# Production Testing of Operational Amplifiers

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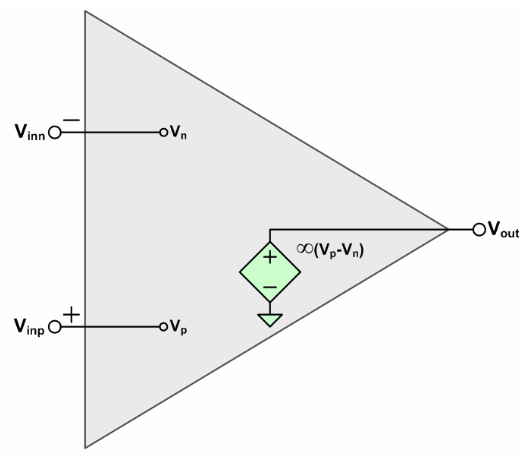
## Agenda

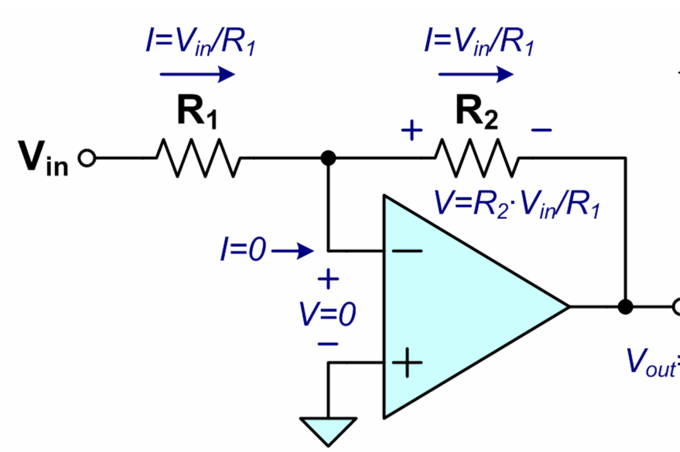
- Opamp Overview
- Production Test Strategy
- The Opamp Servo Loop
- DC Parameter Testing Methods
- Embedded Opamp Servo Loop
- Opamp Testing at TI

## Ideal OpAmp Model



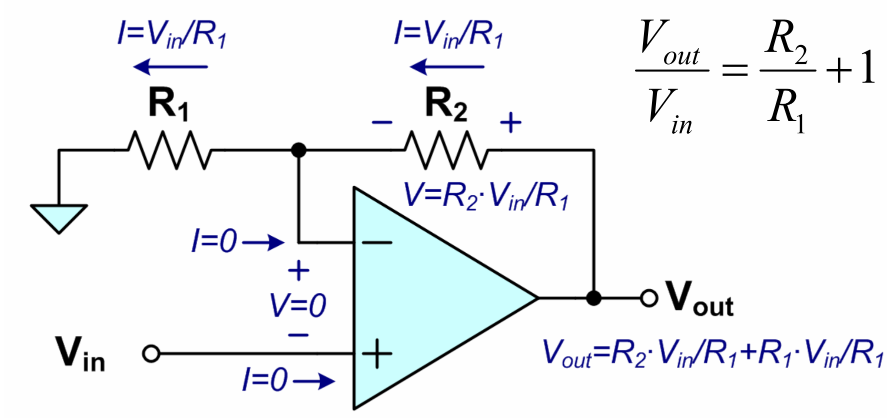

- No current flows into $\mathbf{V_{inn}}$ or $\mathbf{V_{inp}}$
- When operated in negative feedback, $\mathbf{V_{inp} - V_{inn}} = 0$

## Inverting Opamp Configuration



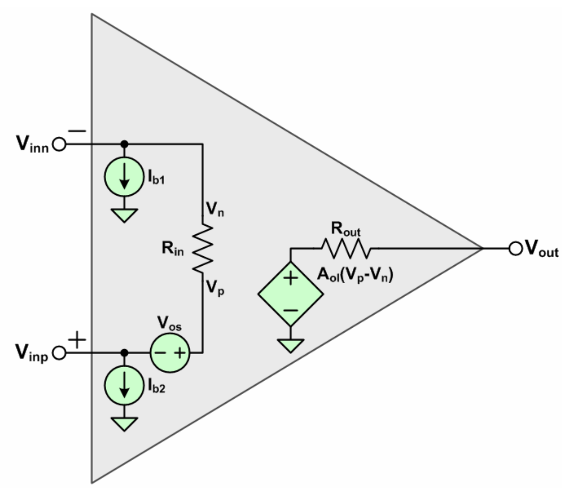

$$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

# Noninverting Opamp Configuration




$$\frac{V_{out}}{V_{in}} = \frac{R_2}{R_1} + 1$$

# OpAmp DC Model with Imperfections




- $V_{inn}$ – Negative Input
- $V_{inp}$ – Positive Input
- $V_{out}$ – Output
- $I_{b1}$, $I_{b2}$ – Input Bias Current
- $R_{in}$ – Input Impedance
- $R_{out}$ – Output Impedance
- $V_{os}$ – Input Offset Voltage
- $A_{ol}$ – Open Loop Gain

## OpAmp - Typical Specs

| OpAmp Characteristics | OPA277 *Low $V_{os}$* | OPA129 *Low $I_B$* | OPA627 *$V_{os}$/$I_B$/ BW* | THS4031 *Hi BW* |
|---|---|---|---|---|
| Open Loop Gain ($A_{ol}$) | 160db | 120db | 120db | 98db |
| Input Offset Voltage ($V_{os}$) | 5uV | 0.5mV | 40uV | 0.5mV |
| Input Bias Current ($I_B$) | 2.5nA | 30fA | 1pA | 3uA |
| Input Offset Current ( $I_{OS}$) | 2.5nA | 30fA | 0.5pA | 30nA |
| Gain Bandwidth (BW) | 8Mhz | 1Mhz | 16Mhz | 100Mhz |
| Common Mode Rejection ( CMRR) | 138db | 118db | 116db | 95db |

- **TI currently manufactures more than 1000 different opamp models!**

## Production Testing Strategy

**Characterization vs. High Volume Production**

- It is not cost effective to extensively test all parameters in production
- Generally a shorter test list is sufficient to guarantee performance
- Key data sheet and predictive parametric items should be selected

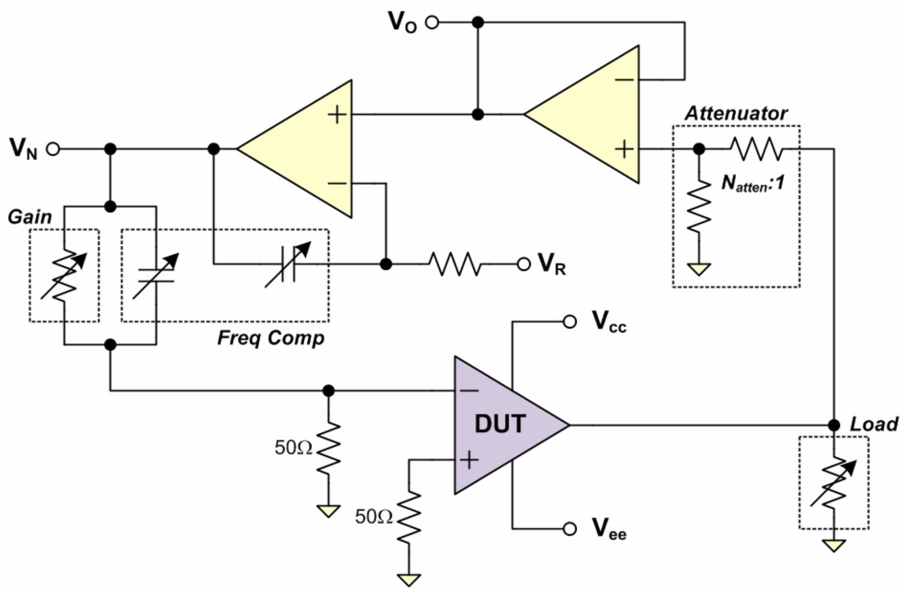
**AC vs. DC Testing**

- Precision Opamps have a test list dominated by DC parameters
- High speed Opamps may have mostly AC parameters tested
- This presentation focuses on DC testing

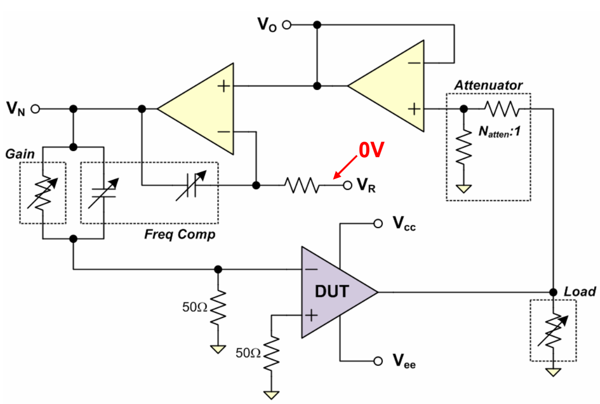
**Embedded vs. Standalone Opamps**

- Embedded Opamps generally have a more limited test list and often operate with unipolar supplies
- This presentation focuses primarily on standalone Opamps

## OpAmp Servo Loop




## Input Offset Voltage ($V_{os}$)

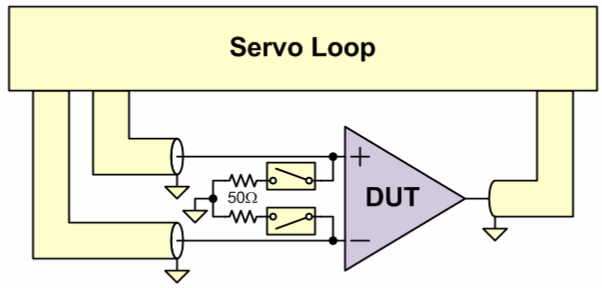



- Set $V_{cc}$ and $V_{ee}$ to desired voltages
- Connect desired Load
- Set Gain and Freq Comp
- Set $V_R$ to 0V
- Measure $V_N$

$$V_{os} = \frac{V_N}{Gain}$$

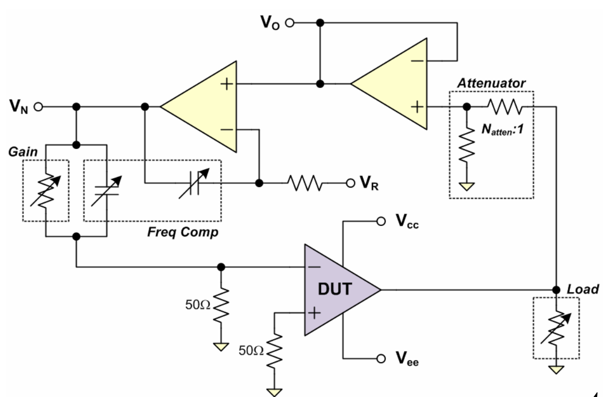
- The Gain should be chosen as large as possible such that worst case $V_{os}$ will not saturate the servo amp (i.e. $V_N$ will be saturated)
- Adjust Frequency Compensation to insure the loop does not oscillate

## Achieving Low $V_{os}$ Measurements




- The 50Ω terminations are generally part of the Servo Loop instrument
- Each point of interconnect between the Servo Loop and the DUT adds to the chance of thermal EMF voltage error (i.e. relays, connectors, etc)
- Thermal EMF occurs at dissimilar metal junctions with a thermal gradient
- Locating the termination near the DUT with Low EMF or Latching Relays greatly reduces the potential for $V_{os}$ measurement error due to EMF

## Open Loop Gain ($A_{ol}$)

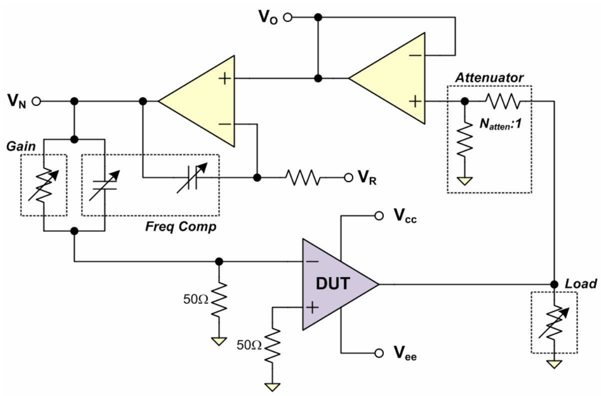



- Set $V_{cc}$ and $V_{ee}$ to desired voltage
- Connect desired Load
- Set Gain and Freq Comp
- Set $V_R$ to $V_{R1}$
- Measure $V_{N1}$
- Set $V_R$ to $V_{R2}$
- Measure $V_{N2}$

$$A_{ol} = \left| \frac{V_{R2} - V_{R1}}{V_{N2} - V_{N1}} \right| \cdot \frac{Gain}{N_{atten}}$$

- As in the $V_{os}$ setup, it is critical to choose Gain and $V_R$ levels such that $V_N$ does not become saturated
- Aol is often reported in uV/V or dB units

## Common Mode Rejection Ratio (CMRR)

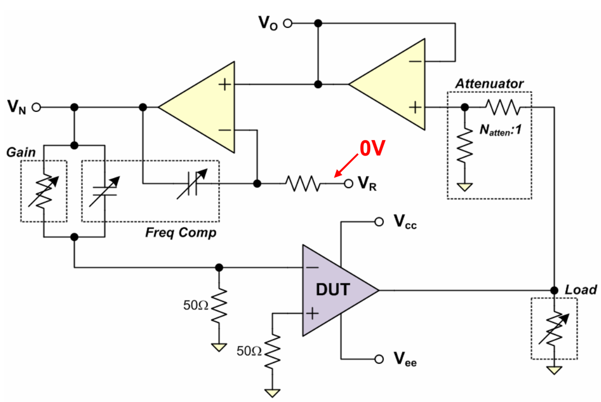



- Set $V_{cc}$ and $V_{ee}$ to desired voltage + $V_{cmrpos}$
- Connect desired Load
- Set Gain and Freq Comp
- Set $V_R$ to $V_{cmrpos}$ / $N_{atten}$
- Measure $V_{N1}$
- Set Vcc and Vss to desired voltage - $V_{cmrneg}$
- Set $V_R$ to $V_{cmrneg}$ / $N_{atten}$
- Measure $V_{N2}$

$$CMRR = \left| \frac{V_{cmrpos} - V_{cmrneg}}{V_{N2} - V_{N1}} \right| \cdot Gain$$

- This method actually moves the power supplies and output and leaves the common mode at 0V. The net effect is the same, however.
- CMRR is often reported in uV/V or dB units

## Power Supply Rejection Ratio (PSRR)

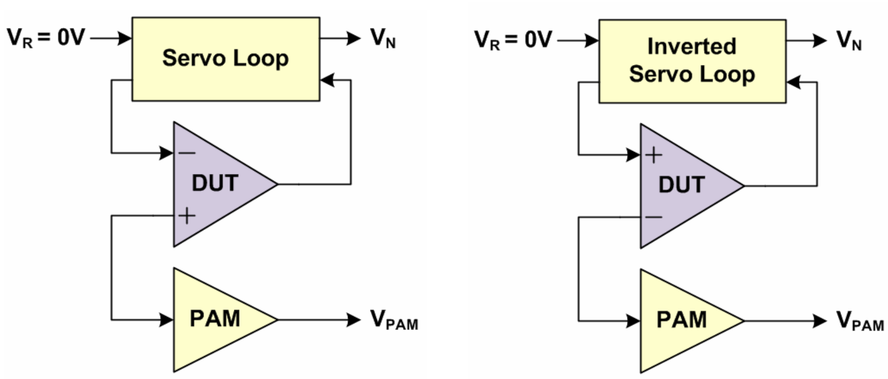



- Set $V_{cc}$ and $V_{ee}$ to minimum voltages
- Connect desired Load
- Set Gain and Freq Comp
- Set $V_R$ to 0V
- Measure $V_{N1}$
- Set $V_{cc}$ and $V_{ee}$ to maximum voltages
- Measure $V_{N2}$

$$PSRR = \left| \frac{|\Delta V_{cc}| + |\Delta V_{ee}|}{V_{N1} - V_{N2}} \right| \cdot Gain$$

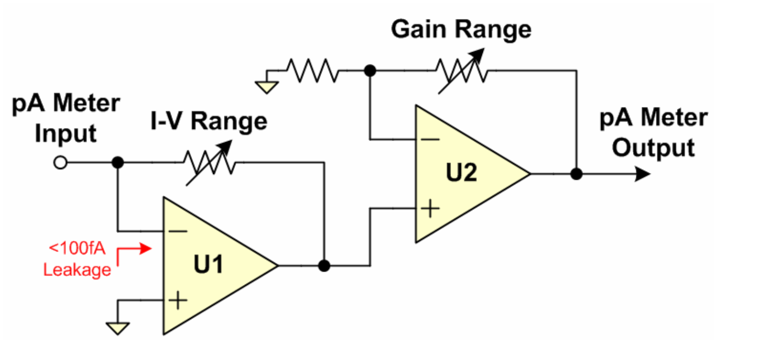
- This test can be combined with the $V_{os}$ test if the given supply values and load are acceptable
- PSRR is often reported in uV/V or dB units

## Input Bias Current ($I_B$) – Picoamp Meter




- When $I_B$ > ~250pA, the Picoamp Meter (PAM) is effective and efficient
- The Servo Loop must support Inverted operation to measure $I_B$ on $V_{INN}$
- The PAM is usually collocated with the Servo Loop

## Input Bias Current ($I_B$) – Picoamp Meter…




- U1 forms an I-to-V converter and should be a low $I_B$ opamp (OPA129)
- U2 forms a gain stage for ranging of the I-to-V output
- The $V_{INP}$ terminal of U1 sets the Input Common Mode Voltage
- Open Socket Measurements should be made to negate stray leakage and the compounded offsets of U1 and U2

## Picoamp Meter Limitations

### Cleanliness

- Since the PAM is usually collocated with the Servo Loop, the path can be quite long. To keep stray leakage low, the entire path must be clean.
- Contamination can include: flux, finger oils, absorbed moisture, etc

### Dielectric Absorption

- Interconnect dielectrics suffer from "soakage" effects where charge becomes trapped and is slowly dissipated
- This can cause mysterious readings and excessive settling time

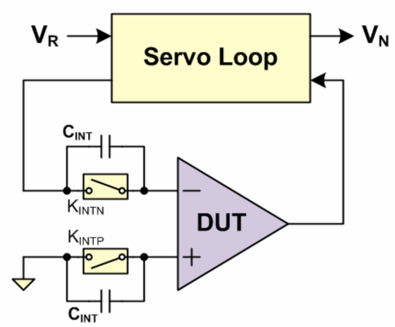
### Piezoelectric Charging

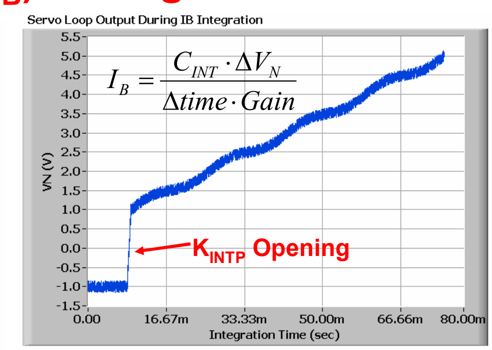
- Most coaxial cabling is susceptible to stray charging during flexure due to the piezoelectric effects of the braid rubbing against the dielectric

### I-to-V Input Leakage, Offset Stability, Etc…

- U1 will ultimately limit the low end of measurement capability even in a perfect environment

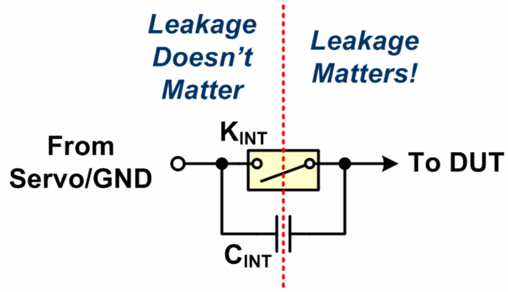
## Input Bias Current ($I_B$) – Integration Method




- $K_{INTP}$ and $K_{INTN}$ are closed for normal operation (i.e. $V_{os}$, $A_{ol}$, etc)
- Opening one of the relays allows bias current to integrate into $C_{INT}$
- Charge Injection during switching will cause a jump in $V_N$ (coaxially shielded relays should be used to keep this manageable)
- Integration times set to a multiple of 16.6ms will reject 60Hz noise
- A typical choice for $C_{INT}$ is a 1000pF WIMA Film

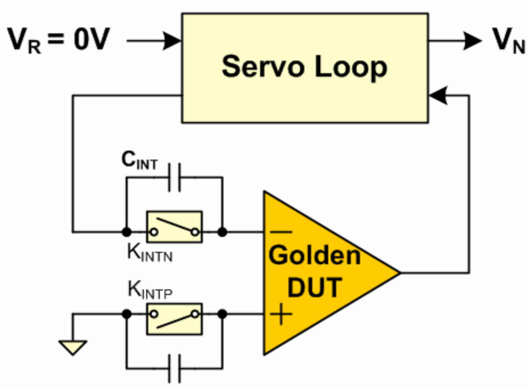
## Integration Method…




**Leakage only matters on the DUT side of $C_{INT}/K_{INT}$**

- **Cleaning** – We must now only clean around the DUT
- **Dielectric Absorption** – Only PCB Dielectric around DUT + $C_{INT}$
- **Piezoelectric Charging** – Effectively a non issue
- **Environmental Noise** – We can now easily integrate out 60Hz Noise
- **Opamp Limitations** – No Opamp needed, no issue

## Integration Method – Open Socket Cal…




**Open Socket Calibration requires an Opamp to close the loop**

- "Golden" data logged unit with known $I_B$

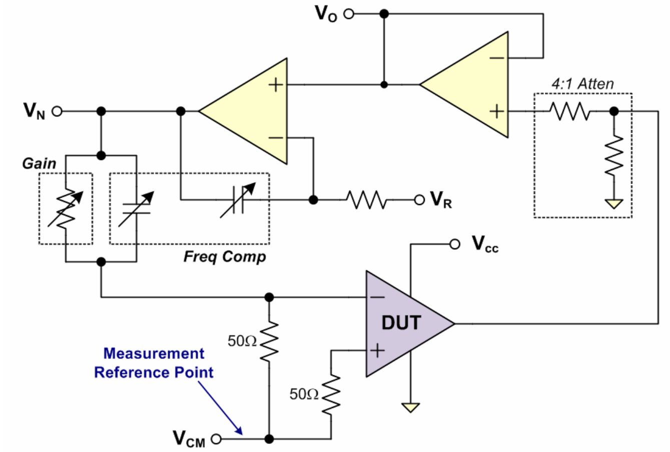
## Relating to Small Bias Currents…

- 1 Coulomb (C) of Charge = 6.24E18 Electrons
- 1 Ampere (A) = 1 C/sec
- 1 femto Ampere (fA) = 1E-15 A
- 1 fA = 1E-15*6.24E18 = 6240 Electrons/sec
- 1 60Hz Line Cycle = 16.6 msec
- 1 fA over 1 Line Cycle = 6240*0.0166 = ~104 Electrons
- **Small Bias Current measurement is about counting Electrons!**

## Tips for Measuring sub 10pA $I_B$

- DIB should be immaculate between $C_{INT}/K_{INT}$ and Socket
- Baking the DIB can help drive out excess absorbed moisture
- Some types of sockets can have higher background leakage and dielectric absorption
- Some types of low $I_B$ Opamps can trap charge in their input stages if not handled carefully resulting in erratic $I_B$ measurements
- Use an ionizer
- Keep stray unionized air flow away
- Integrate over multiple line cycles
- Data logged "Golden" unit for offset cal

## Embedded Opamps

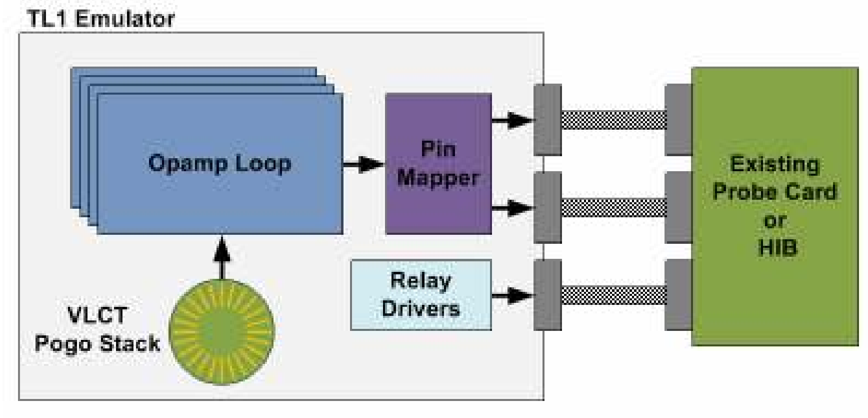



- Embedded Opamps generally do not have bipolar power supplies
- A $V_{CM}$ is required to insure a legal common mode input voltage
- All measurements should be with respect to $V_{CM}$

## TL1 – TI Legacy Opamp Tester

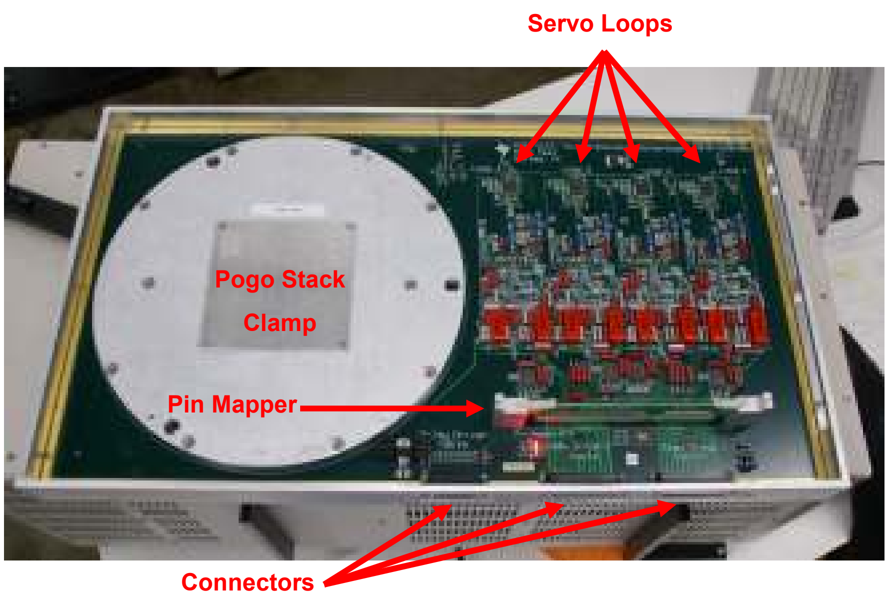
- Early 1980s era internally developed Opamp Tester

## Retiring the TL1 – Emulation

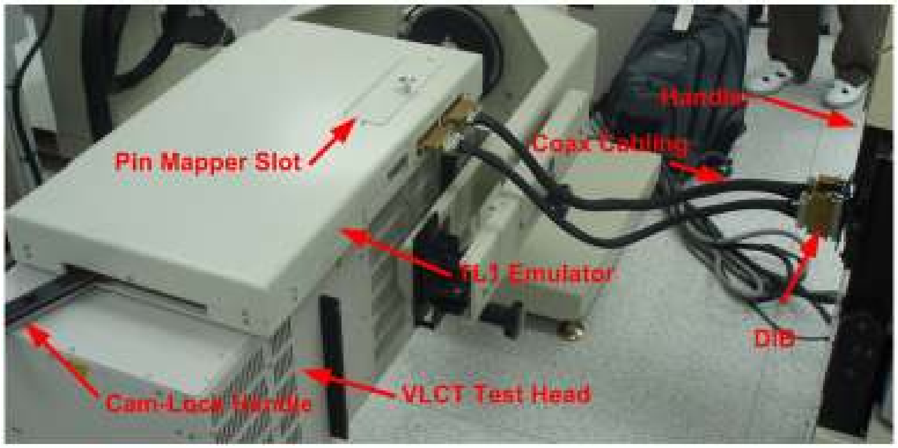



- "Add On" developed for our internal low cost tester to emulate the TL1
- Existing Probe Cards and HIBs were reused
- Rapid program migration tools were developed to speed conversions

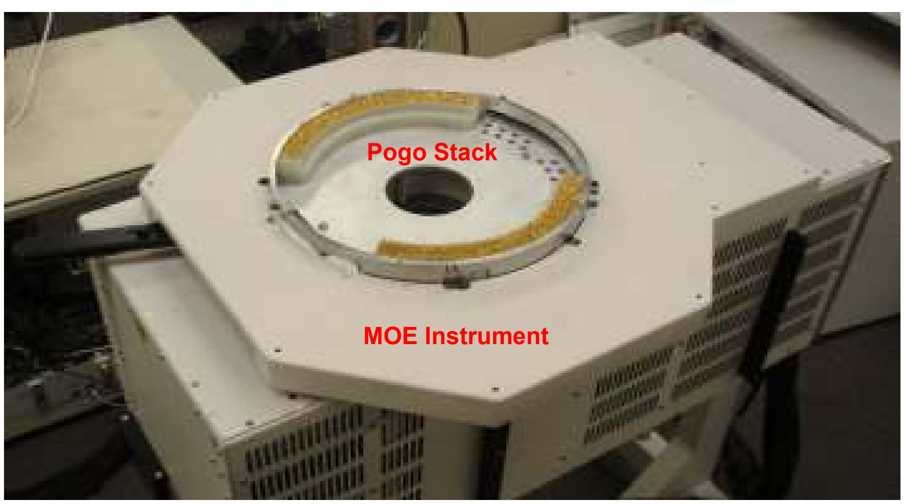
## TL1 Emulator - Insides



## TL1 Emulator – Connected to Handler

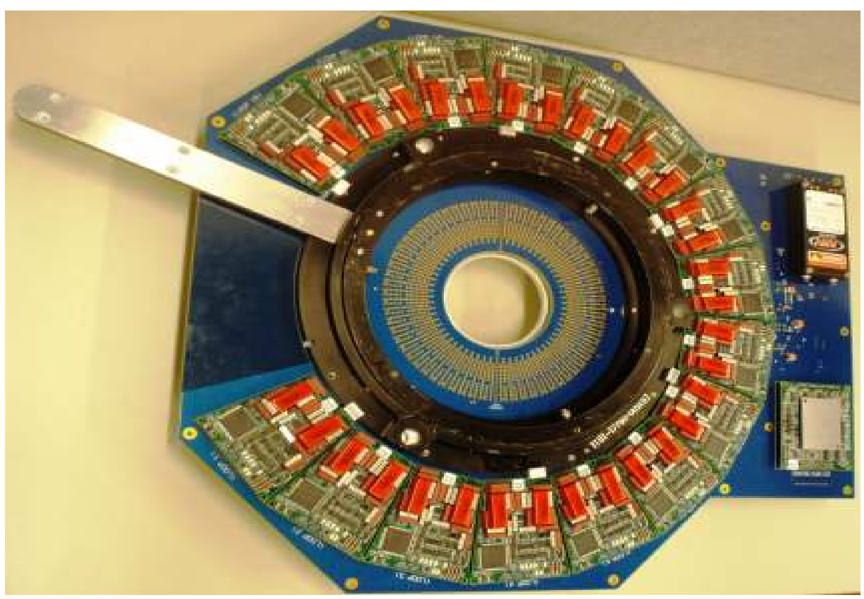



## Increasing Throughput – Multisite Opamp Emulator (MOE)



## MOE with Quad site SOIC DIB

## MOE – Loop Modules



## Contact Information…

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