness of the outside layer for the embedded case is d* = 5 μm. Squares (SP): spacer only. Round dots (EM): embedded.

Fig.14. Two metal meshes with spacer of refractive index n = 3.4 and thickness d = 4 μm. Geometrical parameters of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm. Shaded line (A): Micro-Stripes calculation of filter. Solid line (B): Micro-Stripes calculation of filter. Broken line: Transmission line theory (TLT) using parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001.

Fig.15. Two metal meshes with spacer of refractive index n = 3.4 and thickness d = 8 μm. Geometrical parameters of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm. Shaded line (A): Micro-Stripes calculation of filter. Solid line (B): Micro-Stripes calculation of filter. Broken line: Transmission line theory (TLT) using parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001.

Fig.16. Two metal meshes embedded in a dielectric of refractive index n = 3.4, spacer thickness of d = 4 μm and outside layer of thickness d* = 5 μm. Geometrical parameters of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm. Shaded line (A): Micro-Stripes calculation of filter. Solid line (B): Micro-Stripes calculation of filter. Broken line: Transmission line theory (TLT) using parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001.

Fig.17. Two metal meshes embedded in a dielectric of refractive index n = 3.5, spacer thickness of d = 8 μm and outside layer of thickness d* = 5 μm. Geometrical parameters of g = 24 μm, 2a = 9.6 μm, 2b = 3.6 μm and thickness of 0.2 μm Shaded line (A): Micro-Stripes calculation of filter. Solid line (B): Micro-Stripes calculation of filter. Broken line: Transmission line theory (TLT) using parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001.

Fig.18.
Transmission line calculations of peak wavelength of two meshes of spacer thickness of 8 μm. Transmission line parameters λ_o = 32.4 μm, A1 = 0.1, a1 = 0.001. Free standing meshes (F), spacer of refractive index n = 1.5 (SP) and embedded in dielectrics of refractive index n = 1.5 with d* = 10 μm (EM). The ratio of bandwidth at half height to peak wavelength is for all three about 0.1.

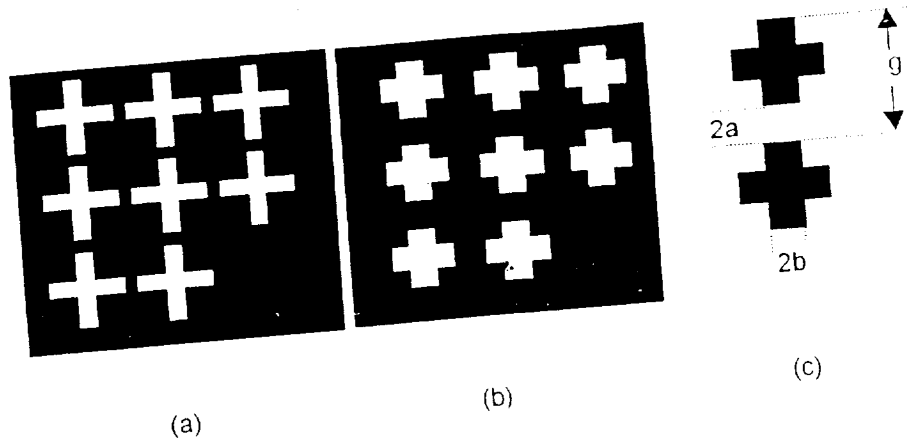

Fig. 1

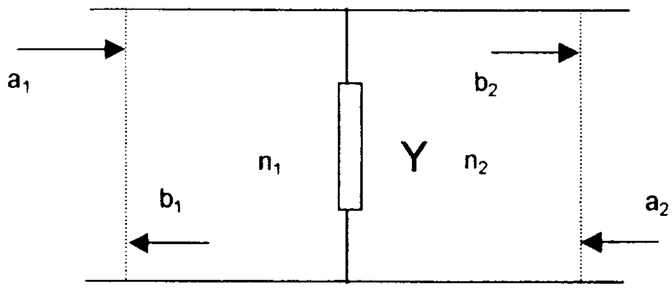

Fig. 2

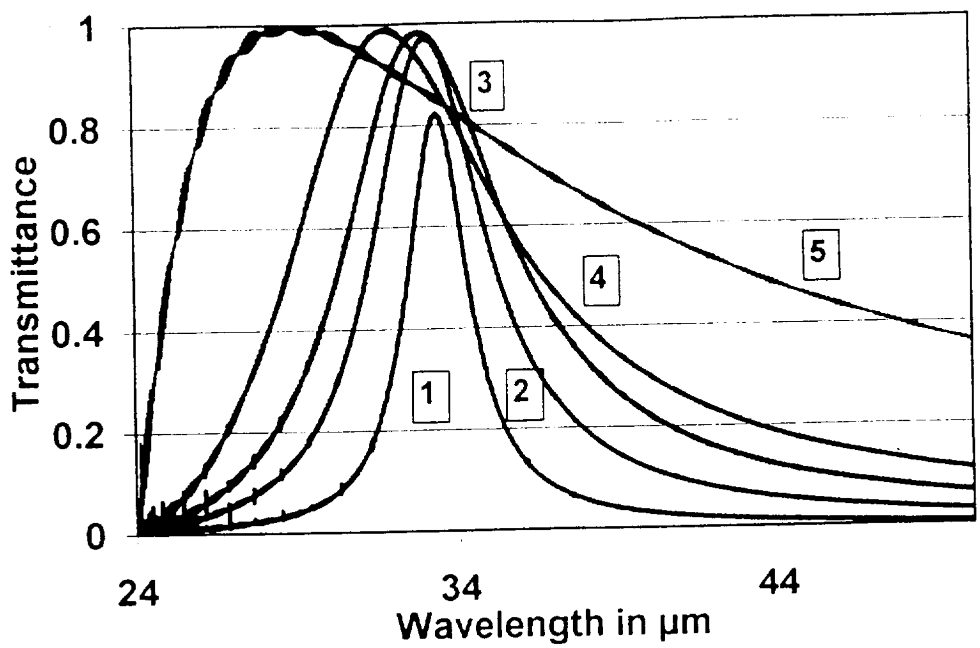

Fig. 3