

## Cost Equation for the SKA

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1. General form of spreadsheet
2. Performance and cost parameters
3. Results: Cost vs antenna diameter and other parameters
4. Front-end model
5. Signal processing model

# SKA Cost Equation Spread Sheet

**Rows** are for input or computed parameters such as cost coefficients or performance parameters

**Columns** are for varying antenna diameters

**Sheets** are for varying major parameters such as cryogenic temperature or era of electronics costs.

**Output** of the program is the total cost and cost of each subsystem. The Aeff/Tsys is constrained at 20,000 by computing the number of antennas needed for each station.

**Parameters** – There are 14 performance parameters and 19 cost parameters listed on the next page

**Models** – Details are in the equations in the spreadsheet. Antenna cost is  $0.1 \cdot D^3$  K\$.

SKA Cost Estimation July 7, 2004		File SKACost1					
Units: \$B/\$C/D/E/L meters, GHz		9.0		10.0		11.0	
Parameter	Antenna Diameter, meters	Value	Value	Value	Value	Value	Value
A	Antenna Parameters	9.0	10.0	11.0	12.0	13.0	14.0
CA	Total array cost, land, civil, electronics, processing	227,271	328,113	469,147	658,369	924,112	1,287,292
CB	Total antenna cost, land, civil, electronics	127,271	188,113	269,147	388,369	544,112	787,292
CC	Total electronics cost, land, civil, electronics	100,000	140,000	199,000	280,000	390,000	560,000
CD	Total processing cost, including electronics	127,271	188,113	269,147	388,369	544,112	787,292
CE	Signal processing cost	100,000	140,000	199,000	280,000	390,000	560,000
CF	Total cost per station - design + central cost	50,000	70,000	100,000	140,000	200,000	280,000
CG	Total station cost, antenna + cooling electronics	1,419	1,889	2,624	3,807	5,259	7,292
CH	Total station cost, antenna + receiver + processing	207	287	397	557	757	1,057
CI	Cooling signal processing costs	31,000	40,000	55,000	75,000	100,000	140,000
CM	Number of stations in array	146	100	70	50	36	26
CL	Number of elements per station	351	502	68	47	35	27
CO	Equivalent single-antenna diameter of station	91	91	91	91	91	91
CP	Total number of elements, M = N*Trays	51,506	50,000	4,854	4,500	2,912	2,000
CQ	Effective area of array, Aeff/m^2	300,000	300,000	300,000	300,000	300,000	300,000
CR	Skimmed figure of merit, M = A/Trays	20,000	20,000	20,000	20,000	20,000	20,000
CS	Figure of merit, M = A/Trays	20,000	20,000	20,000	20,000	20,000	20,000
CT	System noise temperature at feedhorn, K	15	15	15	15	15	15
CU	Processed total continuous bandwidth	4.0	4.0	4.0	4.0	4.0	4.0
CV	Number of spectral line channels	10,000	10,000	10,000	10,000	10,000	10,000
CW	Antenna-to-cosmos ratio, lambda	0.04	0.04	0.04	0.04	0.04	0.04
CX	Minimum cost ratio, (M+1)/(M-1)	2.0	2.0	2.0	2.0	2.0	2.0
Antenna Parameters		9.0	10.0	11.0	12.0	13.0	14.0
DA	Physical diameter of element (meters)	9.0	10.0	11.0	12.0	13.0	14.0
DB	Physical area of element, sq m = 0.785*D^2	63	79	113	177	241	314
DC	Aperture efficiency	0.50	0.78	0.50	0.78	0.50	0.78
DD	Effective area of element, Aeff/m^2	31	62	57	138	121	242
DE	Antenna noise temperature, Tant = 10 + 40*(D/10)	14	14	14	14	14	14
DF	Cost per station, CA = CA + 0.1*D^3	1,419	1,889	2,624	3,807	5,259	7,292
DG	Fixed cost per station, land, civil, burden, salaries	300	300	300	300	300	300
DH	Cost per antenna, CA = CA/CP	15	19	38	76	145	280
DI	Antenna cost coefficient	0.10	0.10	0.10	0.10	0.10	0.10
DJ	Antenna cost exponent	3.0	3.0	3.0	3.0	3.0	3.0
DK	Antenna cost per square meter, physical area (m^2)	0.002	1.019	1.014	1.020	1.011	1.008
Receiver Parameters		9.0	10.0	11.0	12.0	13.0	14.0
DL	TR = TR + Tant	10	10	10	10	10	10
DM	TR = TR + Tant	10	10	10	10	10	10
DN	Long coefficient dependent upon cooler	0.40	0.40	0.40	0.40	0.40	0.40
DO	Physical temperature of LNA	15	15	15	15	15	15
DP	Frequency for system temperature specification	10	10	10	10	10	10
DQ	Electronics cost per antenna, cost	150	150	150	150	150	150
DR	Cost per antenna, CA = CA/CP	14.9	14.9	14.9	14.9	14.9	14.9
DS	Cooling cost per antenna	4.0	4.0	4.0	4.0	4.0	4.0
DT	Number of frequency bands	2	2	2	2	2	2
DU	Average bandwidth, fixed cost	0.8	0.8	0.8	0.8	0.8	0.8
DV	Average LNA + mixer cost	0.8	0.8	0.8	0.8	0.8	0.8
DW	LO cost	0.0	0.0	0.0	0.0	0.0	0.0
DX	Cost of cost, CA = CA/CP	1.4	1.4	1.4	1.4	1.4	1.4
DY	Fixed cost per station	0.0	0.0	0.0	0.0	0.0	0.0
DZ	Cost of cost, CA = CA/CP	0.1	0.1	0.1	0.1	0.1	0.1
Signal Transmission Parameters		9.0	10.0	11.0	12.0	13.0	14.0
EA	Cost of transmission, CA = CA/CP	21,170	20,170	21,170	20,170	21,170	20,170
EB	Cost per receiver, cost, CA = CA/CP	0.80	0.80	0.80	0.80	0.80	0.80
EC	Transmitter cost per GHz	0.26	0.26	0.26	0.26	0.26	0.26
ED	Average station to central center distance, km	100	100	100	100	100	100
EE	Fiber installed cost, per fiber per km	2	2	2	2	2	2
Signal Processing Parameters		9.0	10.0	11.0	12.0	13.0	14.0
EF	RFI window loss coefficient for continuous processing (signal channel)	2.00	2.00	2.00	2.00	2.00	2.00
EG	Digitization coefficient	0.40	0.40	0.40	0.40	0.40	0.40
EH	Digitization equipment	3.00	3.00	3.00	3.00	3.00	3.00
EI	Digitization constant	0.10	0.10	0.10	0.10	0.10	0.10
EJ	Number of separately digitized channels	4	4	4	4	4	4
EK	Transmission, M = M + 0.1*D^3	3.00	3.00	3.00	3.00	3.00	3.00
EL	Average distance, element to station center	0.90	0.90	0.90	0.90	0.90	0.90
EM	Tracking coefficient (per GHz)	0.10	0.10	0.10	0.10	0.10	0.10
EN	Tracking constant	0.06	0.06	0.06	0.06	0.06	0.06
EO	Streams per station	4	4	4	4	4	4
EP	Element processing cost = 0.10*D^3/CP	4.00	4.00	4.00	4.00	4.00	4.00
EQ	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00
ER	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00
ES	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00
ET	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00
EU	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00
EV	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00
EW	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00
EX	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00
EY	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00
EZ	Stream processing cost, CA = CA/CP	0.00	0.00	0.00	0.00	0.00	0.00

## SKA Cost Equation Input Parameters

Units: K\$US(2001), meters, GHz

Param	<b>Array Performance Parameters</b>	Default Value
Ns	Number of stations in array	100
M	Specified Figure of Merit, $M = A/T_{sys}$	20,000
B	Processed total continuum bandwidth	4.0
NI	Number of spectral line channels	16,000
D	Physical diameter of element (meters)	<b>10.0</b>
Ef	Aperature efficiency	0.70
Tant	Antenna noise temperature, $T_{ant} = 10$	14
Kln	Lna noise coefficient dependant upon	0.40
Tphy	Physical temperature of LNA	15
F	Frequency for system temperature sp	10
Nbn	Number of frequency bands	3
Kch	_ Number of separately digitized chan	4
Le	_ Average distance, element to station	0.50
Nbear	_ Beams per station	4

Param	<b>Array Cost Parameters</b>	Default Value
Cso	Fixed cost per station, land, civil,	300
Ka	Antenna cost coefficient,	0.10
X	Antenna cost exponent	3.0
Ccl	Cooling cost per antenna	20.0
Cfd	Average dual-polariz feed cost	2.0
Cln	Average LNA + mixer cost	0.8
Clo	LO cost	3.0
Cifo	Fixed IF cost per polarization	1.0
Kif	Dual IF cost per GHz of bandwidth	0.2
a1	_ Digitization coefficient	2.00
e	_ Digitization exponent	2.00
a2	_ Digitization constant	0.50
d	_ Tracking coefficient (per GHz)	0.72
f	_ Tracking constant	0.10
Kproc	_ Processing cost coefficient (per	0.48
Kmem	_ Memory cost (per word)	2.10E-04
kct	_ Corner turner cost coefficient (p	1.00E-03
Kcor	_ Correlator cost coef (per baselin	0.024
Kchip	Price per large FPGA chip	0.14

Color code:

Purple: correction of error since previous version.

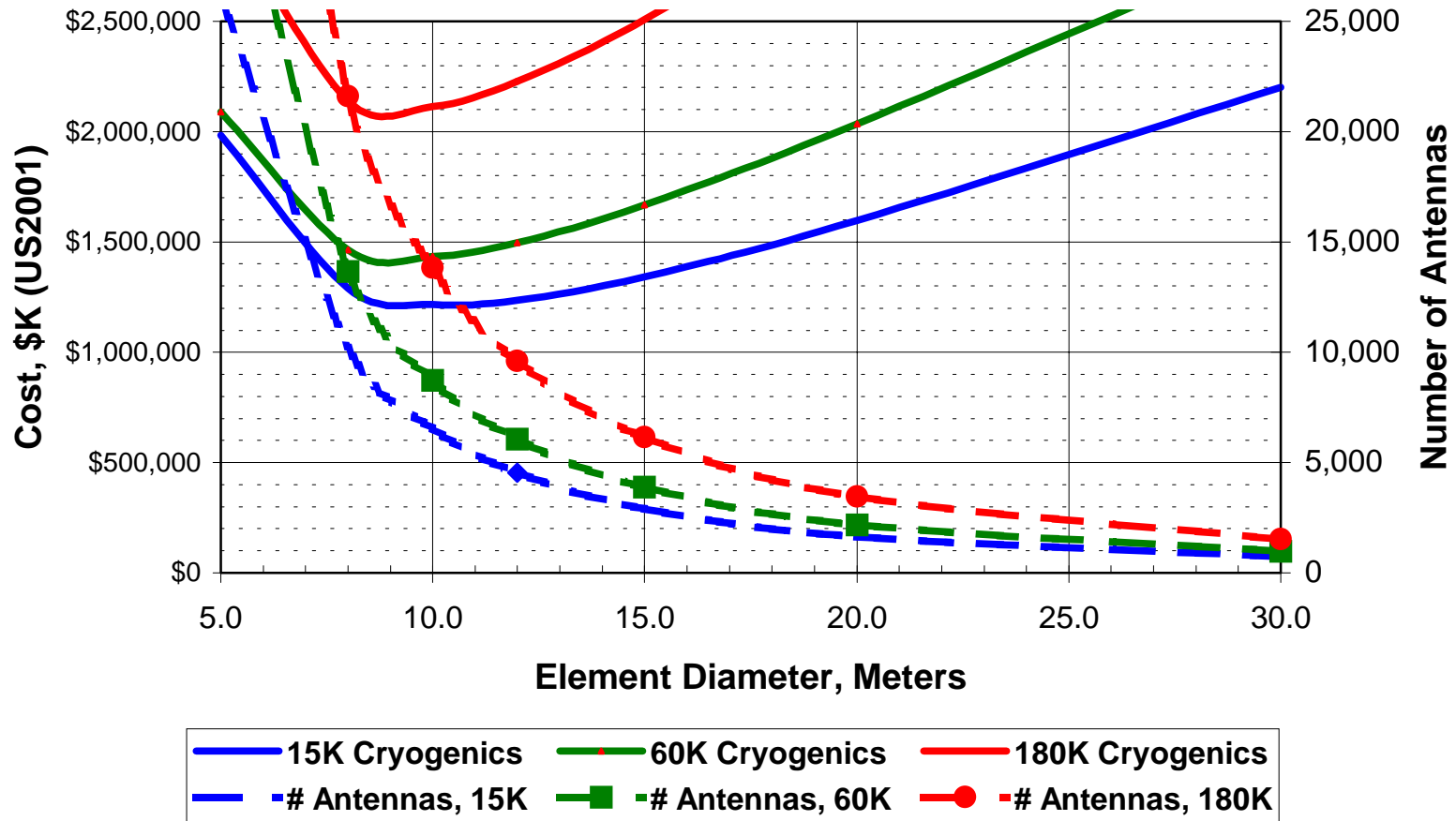
Blue: change to value or formula since previous version.

Red: variable whose value changes across this sheet

Green: variable whose value is different from previous sheet

Bold type: input parameter; normal type means value is calculated.

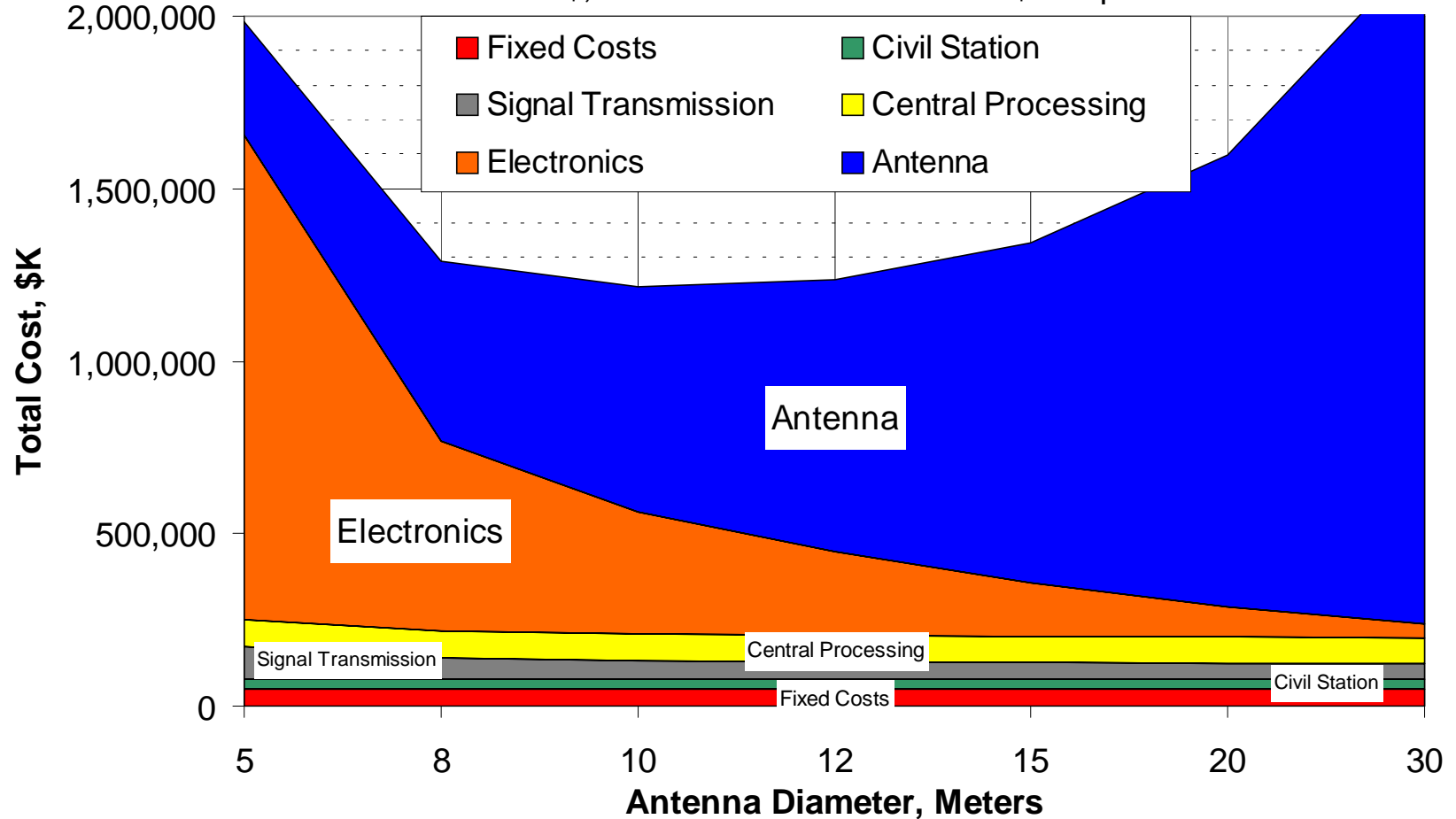
**SKA Cost vs Antenna Diameter for 3 Cooling Temperatures**  
 $A_{eff}/T_{sys} = 20,000$ ,  $A_{eff}=360,000$ ,  $T_{sys}=18K$ ,  $BW=4GHz$ ,  
 Antenna Cost =  $0.1D^3$  K\$, 2001 Electronics Cost = \$54K per Element



### SKA Cost Breakdown by Subsystem vs Antenna Diameter

$A_{eff}/T_{sys} = 20,000$ ,  $A_{eff}=360,000$ ,  $T_{sys}=18K$ ,  $BW=4GHz$ , 15K Cryogenics

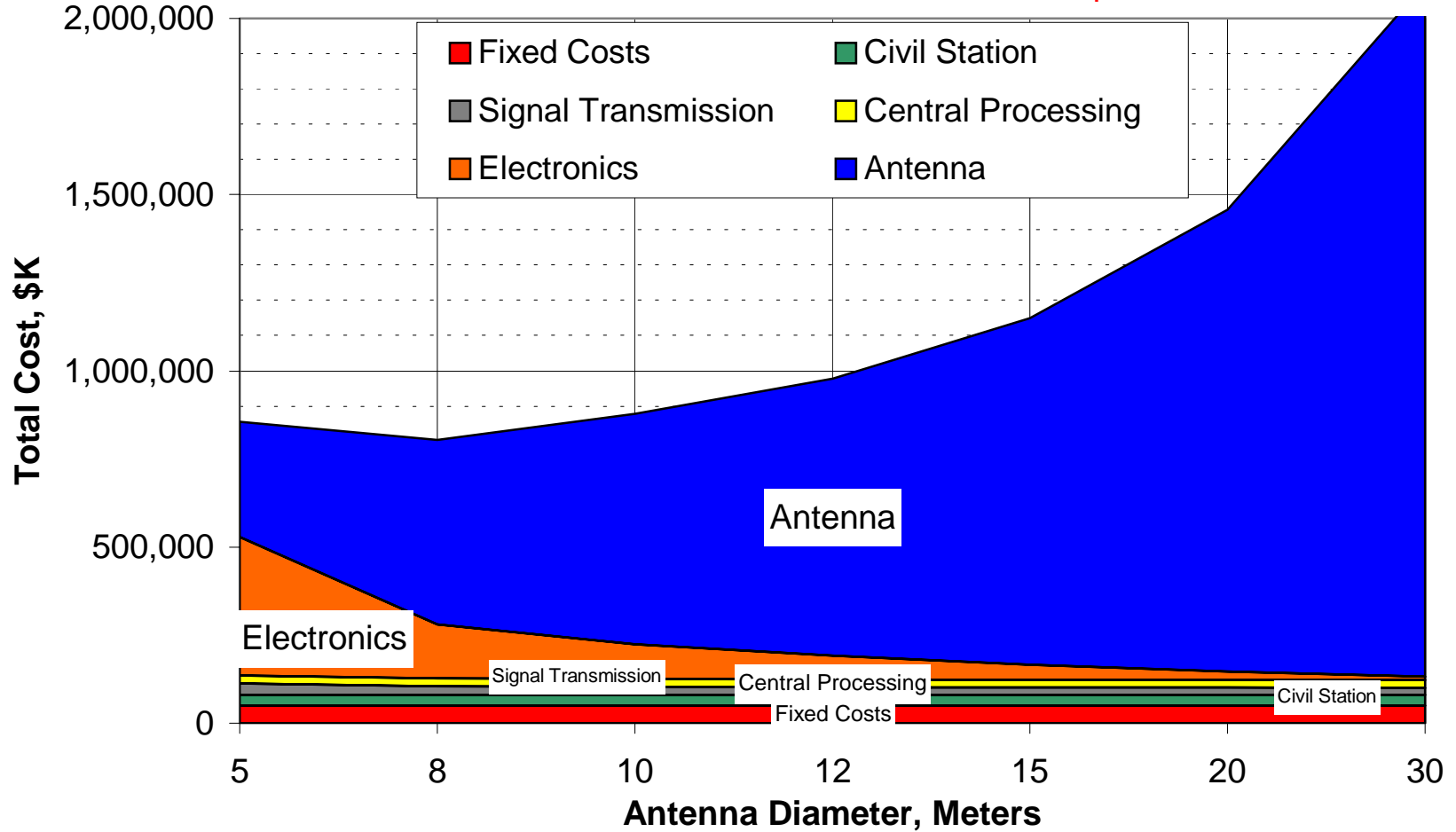
Antenna Cost =  $0.1D^3$  K\$, 2001 Electronics Cost = \$54K per Element



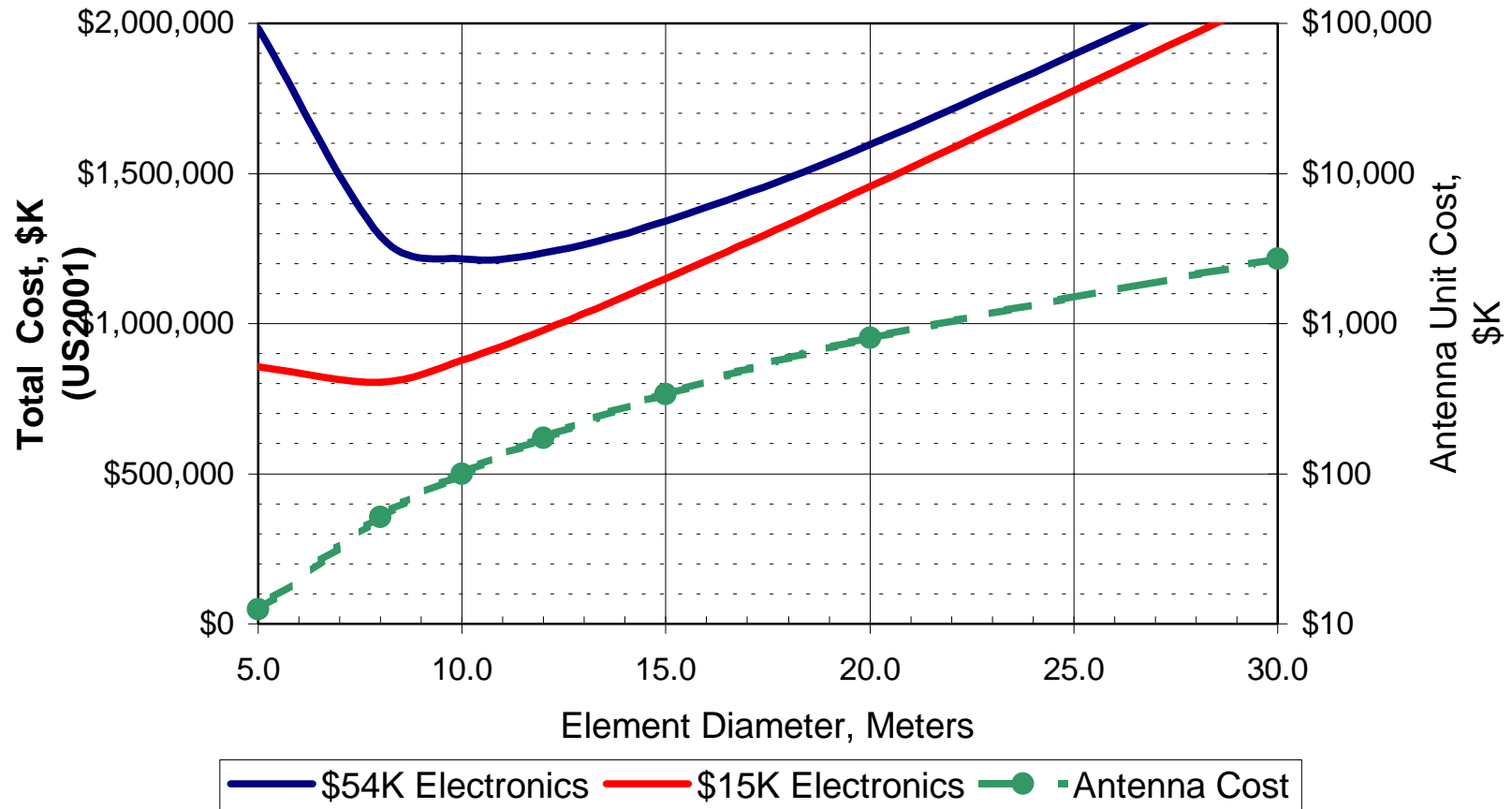
### SKA Cost Breakdown by Subsystem vs Antenna Diameter

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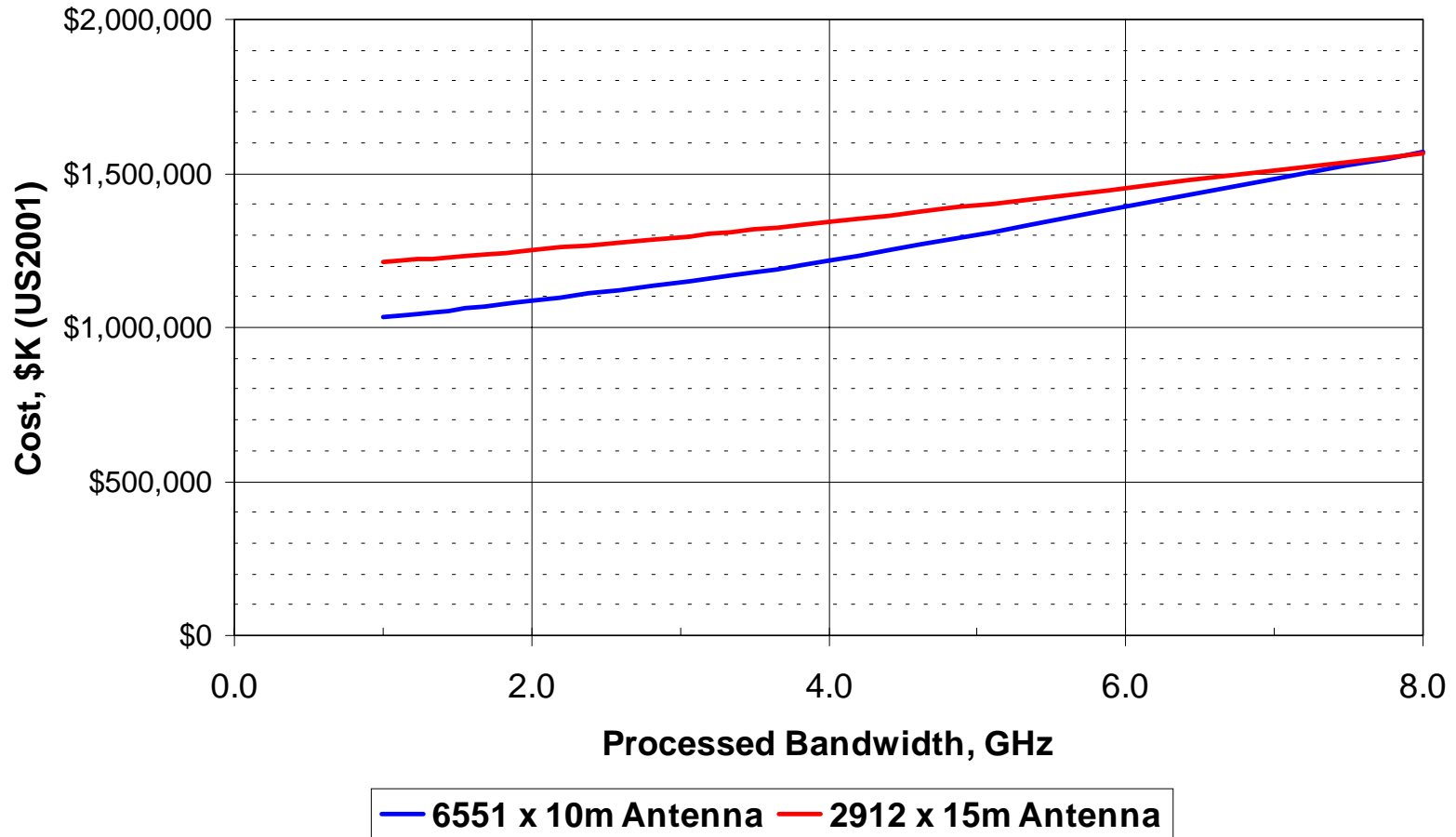
Antenna Cost =  $0.1D^3$  K\$, 2010 Electronics Cost = \$15K per Element



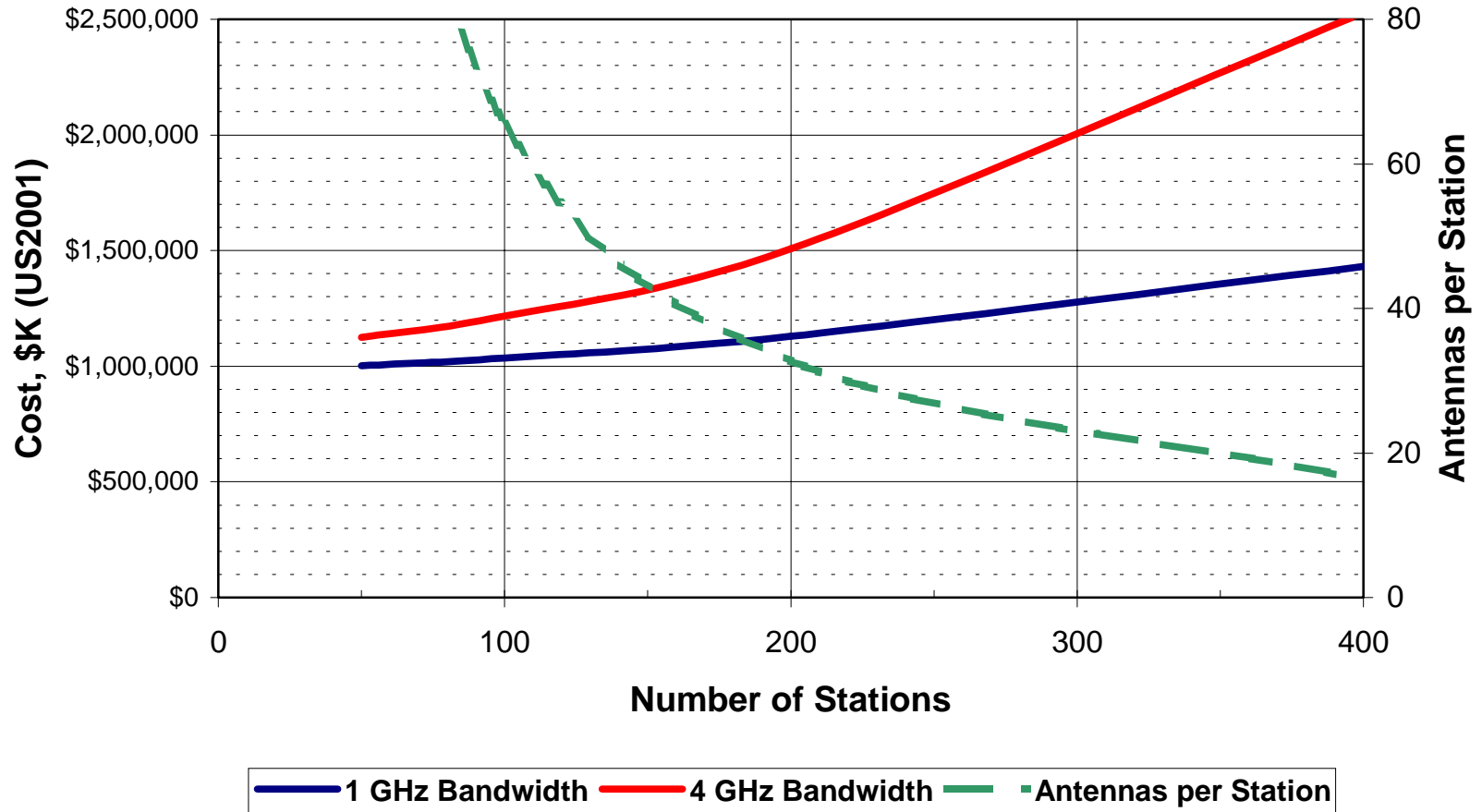
**SKA Cost vs Antenna Diameter**  
**Compares Current and Projected (2010) Electronics Costs**  
 All for 15K cryogenics, 4 GHz BW, 100 Stations, A/T = 20,000  
 Antenna Cost =  $0.1D^3$  \$K



**SKA Cost vs Processed Bandwidth for  
Two Antenna Diameters**  
All for 15K Cryogenics



**SKA Cost vs Number of Stations for  
Two Processed Bandwidths**  
All for 15K Cryogenics, 10m antennas. A/T = 20,000



## Front-End Cost and Performance Model

Cooler Type	Physical Temp	Cooler Cost, K\$	Noise @ 10 GHz	Noise @ 50 GHz	Noise @ F GHz
None	300	1	40	200	4*F
Peltier	180	3	24	120	2.4*F
Pulse or Klemenko	60	6	10	50	1.0*F
Gifford-McMann	15	20	4	20	0.4*F

### Total Front-End Cost, FE\$

$$\begin{aligned}
 \text{FE\$} &= \text{Cooler\$} + 3(\text{Bands}) * 2(\text{Polarizations}) * \text{LNA\$} \\
 \text{LNA\$} &= \$0.8\text{K} * (\text{Fmax}/10)^{.3} \\
 \text{i.e. FE\$} &= \$11.9\text{K} \text{ for Pulse Cooling with Fmax} = 20 \text{ GHz}
 \end{aligned}$$

### Total Electronics Cost, EL\$, per Antenna

$$\begin{aligned}
 \text{EL\$} &= \text{FE\$} + 3 * \text{Feed\$} + \text{LO\$} + \text{IF\$} + \text{Fixed\$} \\
 \text{Feed\$} &= \$1\text{K}, \quad \text{LO\$} = \$5\text{K}, \quad \text{IF\$} = 2 * (0.5 + 2 * \text{BW}), \quad \text{Fixed\$} = \$1\text{K} \\
 \text{i.e. EL\$} &= 11.9 + 3 * 1 + 5 + 2 * 4.5 + 1 = \$29.9\text{K}
 \end{aligned}$$

### Total System Noise, Tsys

$$\text{Tsys} = \text{Tlna} + [10 + 4 * (\text{F}/10)]$$

# Signal Processing Cost Model

- **EACH ANTENNA**

1. Digitization

$$C_d = [k_d (B/N_{ch})^e + c_d] N_{ch} \quad (\text{exponent } e \text{ is approximately } 2)$$

Cost per channel increases *faster* than bandwidth => more channels

- Presently expensive -- total for array is more than the correlator!

2. Tracking

- Primarily delay and phase tracking of sources
- Per antenna per beam -- multi beaming is probably needed to mitigate small FOV of station beam.
- All-digital implementation assumed

- **EACH STATION**

1. Summation to form phased-array, per beam

- Multi-beaming probably needed due to small station beam

2. Transmission to central processing facility

- available bandwidth shared among beams.

- **CENTRAL PROCESSING (CORRELATION)**

1. Per antenna section

- filter bank for  $L$  spectral channels
- cost grows as  $B \log(L)$  if minimum-memory FFTs are used

2. Interconnection section

- can dominate cost for large  $N$
- natural architecture grows as  $B N^3$
- clever architecture grows as  $B N \log(N)$

3. Cross correlation section

- grows as  $B L N^2$  (note  $L$  dependence, even for FX architecture)