NATIONAL RECONNAISSANCE OFFICE

# Developing Space Hardware Box NR CERs at the NRO CAAG

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## About the NRO

- The National Reconnaissance Office (NRO) is:
  - The national program to meet the U.S. Government's intelligence needs through spaceborne reconnaissance
  - A Department of Defense (DoD) agency and an element of the Intelligence Community
  - Funded through the National Intelligence Program and the Military Intelligence Program portions of the federal budget
- The NRO's existence was declassified by the Deputy Secretary of Defense on September 18, 1992

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## Agenda

- Background:
  - Nonrecurring Cost
  - Box-level estimates
  - CAAG Data Set
  - Equipment Groups
  - CER Development
- NRO CAAG NR CER Strategies
  - Selecting cost drivers
  - Segregating cost of NR engineering effort from cost of development units
  - Low % New Design values and Incidental Nonrecurring
  - Selecting the best CER

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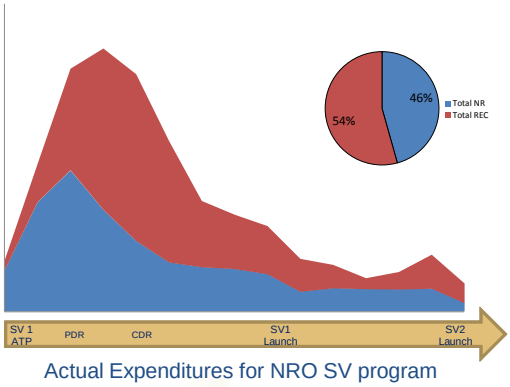
## Nonrecurring Costs are Important




Actual Expenditures for NRO SV program

**Nonrecurring Costs:**
Requirements definition
Engineering design & analysis
Manufacturing tooling
Development units
Simulators
Development and acceptance test procedures
Redesign, rework & retest to correct design flaws

**Recurring Costs:**
Production unit parts & materials
Production unit fabrication, assembly & testing
Spare parts production units
Rework due to workmanship problems

**Nonrecurring cost happens…**
- For initial design, or upgrades and changes
- To address obsolescence in existing designs
- Or, even when there is no new design – "Incidental Nonrecurring"

NR costs can be a significant portion of total SV acquisition costs

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## Why are NR CERs Harder to Develop?

- Less data available for NR CER development than REC CERs
  - All units have recurring cost but not all units have significant NR cost
  - Not all organizations collect data on NRO CAAG preferred cost drivers
- More variance in the data, more "noise" around relationships and trends
- Difficulties in accounting for development units
- Intuitively, there are more cost drivers in play

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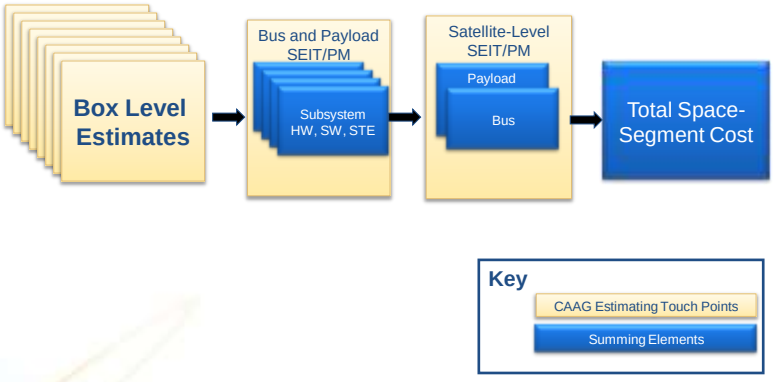
## NRO CAAG Estimates at the Product/Box Level

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## Why Box-Level Parametric Estimates?

Box Level

- Low enough level to:
  - Support design trades
  - Demonstrate detailed understanding of space vehicle
  - "Tune" the cost estimate to the technical baseline
- High enough level to:
  - Leverage collected data aligned to Standard Work Breakdown Structure
  - Incorporate lowest levels of SEITPM

Parametric

- Unbiased (Statistically)
- Repeatable
- Provides statistically quantifiable uncertainty
- Conducive to sensitivity and affordability analysis

Provides the most utility to support acquisition decisions and program execution

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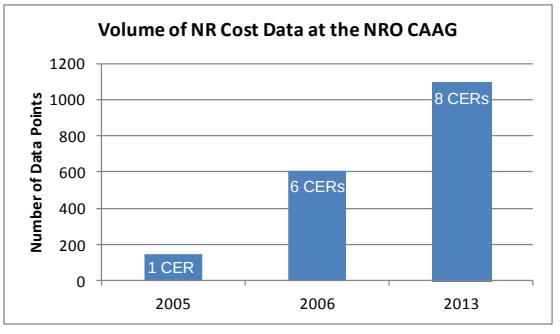
## The Data Set




- The NRO CAAG has a lot of data, from many programs, and multiple sources
  - Disciplined data collection and participation with our industry partners has increased the volume of available cost data in recent years
- A larger and more updated data set is the primary reason to update our models – more data is a great thing
  - Better breakouts by equipment type, validation of trends, additional drivers are possible with more data

*counts only data with NR cost >0, and %new design > 0. Full data volume is closer to 2300 data points.

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## NRO CAAG Product/Box Level CER Inventory

### 8 Nonrecurring CERs

- RF Equipment
- Digital Equipment
- Antennas and Feeds
- Misc. Electrical / Electronics
- Structures and Mechanical
- Wheels, Drives, & Positioners
- ACS Sensors
- Optical

### ~80 Recurring CERs

| | | |
|---|---|---|
| Att. Control Elex (ACE) | Helix antenna | Solid Rocket Motors |
| Back-End RF Electronics | Dipole/Other antenna | Solid-State Transponders |
| Power Monitors | Nutation Dampers | Solid-State Transmitters |
| BAPTAs | Comm Data Processing Electronics | Star Trackers |
| Li batteries | Mission Payload Processing Elex. | Solar-Array Booms |
| NiCd batteries | Positioner assemblies | Other Deployable Structure |
| NiH batteries | Positioner motors | Secondary Structures |
| Booster Adapters | DC power converters | Trusses and Towers |
| Command Receivers | AC power converters | Equipment Compartments |
| GPS Digital | Phased Array Antennas | Optical Payload structures |
| Comm Front-End RF Electronics | Power & Coax Harnesses | Analog sun sensors |
| Comm LNAs | Propulsion Plumbing | Digital sun sensors |
| DC Power Harnesses | Pressurant Tanks | Bus and RF Payload thermal H/W |
| Deployment Drives | Propellant Tanks | EO Payload Thermal H/W |
| Driver Control & Data Routing Elex | Pyro Driver Electronics | Thermal Shields/ Barriers /Louvers |
| Earth Sensors | RF Coax Harnesses | Thermal Heaters and Sensors |
| EPS Electronics | Shunts, Dissipators and Capcitors | Thermal Heat Pipes & Radiators |
| Flight Computers | Feeds | Thermal Blankets |
| IRUs | Front End RF Electronics | Thrusters |
| Accelerometers | Preamplifiers | Oscillators |
| Large Deployable Reflectors | Small Parabolic Antennas | Timers/Clocks |
| Magnetic Torquers | GaAs, deployable arrays | TT&C Digital Electronics |
| Magnetometers | GaAs, not deployable arrays | TWTAs |
| Downlink MW Plumbing | Silicon, deployable arrays | Waveguide Assemblies |
| TT&C MW Plumbing | Silicon, not deployable arrays | Reaction Wheels |
| Horn antenna | Solar Array Drives | CMGs |
| Spiral antenna | | etc. |

- There are recurring CERs for most Space Hardware Equipment Groups, there are far fewer nonrecurring CERs

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## Grouping the Equipment Types

**1) RF Equipment**
- Receivers
- Transmitters
- Transponders
- Up/downconverters
- Modulators
- Oscillators
- Power Divider/Switching Units
- LNAs
- SSPAs
- TWTAs
- Laser Sources
- Analog signal processors and readouts
- Coax harness
- Microwave plumbing

**2) Digital Electronics**
- Payload digital processing and control
- Encoders/decoders
- Command units
- Telemetry units
- Flight computers
- Solid-state recorders
- AD and DA converters
- Digital multiplexers
- Encryption/Decryption units

**3) Antennas and Feeds**
- Reflectors
- Feeds (all types)
- Antennas (all types)

**4) Misc. Electrical/ Electronic**
- Valve drivers
- Heater controllers
- Pyro/squib drivers
- Battery controllers
- Batteries
- Solar arrays
- Solar-array regulators
- ACS electronics
- Servo electronics
- Power converters and conditioning
- Payload power supplies
- Power harness
- Magnetic Torquers

**5) Structure and Mechanical**
- Thrusters
- Tanks
- Propulsion plumbing
- Structure
- Booms
- Thermal blankets
- Heat pipes
- Radiators
- Paints
- Tapes
- Louvers
- Cold plates
- Sensor mounts
- Optical benches
- Outer barrel assemblies
- Optical baffles
- Nutation Dampers
- Booster Adapters

**6) Wheels, Drives, & Positioners**
- Positioners
- Deployment drives
- Gimbals
- Wheel devices
- Actuators
- Solar array drives

**7) ACS Sensors**
- IRUs
- Sun sensors
- Star Trackers
- Earth Sensors
- Accelerometers
- Magnetometers

**8) Optical**
- Mirrors
- Lenses
- Telescope assemblies
- Optical Filters/Grates/Prisms

- Groups should be small enough to have a similar response to NR cost drivers yet large enough to capture sufficient data points

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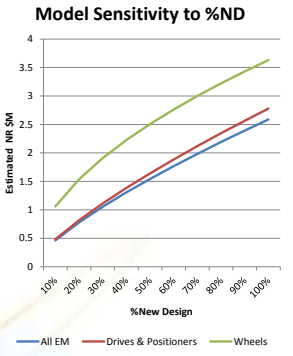
## Equipment Type Stratification

- When multiple equipment types are grouped into one data set we can use dummy variables to stratify a CER based on subgroups
- Models must have similar behavior over the range of expected values for both scale and complexity variables

Good

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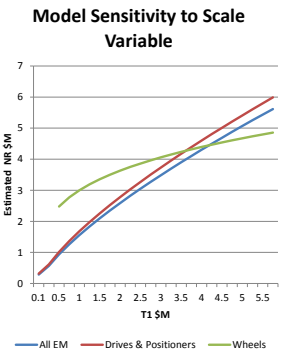
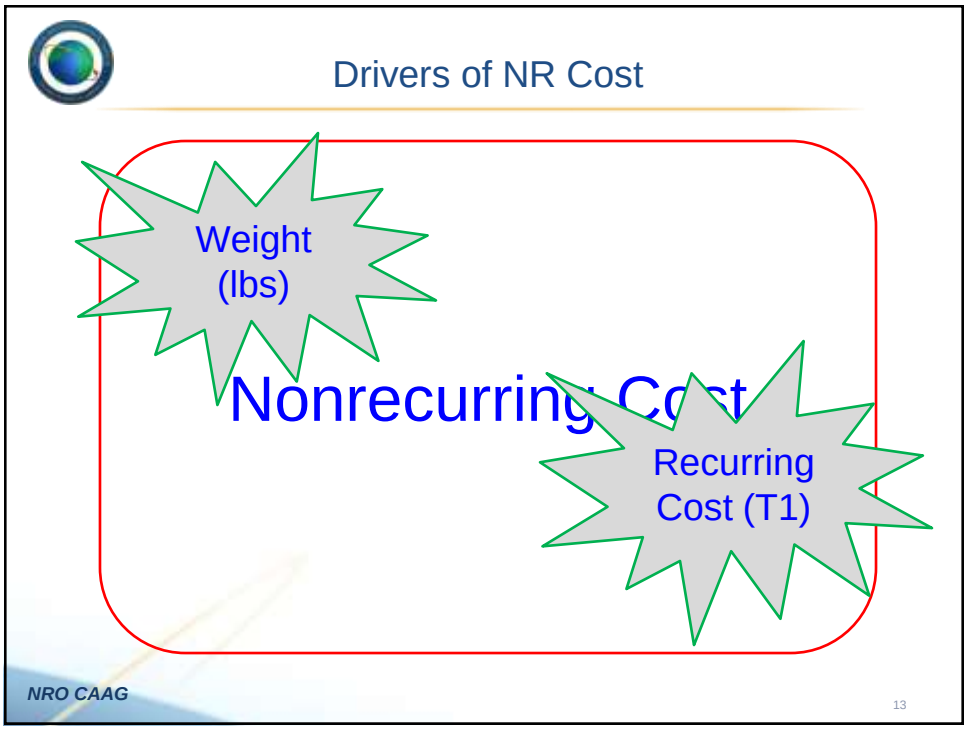



$$NR = a(T1)^{b}(Qty)^{c}(\%ND)^{d}e^{drives\,f\,wheels}$$



## Drivers of NR Cost

Nonrecurring Cost


Drivers of NR Cost
Weight (lbs)
Nonrecurring Cost
Recurring Cost (T1)
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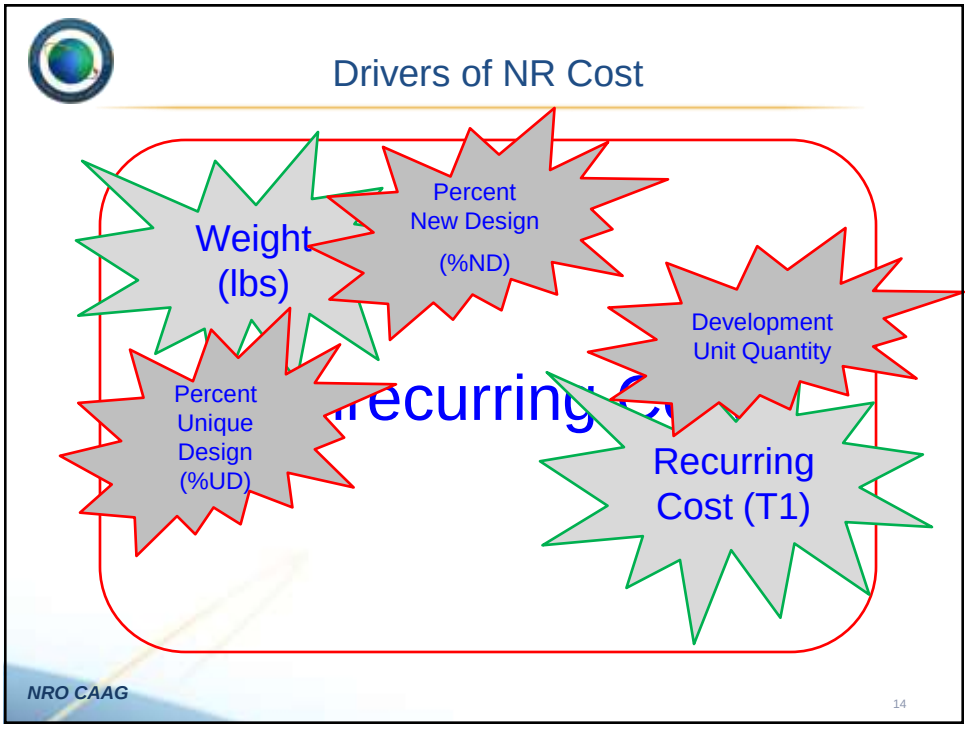
Drivers of NR Cost
Weight (lbs)
Percent New Design (%ND)
Development Unit Quantity
Percent Unique Design (%UD)
Recurring Cost (T1)
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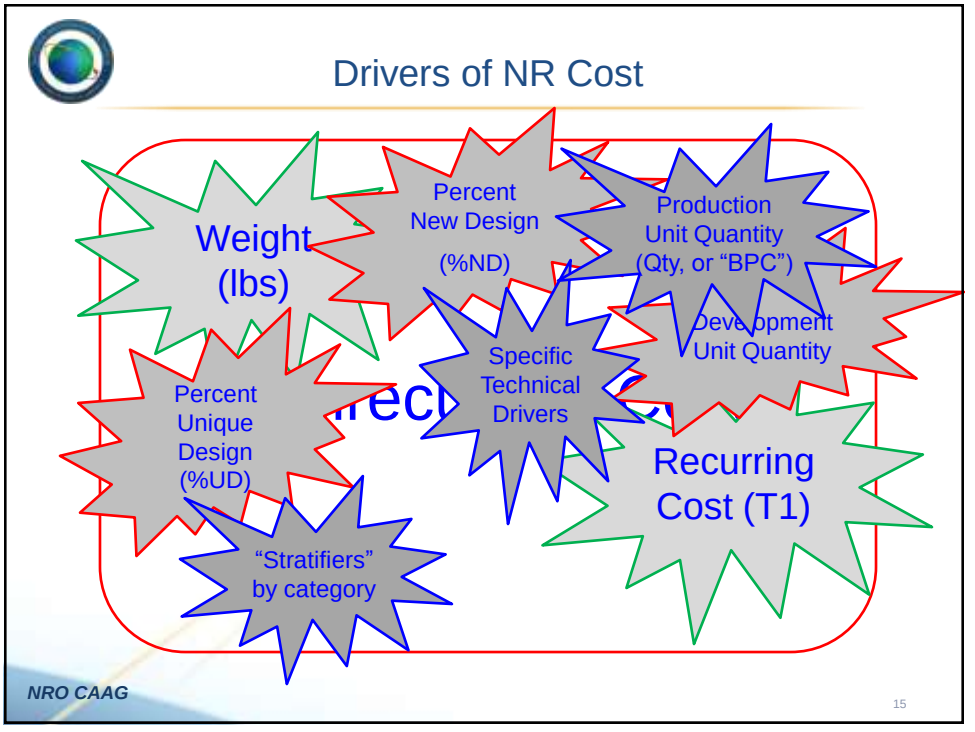
Drivers of NR Cost
Weight (lbs)
Percent New Design (%ND)
Production Unit Quantity (Qty, or "BPC")
Development Unit Quantity
Specific Technical Drivers
Percent Unique Design (%UD)
"Stratifiers" by category
Recurring Cost (T1)
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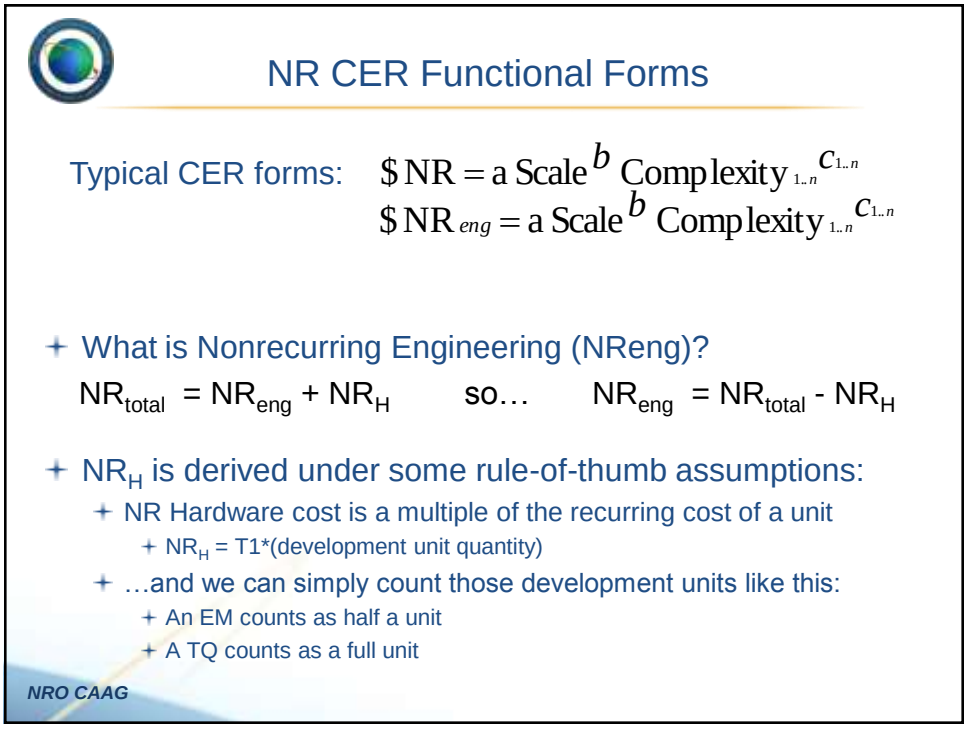
NR CER Functional Forms
Typical CER forms:
$\$\mathrm{NR} = \mathrm{a}\,\mathrm{Scale}^{b}\,\mathrm{Complexity}_{1..n}^{c_{1..n}}$
$\$\mathrm{NR}_{eng} = \mathrm{a}\,\mathrm{Scale}^{b}\,\mathrm{Complexity}_{1..n}^{c_{1..n}}$
What is Nonrecurring Engineering (NReng)?
$NR_{total} = NR_{eng} + NR_H$ so… $NR_{eng} = NR_{total} - NR_H$
$NR_H$ is derived under some rule-of-thumb assumptions:
NR Hardware cost is a multiple of the recurring cost of a unit
$NR_H$ = T1*(development unit quantity)
…and we can simply count those development units like this:
An EM counts as half a unit
A TQ counts as a full unit
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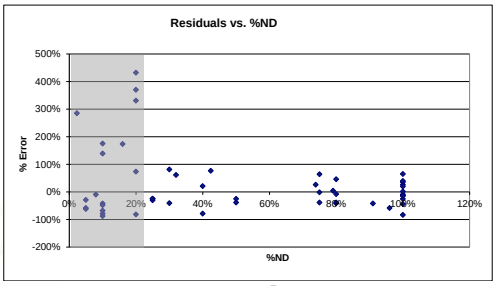
## Estimating for Low %ND Boxes

- Very low %ND points can be very small and create large errors on a percentage basis and have a significant impact on regression coefficients due to their increased dispersion
- High dispersion in costs for low %ND points causes CER summary statistics to overstate estimating uncertainty for the high value points
- All else being equal, points with high %ND are more expensive and are more important to estimate accurately




$$\$\mathrm{NR} = \mathrm{a}\, T1^{b}\, \%ND^{c}$$

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## Incidental Nonrecurring (INR) Costs

- Some boxes with 0%ND have nonrecurring costs, we call this INR
  - Boxes without new design are common in follow-on vehicles
  - Caused by a variety of factors: product improvement, minor obsolescence, startup admin, mfg setup, analysis for use in new environments, requal, etc.
- Inputs with 0%ND would always result in an estimate of zero costs in our standard multiplicative functional form
- In order to capture INR costs, alternative models were attempted for each equipment type

$$\mathrm{NR} = a(\mathrm{T1})^{b}(\%\mathrm{ND}+\mathrm{c})^{\mathrm{d}} \qquad \mathrm{NR} = a(\mathrm{T1})^{b}(\%\mathrm{ND})^{\mathrm{c}} + d(T1)$$

$$\mathrm{NR} = a(\mathrm{T1})^{b}(\%\mathrm{ND}+.05)^{\mathrm{d}}$$

Despite attempts, we recommended continued use of a separate INR model for all equipment groups instead of box specific models

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## Low %ND Values Solution

- Analysts attempted clipping the data set to remove low %ND values
  - Improved reasonableness of coefficient values
  - Improved performance metrics
  - Maintained sufficient degrees of freedom
- The %ND threshold for clipping was determined by performing sensitivity analysis and finding a knee in the curve with diminishing SPE and R2 improvements

| Model | %ND | DOF | SPE | $R^2$ |
|---|---|---|---|---|
| 1 | >0 | 62 | 95.4% | 37.3% |
| 2 | 0.1 | 57 | 77.0% | 36.6% |
| 3 | 0.15 | 50 | 67.6% | 25.2% |
| 4 | 0.2 | 49 | 67.8% | 23.0% |
| 5 | 0.25 | 45 | 57.6% | 49.8% |
| 6 | 0.3 | 40 | 56.3% | 50.8% |
| 7 | 0.5 | 33 | 59.2% | 56.3% |

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## %ND as a categorical variable

- %ND values require engineering judgment and are difficult to calculate accurately
- A categorical variable for %ND would have some benefits
  - Makes more data available for analysis
  - Alleviates lower bound issues
  - Simplifies data collection requirements

Example Categories

| %ND Category Grouping | %ND Range |
|---|---|
| Minor Modification | 0-30 |
| Moderate Modficiation | 30-60 |
| Significant Modification | 60-90 |
| Major Modification | >90 |

- Analysts attempted CER models with this strategy, with mixed results

We continue to use %ND as a continuous variable, but we will explore this strategy further in future studies and CER updates

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# EVALUATING REGRESSION RESULTS



## Pick a Winner

- So, you've generated 120 CER candidates from your data set using multiple regression analysis methods… which will you recommend?

### Criteria for choosing the "best" CER

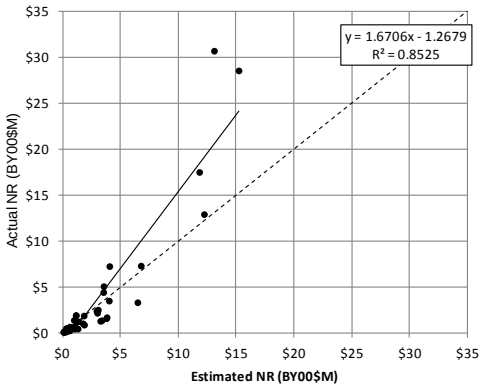
- Consistency with technical evaluation and engineering knowledge
  - Exhibited cost relationships agree with expectations
- Quality and performance metrics
  - SPE (lower is better)
  - Bias (lower is better, typically driven to zero)
  - Trends in residuals charts
- Other factors to consider
  - Degrees of freedom (more is better)
  - Quality of sample data
  - Applicability and Ease of Use
  - Sensitivity to influential data points

*Cost and Acquisition Assessment Group*

Also:

- Sensitivity to desired cost drivers
- Equipment "sub-groups:" - how well does the model estimate each *type* of HW
- Simplicity – lends to ease -of-use
- Residuals Analysis – watch out for trends in the errors (*slides to follow*)

## Spotting the Trends
### Actuals vs. Estimates




CER underestimates at the high end of the data set.

- Examine scatter plots of the resulting estimates to diagnose potential issues with a CER Candidate

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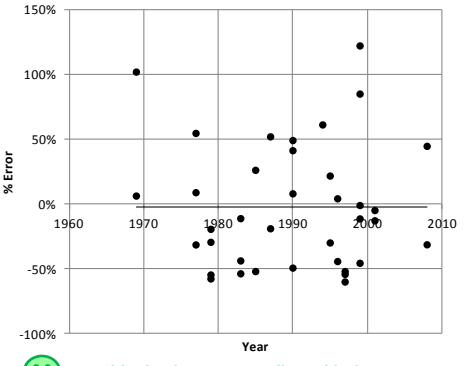
## Spotting the Trends
### Residuals Analysis

CER underestimates these points.

CER overestimates these points.




Residuals show no trending with time.

- Examine scatter plots of the errors against NR drivers both in unit space and log space
- Can help diagnose potential issues with:
  - CER candidates
  - Data quality

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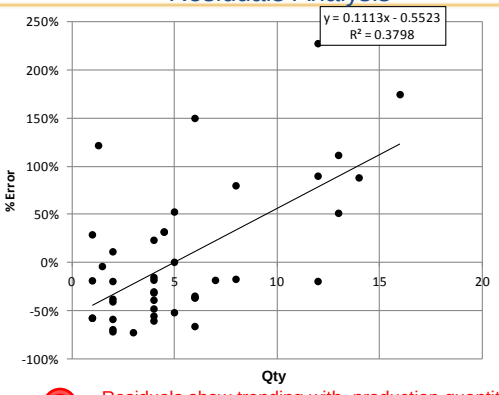
## Spotting the Trends

### Residuals Analysis




Residuals show trending with production quantity, this CER may need to include this driver.

- An evident trend in the residuals can be an indication of a missed driver from the CER data set
- This model will likely perform better once production quantity is added as a cost driver

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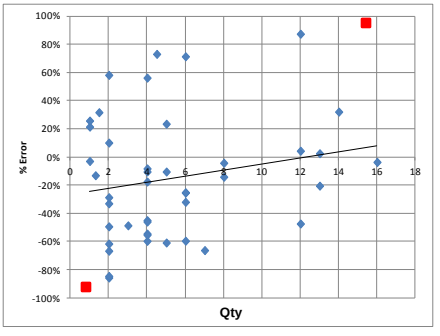
## Search for "High Leverage" Outliers




- In the case that an exponent is unexpectedly high, look for high leverage outliers that are driving the exponent up
- Omitting just one outlier can cause a significant change – *and one or two data points should not determine the trend !*

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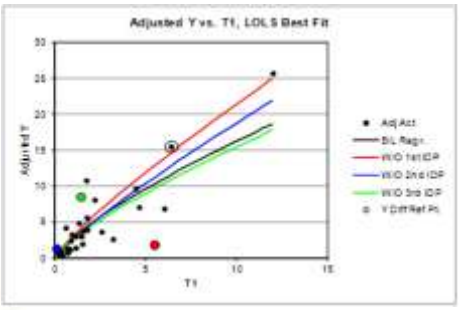
## CER Analysis Tool (CERAT)

### Searching for Influential Data Points

- The outlier data points that really matter to us are those that are "influential" to our CER results, or its resulting coefficient values
- The CER Analysis Tool searches for influential data points (IDPs) by iteratively removing one point at a time and re-running the regression, tabulating and plotting results




- Obvious outlier data points are not always IDPs, and vice-versa
- IDPs are not automatically omitted, it's up to the analyst to decide

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*Image from D. Mackenzie, ISPA-SCEA presentation on IDPs – Feb 2012

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## Summary

- Group data from multiple equipment types to mitigate issues caused by a small data set but watch the trending against drivers
- Watch out for data points with very small values (cost or scale) and consider omitting these points
- Screen CER candidates for reasonable coefficient values and satisfactory quality metrics
- Evaluate residual trending vs. all cost drivers, stratifiers and other related parameters
- Search for overly influential data points

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## Questions?

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