Antenna and Electronics Cost Tradeoffs For Large Arrays

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Outline

- Cost modeling for large arrays
- Antenna mechanical cost over a wide range of sizes
- Cost of per-antenna electronics

Cost Modeling

- Cost modeling is different from costing a given design
  - No design exists yet, but tradeoffs should be understood and optimization undertaken before a design is selected.
  - Model == parameterized cost
    - some parameters fixed, especially performance measures
    - other parameters free, preferably over a wide range
  - Model should show parameter dependence accurately, but may give a poor absolute cost estimate for any fixed set of parameters.
- *Empirical:* fit formula to known costs of full systems
- *First principles:* use market data for basic costs (labor rates, raw material prices); derive system cost by analysis.

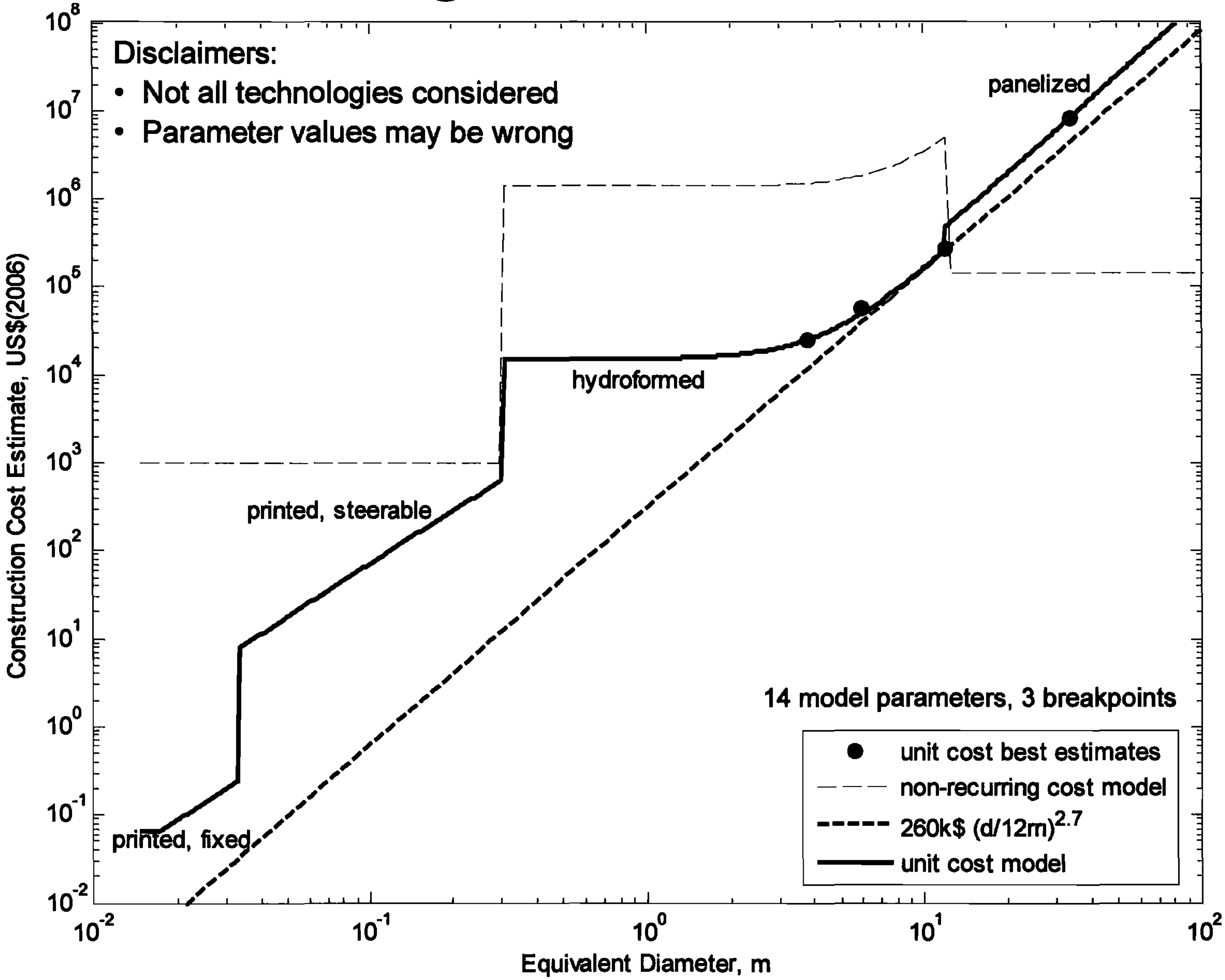
Antenna Mechanical Cost: Traditional Model

- Power law model
  - $C_a(A) = (A / A_{ref})^{\alpha} C_{ref}$
  - first principles: Blackman and Schell 1966, *IEE Conf.*
    - cost, including labor, proportional to mass of raw materials
    - NRE neglected
    - deflection at a fixed wind speed held constant
    - exponent $\alpha \approx 4/3$ ($2\alpha = 8/3 \approx 2.7$)
  - empirical: JPL study, Wallace 1979
    - exponent $\alpha \approx 1.27$ ($2\alpha = 2.55$)
- Valid only in limited circumstances
  - large antennas, where material cost dominates
  - fixed technology of construction

Antenna Mechanical Cost: Improved Models

- Cover a wide size range, sub-wavelength to ~100m.
- Let construction technology vary with size:
  - 100m to ~10m: panelized reflectors
  - ~10m to ~1m: single-piece reflectors
    - hydroformed metal
    - composite
  - 10s of cm: printed or open-waveguide/Vivaldi
  - sub-wavelength: printed antennas, not steerable
- Use separate models for major elements:
  - Reflector (including backup structure, if any)
  - Mount and drive
- Separate NRE from replication cost

Wide-Range Cost vs. Size Model



Why Traditional Model Does Not Work

- Cost of *complex* components is not proportional to mass of materials.
  - Motors, encoders, gearboxes, bearings
  - Assembly labor (as opposed to raw machining)
  - Testing
- Minimum-cost technology varies with size
- As size decreases, cost of some components stays constant
  - Servo electronics
  - Foundation
- For steerable reflectors:
  - At large sizes, cost of reflector dominates
  - At small sizes, cost of reflector is negligible

Why Empirical Modeling Does Not Work

- Little reliable data exists
- Variations in accounting methods
  - What is included in the reported costs?
  - How was responsibility divided?
  - How was NRE handled?
- Variations in specifications
  - Frequency limit
  - Transportable vs. fixed
  - Operating environment, reliability
- Mass production has not been attempted at most sizes
  - ATA is providing the first experience, N=34+, d=6m size only
  - VLA is next largest example, N=28, ~30 years ago.

Case Study: Cost of 12m Antennas

- 2004 survey of manufacturers commissioned by JPL
  - Identical specs provided to all, including
    - 0.3 mm rms surface
    - 44 m/sec survival wind, 13 m/sec operating wind
    - 18 arcsec blind pointing
    - quantity 100
  - 7 responses; estimates ranged from **217k$** to **1653k$** (7.6:1).
- 2005 study for SKA (R. Schultz, SKA Memo 63)
  - More thorough design, intended for mass production
    - 0.3 mm rms required only at night
    - lower operating wind speed
    - quantity > 1000
  - Unit cost estimate **200.9k$**, incl. overhead and profit, excl. NRE
- Actual cost of 1 each antenna purchased by JPL
  - Approximately **750k$**, including NRE
- ALMA antenna, quantity 25, .025 mm rms: **6.76M$**

Per-antenna Electronics

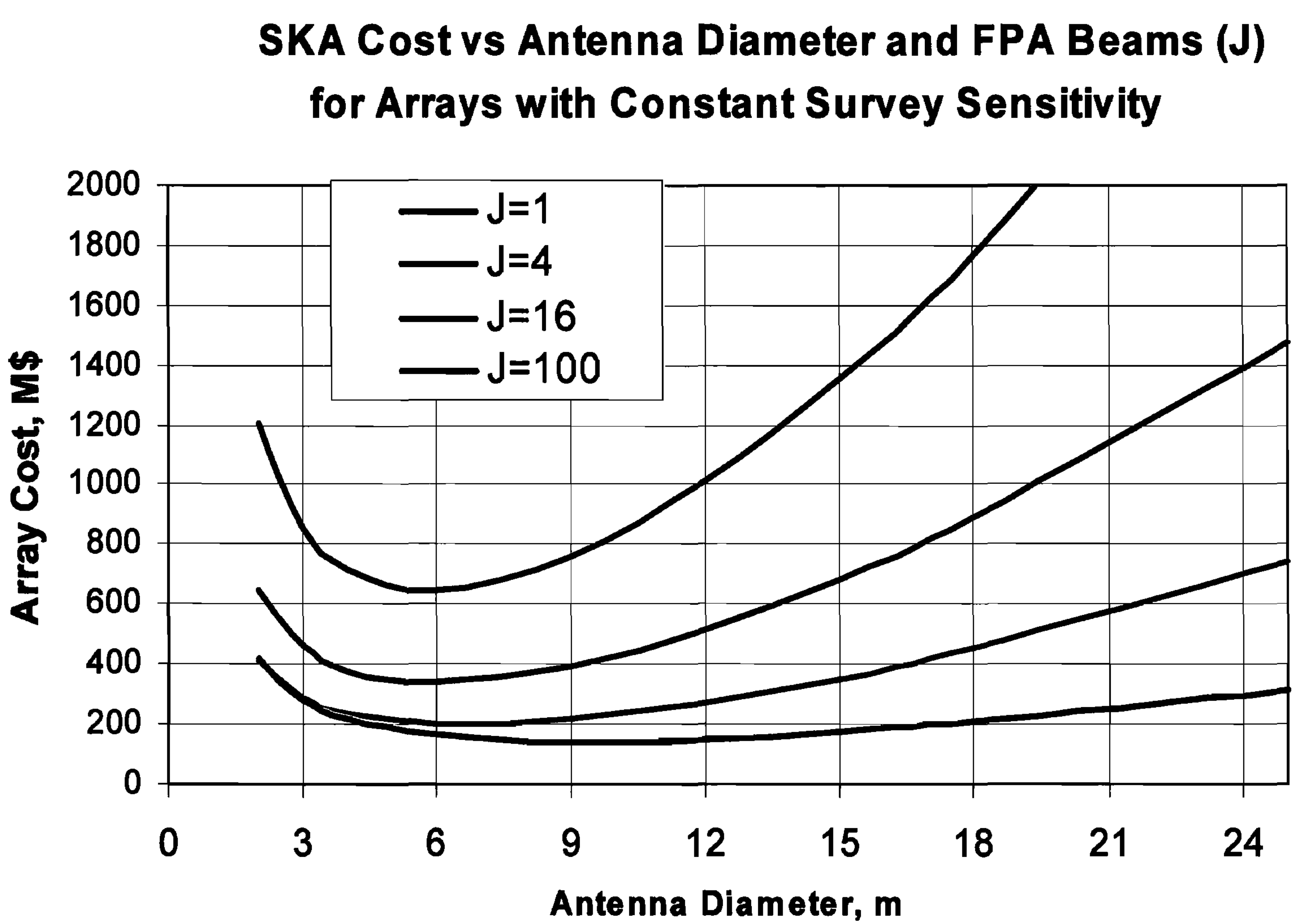
- Includes feed, LNA, downconverter/LO (if any), channelizer, digitizer
  - Not all are necessarily located at antenna, but must be duplicated for each antenna.
  - Includes all support hardware, e.g. cryocooler (if used).
- Cost is dominated by integration: packaging, interconnections, power supplies, assembly labor – not by the semiconductor devices.
  - Not subject to Moore's Law
  - Improved by more design effort, more custom-engineered parts
  - For single dishes or small arrays, this "NRE" is not justified; it makes sense for large arrays
- Designing for mass production; economies of scale

Electronics Cost Trends

- Improvements
  - Wider bandwidth feeds and LNAs require fewer to cover a given frequency range.
  - Lower noise at room temperature increases frequency at which cryocooling is cost effective.
  - Higher integration levels produce smaller packages, fewer interconnections, and require less power.
    - RF in to optical fiber out on a single chip or multi-chip module
    - Mixed signal chips, including substantial DSP with analog processing
    - Many channels per chip or module
- Limitations
  - Multi-beam antennas require more electronics.
    - for phased array feeds, complex signal processing is added
  - For arrays with steerable reflectors, gain from integration is limited because hardware is geographically dispersed.
  - Custom ICs are cost effective only if large numbers are needed.

backup slides follow

SKA Optimization Example



From: S. Weinreb, SKA Memo No. 77

Model Parameters for Large Arrays

- Figures of Merit (fixed)
  - FOM1 = A_{tot} / T (point source sensitivity)
  - FOM2 = $(A_{tot} / T)^2(B/A) = NBA_{tot} / T^2$ (survey speed)
- Dimensions (free)
  - Size of each antenna element, A
    - Number of elements is $N = A_{tot} / A$
  - Physical temperature of front end electronics, T_{phys}
  - Number of simultaneous beams, B
- Cost models discussed in this paper
  - Antenna mechanical $C_a(A)$
  - Antenna-connected electronics $C_e(B, T_{phys})$

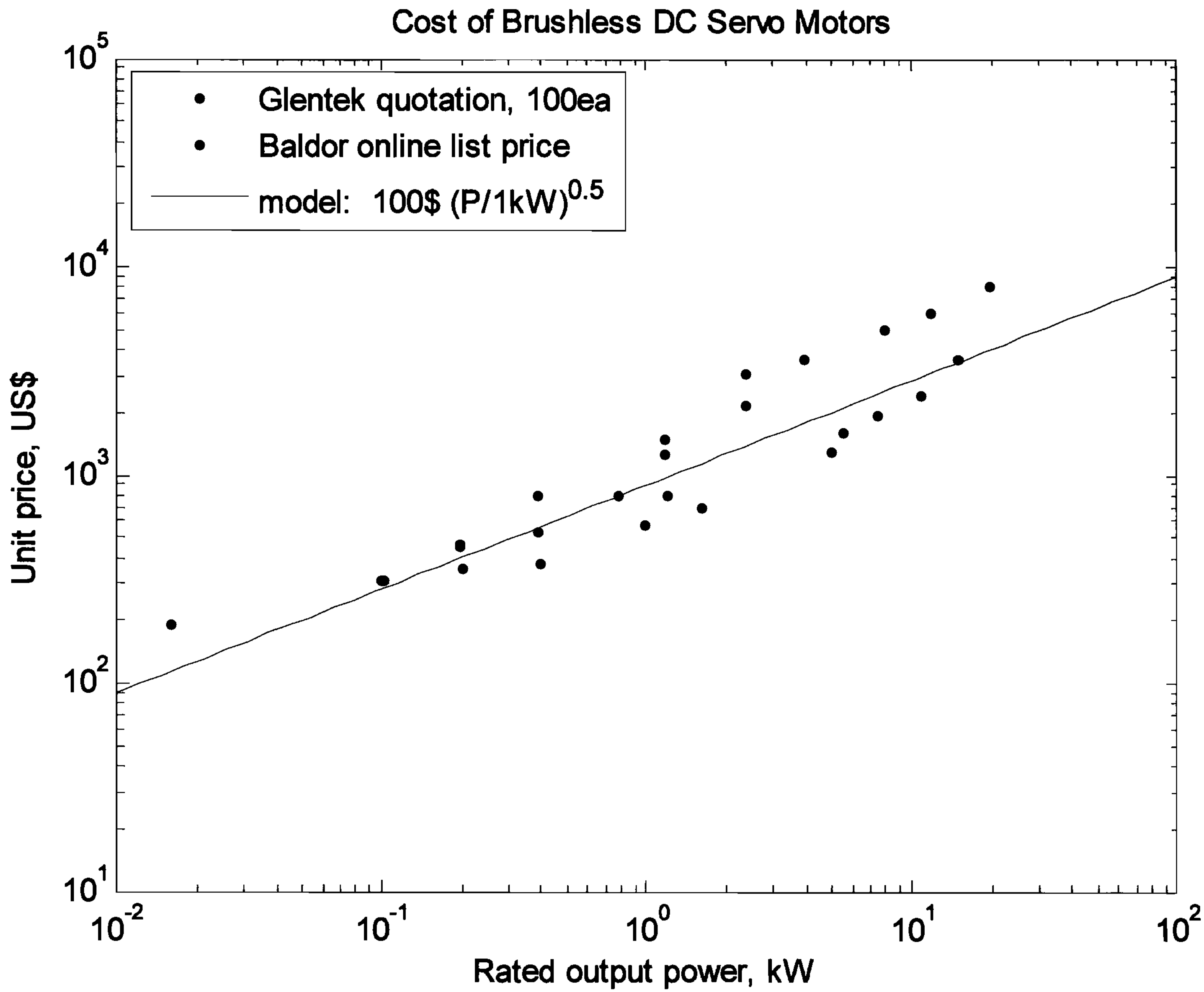
List of Model Parameters

```
par.a(1)=214;                   %PCB cost $0.14/in^2 = $214/m^2.
par.a(2)=1000;                  %NRE for PCB

par.a(3)=1.385e6;               %Hydroforming factory: $1.385M fixed
par.a(4)=3.64e6/12^3;           %Hydroforming mold: $3.64M for 12m dia
par.a(5)=30000/12^2;            %Hydroforming reflector:  $30k for 12m dia

par.a(6)=2.2e5/12^3;            %Drives,mount,foundation: $220k for 12m dia

par.a(7)=2.5;                   %Panelized reflector exponent
par.a(8)=2.5e5/12^par.a(7);     %Panelized reflector:  $250k for 12m dia
par.a(9)=142000;                %Panelized NRE, const, 142k$ for 12m dia.

par.a(10)=0.60;                 %Aperture efficiency, hydroformed & panelized
par.a(11)=pi/180*63;            %Max off-boresight angle for non-steerable
par.a(12)=pi/180*82.6;          %Max zenith angle for steerable
par.a(13)=1;                    %Min size of steerable mount, m.
par.a(14)=15000;                %Base cost of mount: mountCost = a14 + a6*d^3.

    % Antenna size breakpoints by effective area
par.b(1)=(lambda./(1+cos(par.a(11)))).^2 .* sin(par.a(11));     %Max non-steerable
par.b(2)=pi/4*0.3^2*par.a(10);  %Minimum hydroformed = 0.3m
par.b(3)=pi/4*12^2*par.a(10);   %Maximum hydroformed = 12m
```

Lessons

- Cost estimates, even by experienced manufacturers, are not reliable because
  - No commitment is made if a firm bid is not required
  - Insufficient engineering effort is expended in the absence of payment
- To obtain believable estimates, either
  - require firm bids and show that funds exist, or
  - pay for the estimation work

Motor cost vs. size over a wide range



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