Array Technology Development Plans at Caltech and JPL

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- A Long Range Plan for DSN
- Radio-Optical, Current-Future Comparison
- Recent Developments
  - Mystery Feed
  - Antenna Design
  - Signal Processing - FX vs XF, FPGA vs ASIC
- Student Activity
- Caltech Array Technology Center

A Long-Range Plan for the DSN

JPL/Caltech 3 x 6m Interferometer - 2003 to 2005

• Provides an early, inexpensive (< $1M) test of breadboard components of the system.

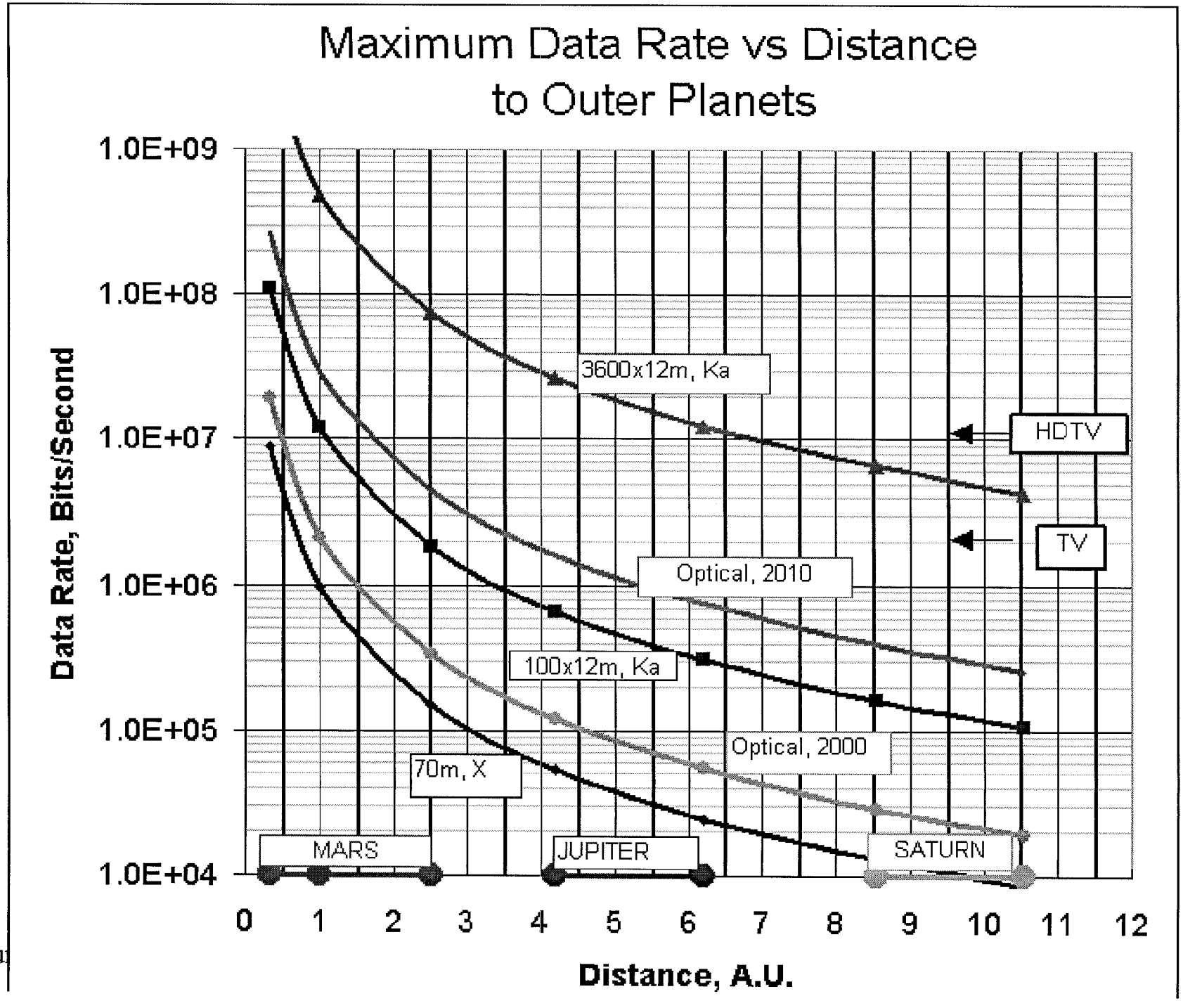
• Develops a JPL/Caltech team for array technology development

DSN Prototype 100 x 12m Array – 2003 to 2008

• Provides a solid test and demonstration of performance, cost, and operational aspects of a large array

DSN Operational Large Array – 2007 to 2015

• Provides NASA with a 100X improvement in communications infrastructure to support space exploration in the 2015 – 2040 era.

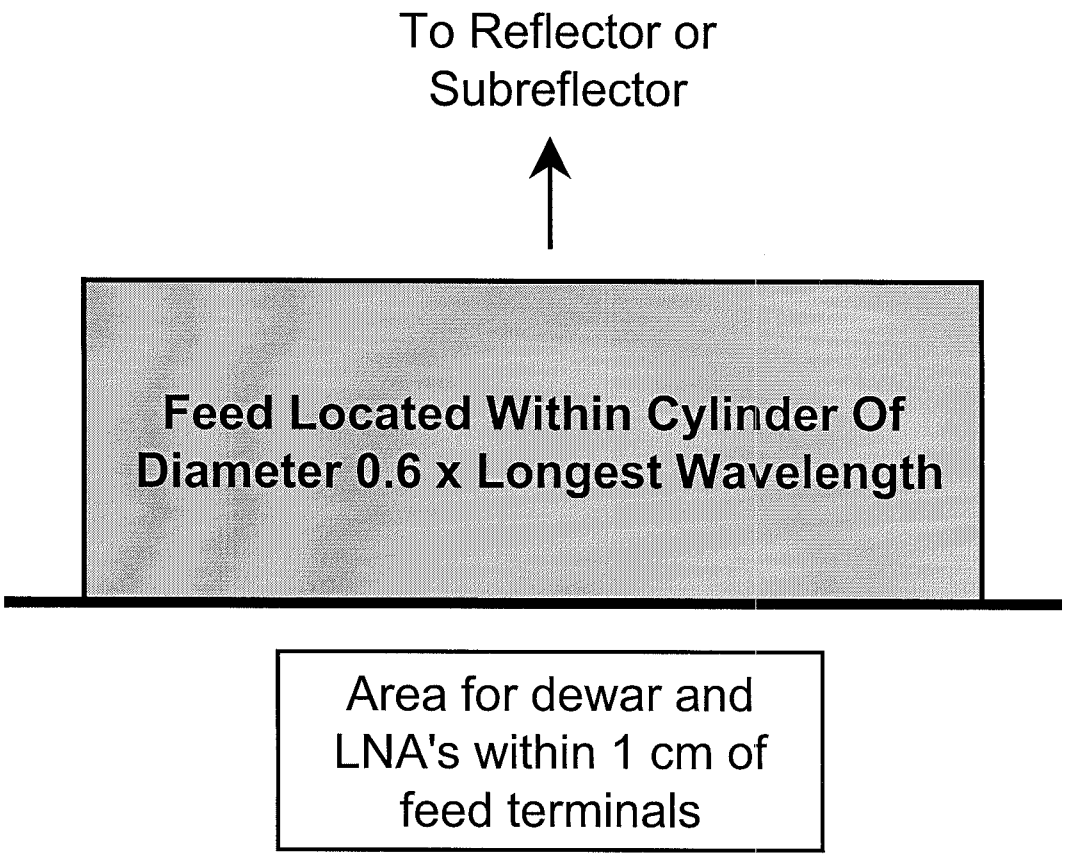

Maximum Data Rate vs Distance
to Outer Planets
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
Data Rate, Bits/Second
3600x12m, Ka
HDTV
TV
Optical, 2010
100x12m, Ka
Optical, 2000
70m, X
MARS
JUPITER
SATURN
0
1
2
3
4
5
6
7
8
9
10
11
12
Distance, A.U.

Prototype DSN Array Summary Schedule

D=Design F=Fabricate A=Assemble T=Test

Task	FY02	FY03	FY04	FY05	FY06	FY07	FY08
Rapid Prototype 6m Interferometer							
Design	DDDD	D					
Fabricate		FFF					
Integrate		A	AAA				
Test			T	TTTTT			
Prototype 100 x 12m Array							
Design	DDDD	DDDD	DD				
Fabricate			FF	FFFFF	FFF		
Integrate				AA	AAAA	AA	
Test						TTTTT	TTTTT
Funding Requirements	**$1.2M**	**$5.8M**	**$10.9M**	**$22.0M**	**$21.9M**	**$11.1M**	**$3.1M**
Total	**$76.0M**						

"Mystery" Feed

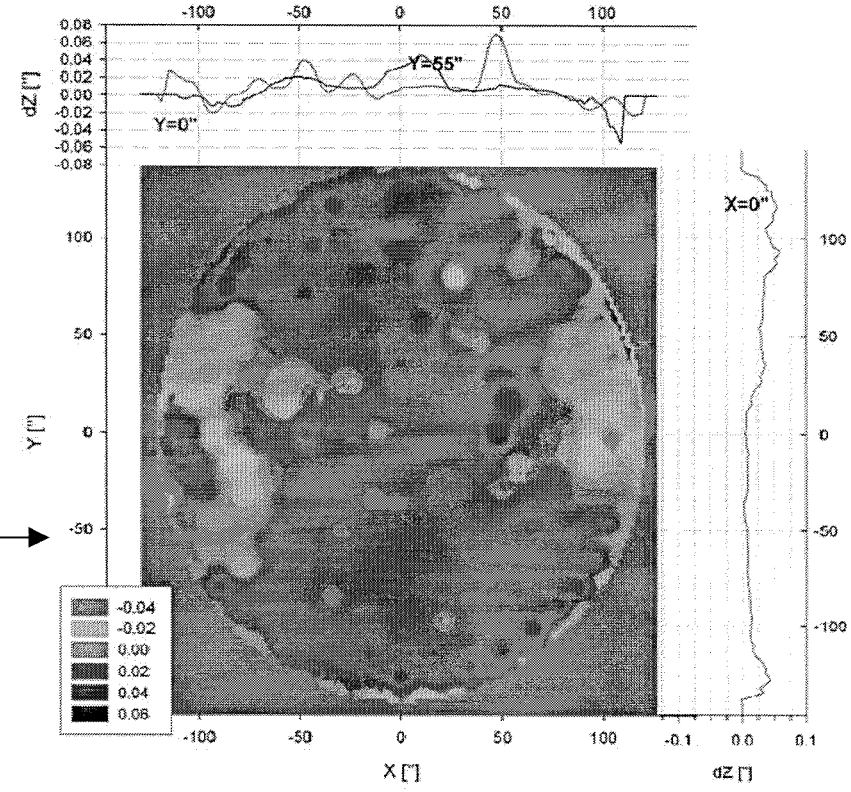


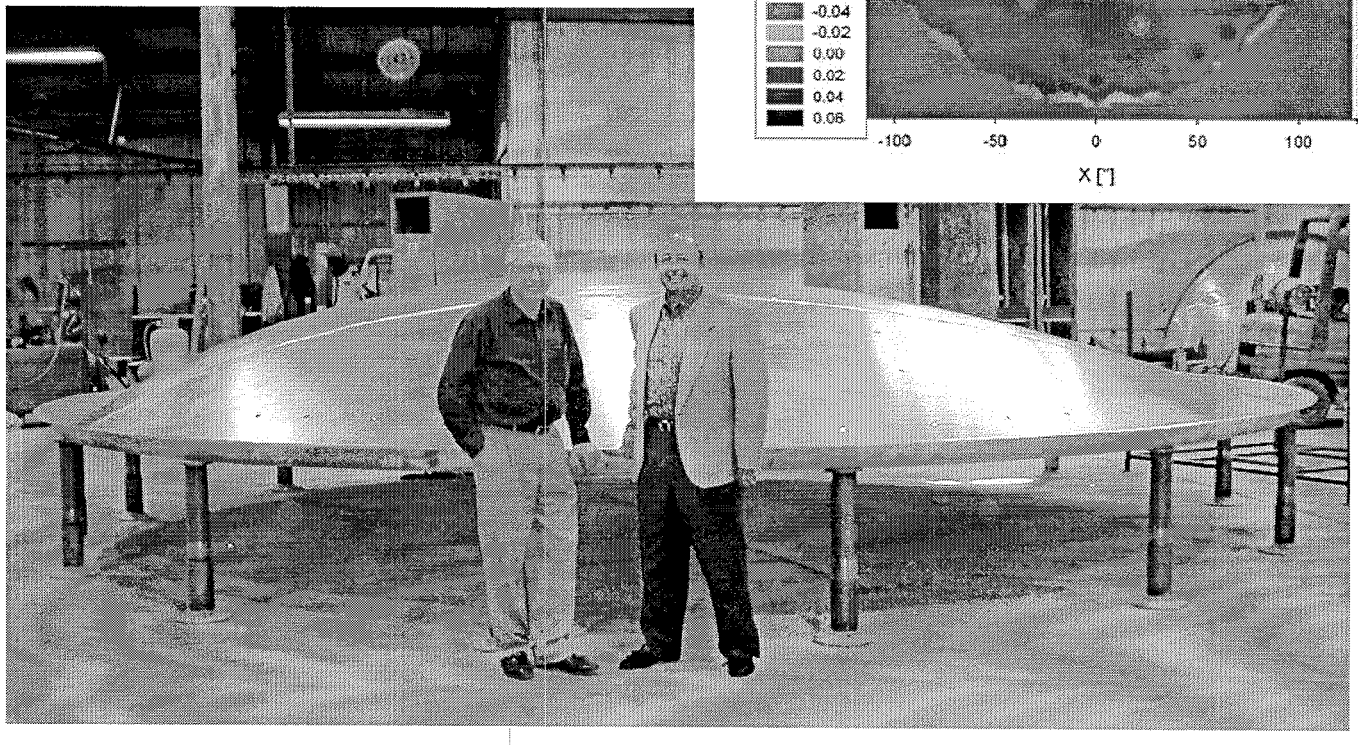
Frequency Range, GHz	Diameter Temperature Optics
.15 -1.5	1.2m Ambient Prime Focus
1.2 - 12	15cm Cryogenic Gregorian
12 - 43	1.5cm Cryogenic Gregorian

6m Hydroformed ATA Antenna at Anderson Plant, May, 2002

- RMS deviation is 0.68mm which is sufficient for 11 GHz ATA operation.
- Mold will be further machined with a goal of 0.20mm for JPL/Caltech 40 GHz antenna

Error map of surface →





Current 12m Antenna Cost Breakdown

May 3, 2002

Item	Typical Vendor/ Comment	Quantity	Cost per Unit	Total ($K)
Reflector	Anderson	1	$50,000	50.0
Sub-reflector	2.4 m	1	$2,000	2.0
Aluminum Back Structure	Local aluminum fabricator	5200 lbs	$3.25	16.9
Steel Pedestal	Local steel fabricator	19,900 lbs	$1.70	33.8
Azimuth Bull Gear	Rotek	1	$8,800	8.8
Azimuth Speed Reducer	Sumitomo	2	$3,000	6.0
Azimuth Motors	GE	2	$2,000	4.0
Elevation Actuator	Ball-screw or gear drive	1	$9,500	9.5
Elevation bearings		2	$1,500	3.0
Metrology	Incremental 16 bit	2	$1,000	2.0
Servo Electronics		2	$1,000	2.0
Assembly	In automated factory	50 hours	$60	3.0
Miscellaneous		1	$9,000	9.0
			Total	$150.0

SKA Signal Processing Concepts

Correlation of 2500 antennas at 3.2 GHz bandwidth with 16,000 spectral channels, 0.2 MHz resolution, is feasible for < $80M with current technology for the following reasons: (More channels can be accomodated at lower bandwidths).

1) The **F-X** type of array processing (Chikada, Bunton, and Daddario) in which the signal from each antenna is first filtered in a digital filter bank to the final desired resolution and then correlated with only one lag in the correlator,

2) New "**polyphase**" algorithms for digital filtering (Vaidyanathan, Ferris, Werthimer) which have reduced the required number of operations per second for sharp cut-off filters by orders of magnitude

3) Use of application specific integrated circuits **(ASIC's**) which have of the order of 20 times greater logic density than field-programmable gate-arrays (FPGA's).

Comparison of Field Programmable Gate Arrays (FPGA) and Application Specific Integrated Circuits (ASIC)

May, 2002

Application	XPressArray (0.18μ)	FPGA	Standard cell (0.18μ)	Standard cell (0.15μ)
Density (ASIC gates/mm^2)	41k	3k	45 to 90k	80 to 140k
Performance (MHz)	350	150	350	600
Power (μW/gate/MHz)	.02 to .03	0.5	.018 to .035	.012 to .016
NRE cost	$50k to $200k	<$2k	$500k	$1,000k
Proto time (sign-off)	Two weeks	Immediate	10+ weeks	15+ weeks
Unit cost	$6 to $200	$40 to $5,000	$4 to $120	$3 to $80
Volumes	1k to 1M/yr	1k to 5k/yr	>10k to 2M/yr	>20k to 5M/yr

Array Technology Work in Progress at Caltech and JPL
May, 2002

At Caltech

- **ATA Low Noise Receiver** – Niklas Wadefalk works on MMIC design and prototype construction for 0.5 to 11 GHz cryogenic low noise receiver.
- **Caltech 6m Antenna** – Contracted to Andersen to improve surface of ATA reflectors to allow 40 GHz operation.

At JPL

- **DSN Array System Design** – Durga Bagri, Mick Connally, Dayton Jones work on system requirements and block diagram design
- **Antenna Pedestal Design** – Roger Schultz is designing a pedestal and drive system for the Andersen 6m reflector.
- **8/32 GHz Feed Design** – Dan Hoppe is designing a concentric dual frequency feed.
- **8.4 and 32 GHz LNA Design** – Sandy Weinreb is working with Jose Fernandez, Steve Montinez, and UCSB on assembly and testing of MMIC LNA's

Students Participating in Array Development at Caltech
2002

Student	School	Project
Summer Undergraduate Research Students, 2002		
Eric Anderson	Caltech	Modeling of hydroformed reflector fabrication
Joe Barden	UCSB	Precision timing distribution by commercial satellite
Glenn Jones	Caltech	Cryogenic transistor testing
Anton Aboukhalil	McGill	Design of antenna servo system
Muhammad Ahmed	Georgia Tech	Digital data processing for Caltech/JPL interferometer.
Graduate Students		
Matthew Morgan	Caltech	MMIC design and test, 32 GHz LNA
Robert Hu	U. Michigan	Cryogenic noise parameters, 8-20 GHz LNA
Patrick Cesarano	Caltech	New student starting July, 2002

Caltech Array Technology Development Center

Concept

A center on the Caltech campus for development of technology for both radio astronomy and space communications. Financial support from a $10M endowment from Caltech gift funds is proposed.

Technology Areas of Interest

1) Design of precision reflector and drive system structures which can be reproduced at low cost.

2) Development of very wideband low noise receivers including long life cryogenic systems

3) Systems for one picosecond time synchronization at antennas which may be over 1000 km apart

4) Affordable gigabit data transmission systems

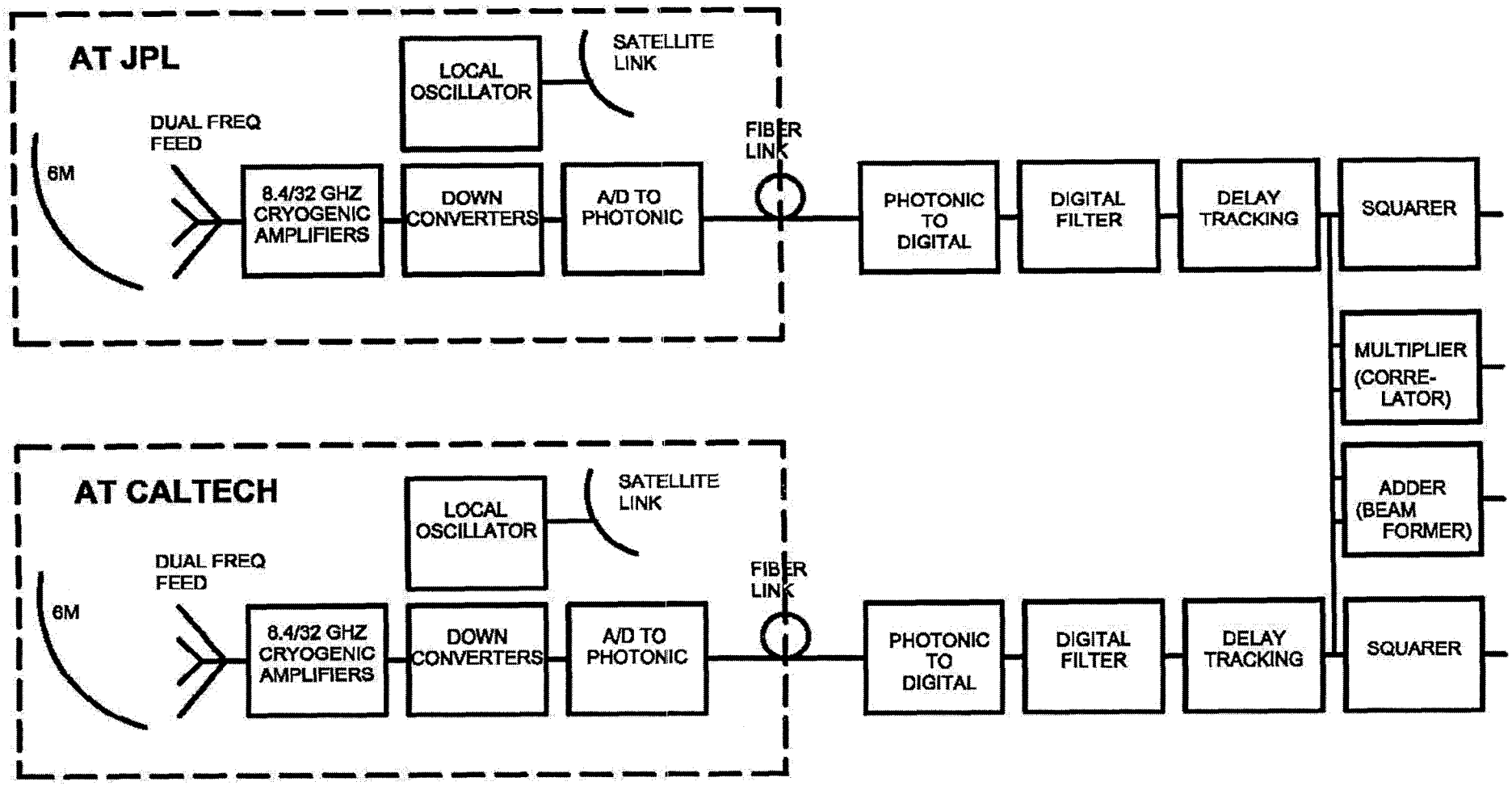
5) Hardware and software for processing of the order of 10^{14} bits per second which will be received by the array.

Comparison of Array Requirements for Space Communications and Radio Astronomy

Parameter	Communication	Radio Astronomy
Frequency	8 and 32 GHz	.5 to 20 GHz
Array Configuration	Any but lower cost if closely packed	Sparse for better image sharpness
Element Size	Minimum cost probably in the 3.5 to 10 meter range	May be slightly larger because of more complex receivers
Data Processing	Digital beam forming of< 10 beams	Correlation processing of full image; > 10,000 beams
Bandwidth	<10 MHz	1000 MHz

JPL to Caltech Interferometer

- Capable of detecting both spacecraft communications and many radio astronomy sources
- Serves as an easily accessible test bed for prototype DSN and SKA equipment
- An educational instrument for thesis and research projects



Array Technology Overview

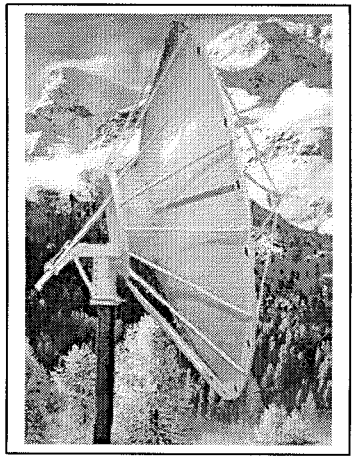
Item	Approach	Key Issues	Challange
System Design	Experience, Breadboard, Prototype	Configuration, Calibrat., Dynamic Range	Both radio astronomy & DSN
Antennas	Aluminum Hydroform	Accuracy, Cost	>12m, Lower Cost
Feed	DSN – 8/32 GHz SKA – Log periodic	Efficiency, Noise Pickup	Cryogenic Feed Window
Low-Noise Amplifiers	0.1um InP HEMT MMIC	Low Noise	Low Noise at Higher Temp
Cryocoolers	Gifford-McMann 15K Or Pulse Tube	Maintenance Cost or Development Time	No Cryo Moving Parts
Local Oscillator, Timing	Round-trip Fibers and Round-trip Satellite	Phase Stability	Commercial Satellite Link
Data Transmission	Photonic Fibers	Installation Costs for Long Distance	40 GB/s
Element Signal Processing	RF MMIC Modules, A/D Converters, Filters	Cost, RFI, Flexibility	8 GHz Bandwidth
Combinatorial Signal Processing	Digital Beam Formers, Correlators	Connections, Bandwidth	VLSI, Growth Path
Monitor and Control	Standard Modules, Serial Data Transmission	Convenient and Robust Software	Operation over Internet

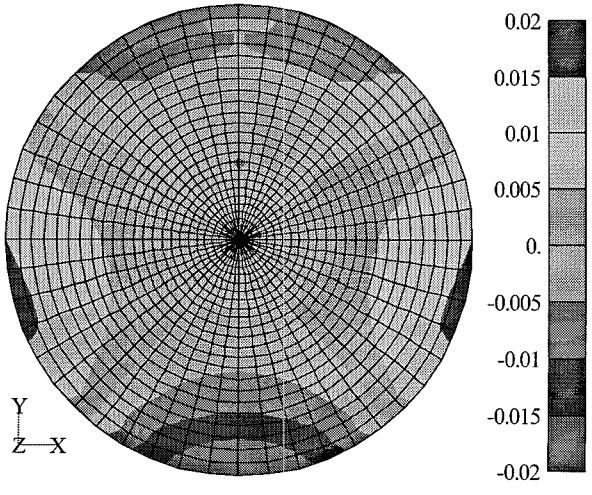
Hydroformed Aluminum Antennas

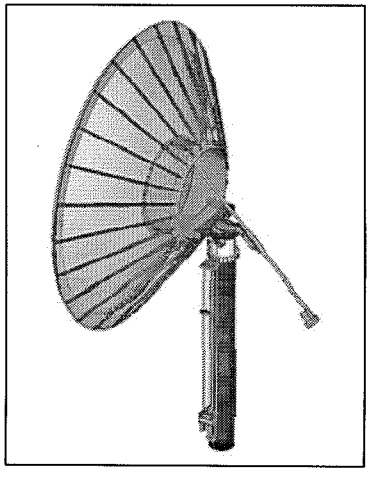
Hydroforming is a process of using a fluid or gas at very high pressure to force aluminum sheet to conform to a mold. The result is a stiff, accurate, and low cost reflector.

JPL has performed a structural analysis of 5m and 8m hydroformed reflectors manufactured by www.anderseninc.com and has found that the wind and gravitational distortions would allow operation at frequencies as high as 100 GHz.

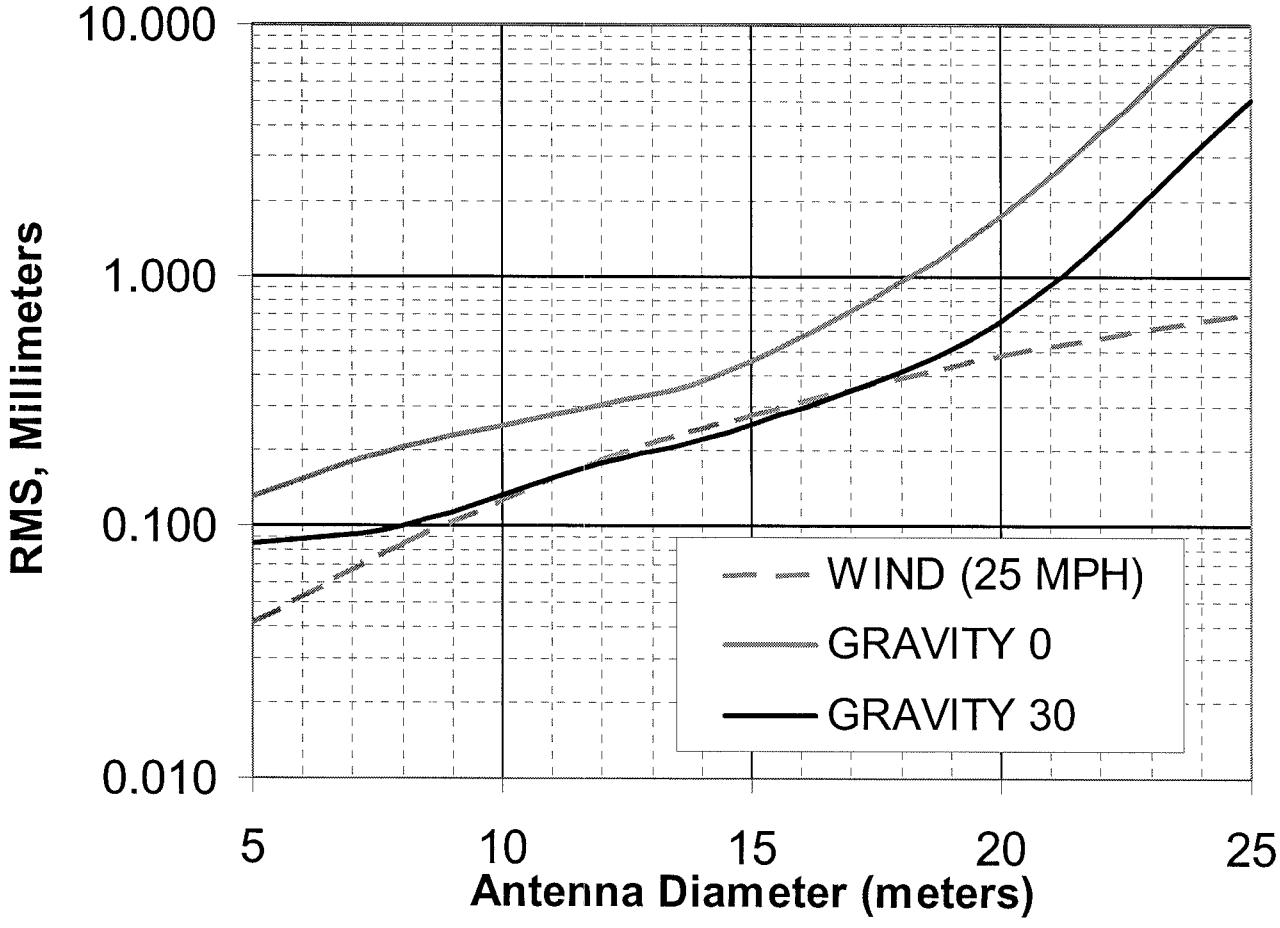
Example	Antenna Diameter	Cost per Antenna	Cost per m^2	Cost per km^2
New 70m DSN antenna	70m	$100M	$40.8K	$40.8B
25m VLBA antenna	25m	$3M	$9.6K	$9.6B
6m ATA antenna	6m	$30K	$1.7K	$1.7B
Target SKA cost	10m	$30K	$600	$0.6B
Hydroformed DBSTV antenna	4m	$2.8K	$350	$0.35B
Aluminum, 3mm thick sheet	Any	NA	$30	$.03B







RMS Deformation Due to Wind and Gravity as a Function of Antenna Diameter for Hydroformed Shell of 3mm Thickness



Current DSN and SKA Antenna Requirements

Reflector Type – 12m offset Gregorian

Surface Accuracy – 0.2mm rms deviation from best fit caused by gravity, wind upto 15mph, an temperature of-–10 to +55C

Pointing Accuracy - .011° or 0.7' after correction table in 15mph wind

Phase Center Stability – Shall move < 1mm due to 15mph wind or sun/shade condition.

Survival – Drive to stow in 50 mph wind and survive at stow in 100 mph wind.

Receiver Mounting – 90 kg at Gregorian focus and 90 kg at prime focus including 2.4m subreflector.

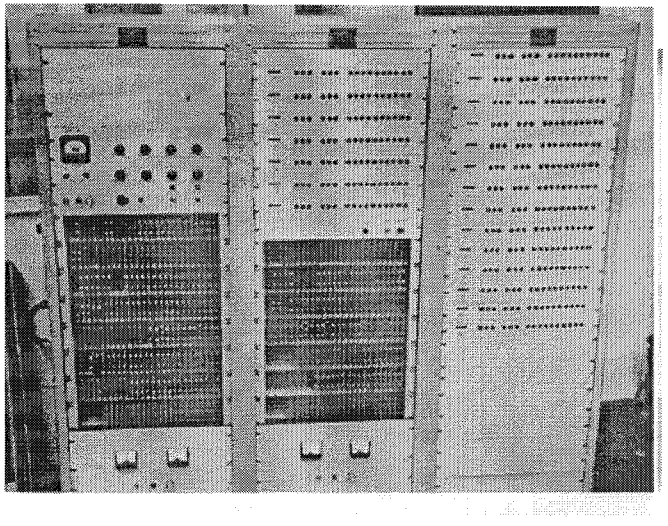
Prototype Array Milestones Through 2003

WBS	Milestone	Name	Date	Event
3.1	31	6m Antenna Designed	Oct-02	Complete design of backup structure and mount for precision 40 GHz version of 6m ATA antenna.
4.1	41	6m Feed Design	Oct-02	8.4 and 32-38 GHz feed design complete.
4.3	46	8 and 32 GHz LNA Design	Oct-02	8 and 32-38 GHz MMIC LNA's designed and tested
2.1	21	Site Selected	Jan-03	Preliminary Site Review
1.,1	11	Requirements Freeze	May-03	Changes after this date may have cost impact.
4.1	42	6m Feed Fabricated	Jul-03	Machining at JPL or outside shop with attention to finding future low cost quality fabricator.
3,1	32	6m Antenna Fabricated	Aug-03	Three 6m antennas including mounts fabricated.
4.3	47	8 and 32 GHz LNA Tested	Aug-03	LNA's packaged, tested, and ready for integration with feed and cryogenics.
6.1	61	Algorithm Design Complete	Sep-03	Algorithms for array calibration and beam forming complete and documented.
4.4	4A	Cryocooler Tested	Oct-03	Cryocooler including dewar for 6m tests ready for integration with feed and LNA.
4.5	4E	RF Analog Design for 6m	Oct-03	Tested RF analog system for 6m interferometer complete.
5.1	51	Interferometer Transmission	Oct-03	Design and implementation complete for interferometer data transmission system
4.1	43	6m Feed Tested	Oct-03	Patterns tested and computation of Aeff/Tsys. Ready for incorporation in cryogenics dewar.
7.1	71	Interferometer Mon & Control	Dec-03	Interferometer pointing control, delay control, and simple data processing functional.

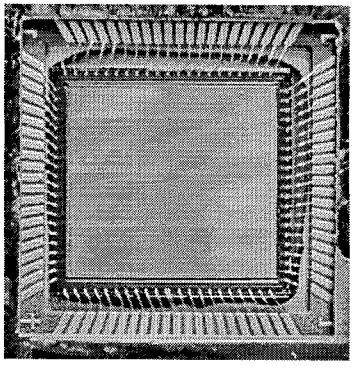
Cost by Subsystem, FY02-04 and Total FY02-08

WBS		FY02			FY03			FY04			TOTAL WBS		
		FTE	MatK$	TotK$	FTE	MatK$	TotK$	FTE	MatK$	TotK$	FTE	MatK$	TotK$
1	**System Development**												
1.1	Requirements, Configuration, & Ca	1.0		**210**	1.5		**328**	1.5		**341**	11.0	0	**2648**
1.2	Test Interferometer	0.3		**53**	0.5		**109**	0.5		**114**	2.3	0	**511**
1.3	Design and Test	0.3		**53**	2.0		**437**	2.0		**454**	12.3	1200	**4150**
2	**Site Development**												
2.1	Site Selection Study and Negotiati	0.8	100	**258**	1.0	100	**318**			**0**	1.8	200	**576**
2.2	Site Civil Work			**0**	1.0	150	**368**	1.0	400	**627**	4.0	6550	**7477**
3	**Antenna Element**												
3.1	6m Reflector and Mount	1.0		**210**	1.0	200	**418**	1.0	100	**327**	3.0	300	**956**
3.2	12m Near-Site Factory			**0**	0.5		**109**	1.0	2000	**2227**	1.5	6000	**6336**
3.3	12m Reflector and Mount			**0**	0.5	200	**309**	1.0	300	**527**	4.5	18500	**19574**
4	**Receivers**												
4.1	8/32/38 GHz 6m Feed	0.5		**105**	0.5	40	**149**			**0**	1.0	40	**254**
4.2	8/32/38 GHz 12m Feed			**0**			**0**	0.5	50	**164**	1.0	350	**582**
4.3	8/32/38 GHz LNA	0.5		**105**	1.0	200	**418**	1.0	250	**477**	6.0	1100	**2521**
4.4	Cryocooler and Dewar			**0**	0.5	80	**189**	1.0	50	**277**	7.0	2130	**3818**
4.5	RF Analog Processing			**0**	2.0	40	**477**	2.0	200	**654**	10.0	1490	**3866**
5	**Data Transmission**												
5.1	Subsystem Design			**0**	1.0	20	**238**	1.0	50	**277**	2.0	70	**516**
5.2	RF/Photonic Transceivers			**0**			**0**	1.0	50	**277**	4.0	1450	**2415**
5.3	Fiber Installation			**0**			**0**	0.5		**114**	4.0	850	**1809**
5.4	Remote Station Study	0.1		**21**	0.5	20	**129**	0.5	20	**134**	3.1	210	**955**
6	**Signal Processing**												
6.1	Processing Design and Coding	0.5		**105**	1.0		**218**	1.0		**227**	2.5	0	**551**
6.2	Beam Former			**0**	1.0	50	**268**	3.0	200	**881**	11.5	1150	**3884**
6.3	Correlator			**0**	1.0	50	**268**	3.0	200	**881**	11.5	850	**3584**
7	**Monitor and Control**			**0**			**0**			**0**			
7.1	Interferometer Mon and Control			**0**	1.5	50	**378**	1.0	20	**247**	2.5	70	**625**
7.2	Array Monitor and Control			**0**			**0**	3.0	100	**781**	12.0	800	**3704**
7.3	Operation Interface			**0**			**0**			**0**	3.5	0	**885**
8	**Project Management**												
8.1	Staffing, Schedule, and Reporting	0.3		**53**	2.0	50	**487**	2.0	100	**554**	9.3	400	**2563**
8.2	Cost Estimation and Control	0.3		**53**	0.5		**109**	1.0		**227**	3.8	0	**871**
8.3	Spectrum Management			**0**	0.2		**44**	0.5		**114**	1.7	0	**398**
	Total FTE Personnel	**5.4**	**100**	**1224**	**20.7**	**1250**	**5771**	**30.0**	**4090**	**10904**	**136.6**	**43710**	**76028**

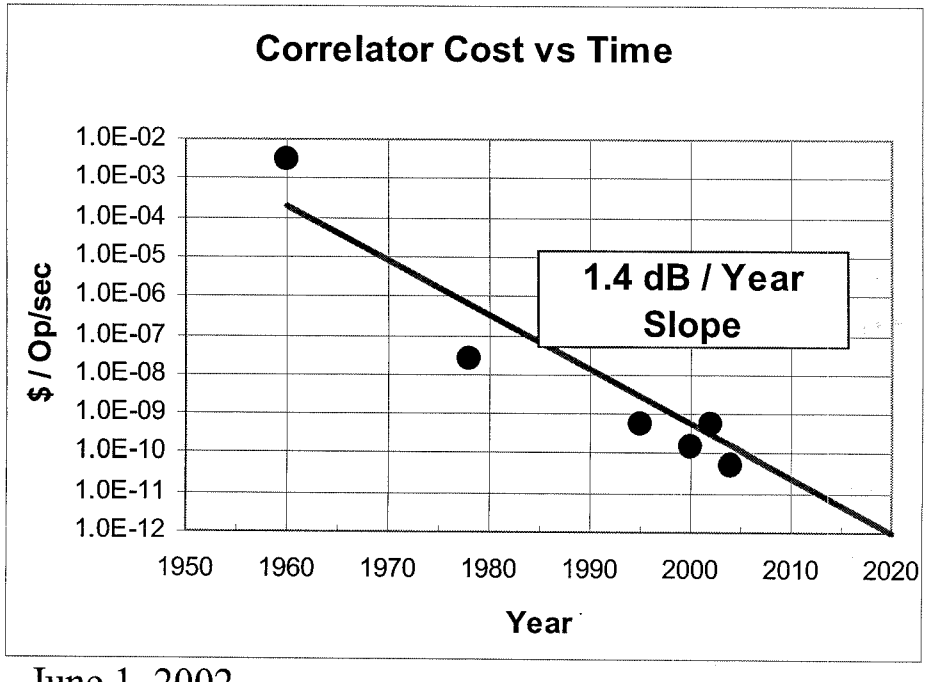
The Development of Correlators in Radio Astronomy



1960 – First Radio Astronomy Digital Correlator, 21 Lags, 300kHz Clock, $19,000



1995 – GBT Spectrometer Chip, 1024 Lags, 125 MHz Clock, $200



2005 – Proposed SKA Chip, 100 x 100 x 1 lag, 400 MHz Clock, $500

Summary of Signal Processing Cost Estimate

May, 2002

Component	Quantity per Array	Cost per Unit ($K)	Totals ($M)
A/D Converters, 6bit 800 MHz	4400x8=35,200	0.5	17.6
Delay tracker, 800 MHz	4400x4=17,600	1.0	17.6
Station beam formers	160	10	1.6
Digital filter bank, 800/0.2 MHz or 100 MHz/1.5 kHz.	4400x4=17,600	0.5	8.8
F to X connections, 10 Gb/s fibers	3200	4.0	12.8
Cross-correlator, 3.3E7 baselines, 1 lag, 2-bit, 2 x 800 MHz	2	4000	8.0
Array beam formers	100	50	5.0
Time domain analyzers	100	50	5.0
ASIC development	2	1000	2.0
System assembly and test	16 person-years	120	1.9
		Total	80.3

Item	Baseline Specification	Driver	Cost
Antennas	4400 x 12 m	Sensitivity, A/T=20000	4400 x $150K = $660M
Frequency Range	0.15 to 34 GHz	Science breadth	Lower limit is cost insensitive; upper limit depends upon antenna studies
Receivers	3 bands	Continuous 0.15 to 34 GHz with T_{sys} of 18K at 8GHz	4400 x $39K = $172M
Data Transmission	3.2 GHz Bandwidth from 2200 inner antennas and 160 outer stations	Bandwidth for continuum sensitivity at high frequencies	4560 optical transducers $73M plus $38M for 1900km of fiber trenching and fiber cables.
Civil Costs	Configuration described below	Resolution and dynamic range	Land, foundations, power, and buildings broken down into inner and outer configurations below.
Inner Configuration	2200 antennas within 35 km individually correlated	1°field, 1.5" image at 21 cm	Central site and 2200 antenna sites at $63M.
Outer Configuration	160 stations x 13 antennas in log density	<0".1 resolution at 21 cm	160 stations and 2200 antennas sites at $133M
Bandwidth and Beams	Four 800 MHz bands selectable polarization, frequency, and beams	Sensitivity, RFI rejection, and versatility	A driver for above data transmission costs and processing costs below.
Signal Processing	2360 correlator inputs 3.2 GHz/ 0.2 MHz or 800 MHz/ 1.56 kHz.	Number of desired channels, bandwidth for line searches & sensitivity	Fix cost at $80 M; take contingency of Moore's Law improvements in performance.
Software and Computing Hardware	Control, monitor, process, and image formation	Dynamic range, calibration AIPS++ heritage	660 person-years = $53 M plus $79 M for computing hardware
Non-Recurring	Design, integration, testing, and management	Complexity, many sites	70 people, 7 years = $59 M
Contingency	15%	Cost uncertainties	$212 M
		Total	**$ 1,665M**