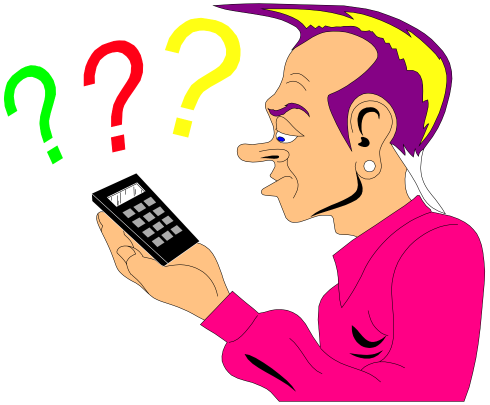
## Technical Information & Training Document

# FREQUENCY DEVIATION OF QUARTZ CRYSTAL UNITS IN OSCILLATOR CIRCUITS



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# 1. PROBLEM DESCRIPTION

- FREQUENCY OF QUARTZ CRYSTAL UNITS (IN THE FOLLOWING CALLED CRYSTAL) DEVIATE FROM THE EXPECTED VALUE.
- FREQUENCY OF CRYSTAL UNITS EXCEED TOLERANCE LIMITS ON ONE SIDE OF THE TOLERANCE WINDOW.

# 2. POSSIBLE ROOT CAUSES

- WRONG TOLERANCE OF CRYSTALS WAS ORDERED (NOT VERY LIKELY AND EASY TO FIX).
- ORDERED LOAD CAPACITANCE OF CRYSTALS AND LOAD CAPACITANCE ON BOARD DO NOT MATCH.
- EXACT LOAD CAPACITANCE ON BOARD WAS NOT KNOWN LEADING INTO ORDER OF INACCURATE LOAD CAPACITANCE FOR CRYSTAL.
- CHANGES ON BOARD LAYOUT AFFECTED LOAD CAPACITANCE VALUE.
- COMPONENT CHANGES IN OSCILLATOR CIRCUIT CAUSE LOAD CAPACITANCE CHANGE.

# 3. WHAT IS LOAD CAPACITANCE ?

- **THE LOAD CAPACITANCE IS THE CAPACITANCE VALUE THAT THE CRYSTAL UNITS WILL BE EXPOSED TO WHEN ADDED INTO THE OSCILLATOR CIRCUIT.**
- **THE LOAD CAPACITANCE IS NOT A PARAMETER OF THE CRYSTAL UNIT, IT IS DEFINED BY OSCILLATOR DESIGN AND MUST BE SPECIFIED BY CUSTOMER SO THAT THE CRYSTAL UNIT'S FREQUENCY WILL MATCH IN THE CIRCUIT.**
- **THE OSCILLATOR DESIGNER HAS TO CHOOSE A CERTAIN VALUE FOR THE LOAD CAPACITANCE IN ORDER TO ACHIEVE A STABLE WORKING OSCILLATOR THAT STARTS UP UNDER ALL OPERATING CONDITIONS.**
- **SUCH CONSIDERABLE PARAMETERS ARE:**
  - **THE FREQUENCY, FOR A CERTAIN FREQUENCY IS A SPECIFIC LOAD CAPACITANCE PREFERABLE (EXAMPLES FOLLOW).**
  - **THE PHASE SHIFT THRU THE WHOLE OSCILLATOR LOOP MUST BE 360°.**
  - **THE CIRCUIT GAIN MUST BE GREATER THAN 1 (Gain >1).**
  - **FUNDAMENTAL OR OVERTONE CRYSTAL OSCILLATOR DESIGN.**
  - **PURPOSE OF OSCILLATOR, SIMPLY A CLOCK OSCILLATOR (XO) OR A VOLTAGE CONTROLLED OSCILLATOR (VCXO) APPLICATION REQUIRE DIFFERENT LOAD CAPACITOR CONSIDERATIONS.**

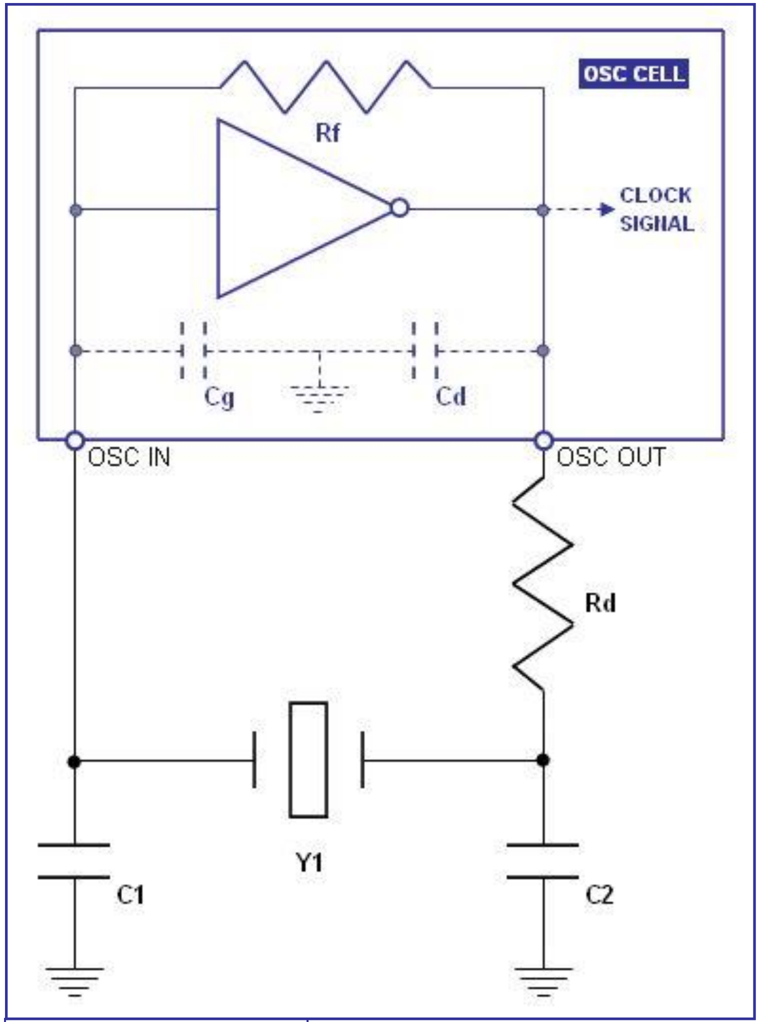
# 4. WHAT'S BUILDING THE LOAD CAPACITANCE IN THE CIRCUIT ?

- **THE LOAD CAPACITANCE IN THE CIRCUIT IS BUILD OUT OF THE SUM OF THE CAPACITORS C1 AND C2 AND THE STRAY CAPACITANCE.**
- **THE STRAY CAPACITANCE IS THE SUM OF THE CAPACITANCES CREATED BY THE PCB TRACES AND SOLDER PADS AND THE IC INPUT / OUTPUT CAPACITANCES AS WELL.**
- **THE EQUATION BELOW DESCRIBES HOW THE TWO CAPACITORS AND THE STRAY CAPACITANCE ARE ADDED UP TO A TOTAL.**

**(ALL VALUES IN pF)**

$$CL_{TOTAL} = \frac{C_1 \times C_2}{C_1 + C_2} + C_{STRAY}$$

**FIGURE 1**




**SCHEMATICS 1**

# 5. TYPICAL LOAD CAPACITANCE VALUES.

- **TYPICALLY USED LOAD CAPACITANCE VALUES USED IN FUNDAMENTAL CRYSTAL OSCILLATORS BASED ON FREQUENCY RANGE ARE SHOWN IN TABLE 1 BELOW.**

| FREQUENCY RANGE | LOAD |
|---|---|
| UP TO 5 MHz | 20 pF |
| 5 TO 10 MHz | 18 pF |
| 10 TO 15 MHz | 16 pF |
| 15 TO 20 MHz | 14 pF |
| 20 TO 30 MHz | 12 pF |
| 30 TO 40 MHz | 10 pF |
| 40 MHz PLUS | 8 pF |

TABLE 1

- **TYPICAL VALUES USED FOR CIRCUIT CAPACITORS C1 AND C2 ARE SHOWN IN TABLE 2 ON THE RIGHT. THE TOTAL CAPACITANCE VALUE MAY BE MORE ACCURATELY IF CAPS OF EIA E24 SERIES ARE USED WHICH WOULD ALSO LOWER THE TOLERANCE TO 5%.**

| LOAD CAP(1) | Oscillator +3.3VDC(2) | | Oscillator +5.0VDC(3) | |
|---|---|---|---|---|
| | C1 | C2 | C1 | C2 |
| 6 | 5.6 | 6.2 | ----- | ----- |
| 7 | 8.2 | 8.2 | ----- | ----- |
| 8 | 10 | 10 | 3.9 | 3.9 |
| 10 | 12 | 15 | 6.8 | 8.2 |
| 11 | 15 | 18 | 8.2 | 10 |
| 12 | 18 | 18 | 10 | 12 |
| 14 | 22 | 22 | 15 | 15 |
| 16 | 27 | 27 | 18 | 22 |
| 18 | 27 | 33 | 22 | 27 |
| 20 | 33 | 33 | 27 | 27 |
| 22 | 39 | 39 | 33 | 33 |
| 24 | 39 | 47 | 33 | 39 |
| 26 | 47 | 47 | 39 | 39 |
| 28 | 47 | 56 | 39 | 47 |
| 30 | 56 | 56 | 47 | 47 |

(1) Rounded values based on E12 values used for C1 and C2

(2) Assuming a stray capacitance of around 3pF.

(2) Assuming a stray capacitance of around 6pF.

(All values in pF)

TABLE 2

# 6. WHY IS FREQUENCY SENSITIVE TO LOAD CAP CHANGES ?

- **THE OSCILLATORS FREQUENCY IS SENSITIVE TO LOAD CAPACITANCE (CL) VARIATIONS DUE TO THE CRYSTAL'S SENSITIVITY TO CHANGES OF CL.**
- **THIS IS A NATURAL EFFECT OF CRYSTALS AND IS CALLED PULLABILITY "S" OR ALSO CALLED TRIM SENSITIVITY "TS" MEANING THE SAME AND BEING EXPRESSED IN [ppm/pF], INDICATING THE FREQUENCY CHANGE PER ONE PICO-FARAD LOAD CAPACITANCE CHANGE.**
- **THE FOLLOWING NEED BE KNOWN ABOUT A CRYSTAL'S PULLABILITY:**
  - **THE HIGHER THE CRYSTALS FREQUENCY (FUNDAMENTAL) THE HIGHER IS HIS PULLABILITY.**
  - **THE PULLABILITY VARIES ALSO DEPENDING PACKAGE SIZES AND CRYSTAL DESIGN BEING USED.**
  - **THE PULLABILITY OF THE CRYSTAL CHANGES WITH THE LOAD CAPACITANCE THE CRYSTAL IS USED AT, THE LOWER THE "CL" THE HIGHER THE PULLABILITY AND VISE VERSA.**
  - **THE PULLABILITY CHANGES BY "CL" FOLLOWING A NONLINEAR FUNCTION. (EXAMPLE SHOWN ON NEXT SLIDES)**
  - **IF LOAD CAPACITANCE IS INCREASED ON A GIVEN CRYSTAL ADJUSTED AT A CERTAIN "CL" THE FREQUENCY WILL DECREASE AND VISE VERSA.**

# 7. CRYSTAL UNIT'S PULLABILITY (TRIM SENSITIVITY).

- THE CRYSTAL'S PULLABILITY IS DEPENDING ON:
  - THE LOAD CAPACITANCE THE CRYSTAL IS USED AT (OR MEASURED AT).
  - THE CRYSTAL'S STATIC CAPACITANCE "C0".
  - THE CRYSTAL'S MOTIONAL CAPACITANCE "C1".
  - DUE TO THE DEPENDENCY ON THESE CRYSTAL PARAMETERS IS THERE ALSO A DIFFERENCE OF CRYSTALS IN VARIOUS PACKAGE SIZES, A DEPENDENCY ON THE FREQUENCY DUE TO CHANGING RESONATOR THICKNESS AND THE DESIGN OF THE QUARTZ RESONATOR (BLANK) INCLUDING ITS PLATED ELECTRODES.
- PULLABILITY EQUATION BELOW WITH PARAMETERS AS EXPLAINED ABOVE.

$$S = \frac{-C_1 \times 1000}{2 \times (C_0 + C_L)^2}$$

FIGURE 2

- PULLABILITY "S" = TRIM SENSITIVITY "TS" [ppm/pF]
- LOAD CAPACITANCE "CL" [pF]
- CRYSTAL'S STATIC CAPACITANCE "C0" [pF]
- CRYSTAL'S MOTIONAL CAPACITANCE "C1" [fF]

- DUE TO THE NONLINEARITY OF THE FUNCTION IS THE RESULT VALID FOR ONLY 1pF CL CHANGE UP AND DOWN FROM THE CALCULATED CL VALUE.

# 8. EXAMPLE FOR A CRYSTAL'S PULLABILITY (TRIM SENSITIVITY).

- FOR A 27MHz CRYSTAL UNIT IN A HC-49/S PACKAGE WITH THE TYPICAL PARAMETERS AS SHOWN BELOW DO WE GET THE FOLLOWING RESULT:

$$S = \frac{-11.2 \times 1000}{2 \times (3.1 + 18)^2}$$

FIGURE 2a

- C0 = 3.1pF
- C1 = 11.2fF
- MANUFACTURED FOR CL = 18pF
- RESULT: S = –12.6ppm/pF

- THE NEGATIVE RESULT REFERS TO THE FACT THAT A LOAD CAPACITANCE INCREASE WOULD RESULT IN A FREQUENCY DECREASE, THIS IS THE ONLY REASON FOR THE POLARITY OF THE RESULT, DATA PRINTOUTS OF CRYSTAL CI METERS SHOW "TS" USUALLY AS A POSITIVE VALUE WHICH MEANS THE SAME.
- IF THE SAME CRYSTAL UNIT WAS USED AND MEASURED AT CL =12pF, ITS PULLABILITY OR TRIM SENSITIVITY WOULD INCREASE TO TS = 24.6ppm/pF.
- THE SAME CRYSTAL AT CL =10pF HAS ITS TS = 32.6ppm/pF.
- WE CAN SEE THAT "TS" DRASTICALLY INCREASES AT LOWER LOAD CAPS.
- THE CURVE ON NEXT SLIDE SHOWS THE TYPICAL BEHAVIOR OF SAME CRYSTAL DESIGN OVER THE WHOLE LOAD CAPACITANCE RANGE.

# 9. A CRYSTAL'S PULLABILITY (TRIM SENSITIVITY).

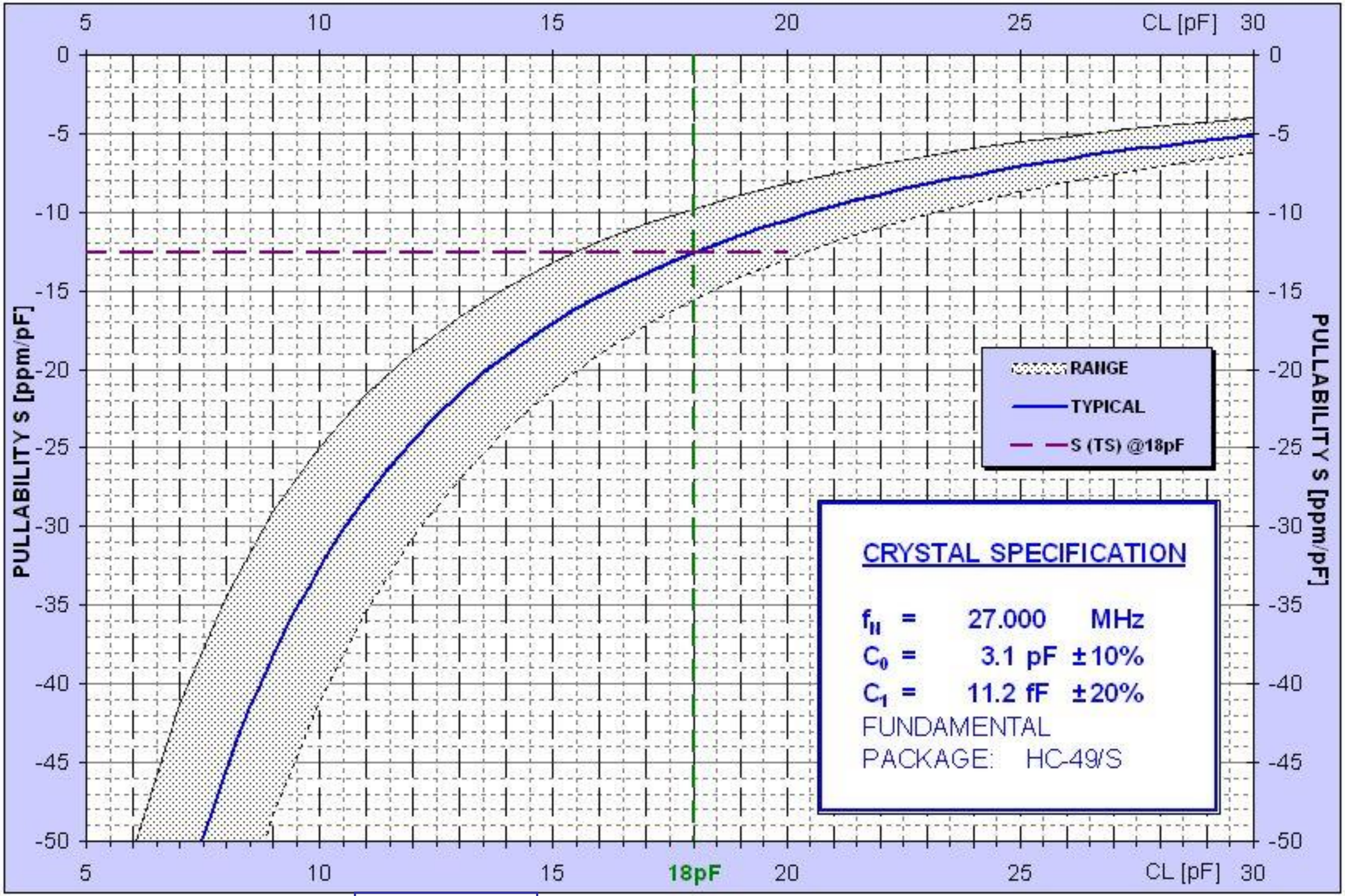



CHART 1

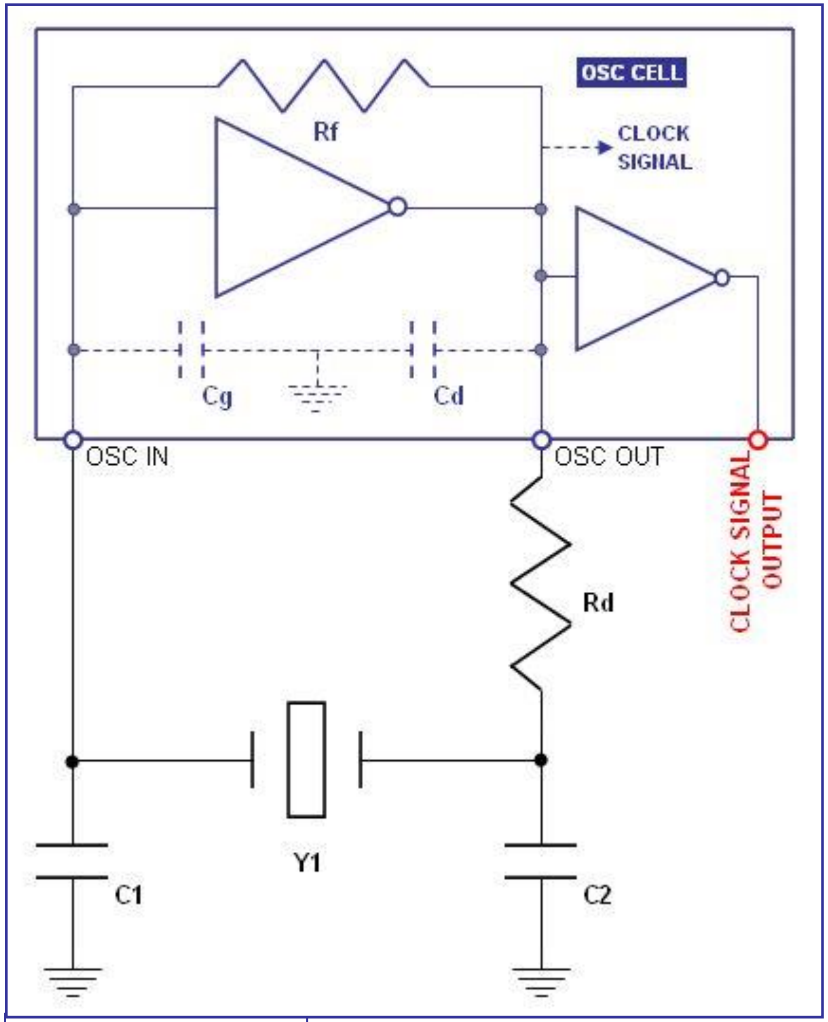
# 10. HOW TO MEASURE THE FREQUENCY OF THE OSCILLATOR ?

- CONSIDERING WHAT WE JUST HAVE LEARNED ABOUT LOAD CAPACITANCE AND THE CRYSTALS PULLABILITY WE CAN UNDERSTAND THAT JUST TOUCHING WITH AN OSCILLOSCOPE PROBE INTO THE CIRCUIT WILL RETURN FALSE RESULTS BECAUSE WE ARE ADDING THE LOAD OF THE PROBE.
- LIKE THE PROBE SHOWN ON THE RIGHT INDICATING A LOAD CAPACITANCE RANGE WE WOULD KNOW HOW MUCH EXACTLY WE ADD TO THE CIRCUIT. THIS IS DEPENDING ON THE FREQUENCY THE PROBE IS USED AND OTHER FACTORS.


- THEREFORE DO WE HAVE TO CAREFULLY CONSIDER THE WAY WE ARE GOING TO MEASURE THE FREQUENCY IN ORDER TO AVOID MISINTERPRETATIONS AND ACTIONS THAT MAY MISLEAD AND RESULT INTO ERRORS AND HIGH FAILURE RATES IN PRODUCTION LINE.
- IN THE FOLLOWING DO WE WANT TO SHOW POSSIBLE WAYS AND DEMONSTRATE THE MOST COMMON ONE THAT IS BEING USED.

# 10.a) EASIEST WAY TO DETERMINE THE FREQUENCY ?

- THE EASIEST WAY TO MEASURE THE FREQUENCY OF AN OSCILLATOR IS IF THE IC DESIGNER HAS BUILT IN A INDEPENDENT CLOCK SIGNAL OUTPUT WHICH IS DECOUPLED FROM THE OSCILLATOR CIRCUIT THRU AN ADDITIONAL GATE OR AMPLIFIER.
  IN THIS WAY THE FREQUENCY CAN BE JUST MEASURED THERE BY TOUCHING UP WITH ANY OSCILLOSCOPE PROBE.
- HOWEVER, SUCH EXTRA PIN ARE ADDITIONAL COST FOR THE IC MAKER AND IS THEREFORE OFTEN NOT AVAILABLE.
- OTHERS MAY USE THEIR INBUILT MICROPROCESSOR TO COUNT THE FREQUENCY AND PROVIDE THE READING THRU SOFTWARE TOOL.




SCHEMATICS 2

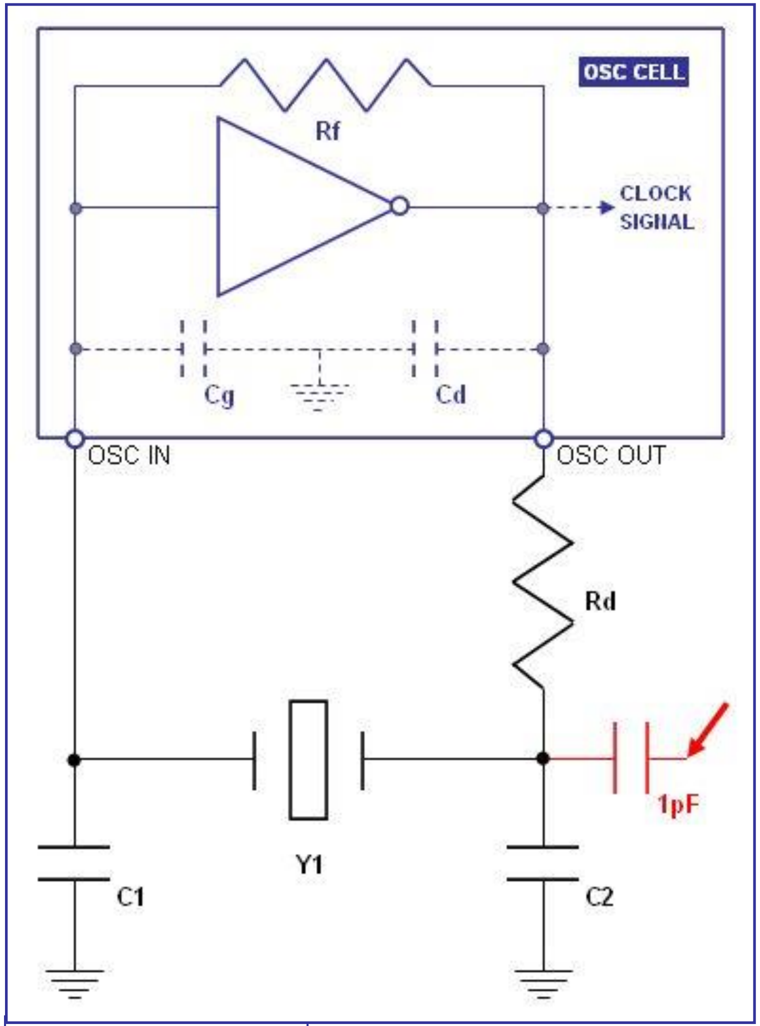
# 10.b) DETERMINE THE FREQUENCY USING A FET–PROBE ?

- **IF THE FIRST METHOD IS NOT AVAILABLE A PROBE NEED TO BE USED TO TOUCHUP AND MEASURE SIGNAL THRU AN OSCILLOSCOPE AND FREQUENCY COUNTER.**
- **AVAILABILITY OF A FET–PROBE CAN HELP TO EASE THE MEASUREMENTS BECAUSE THIS PROBE DOES NOT REQUIRE A DIRECT TOUCH INTO THE CIRCUIT AND THEREFORE THE PROBE DOES NOT AFFECT THE CIRCUITRY.**
- **A FET–PROBE IS AN ACTIVE PROBE (REQUIRING SEPARATE POWER SUPPLY) WHOSE TIP NEEDS TO BE PLACED ONLY VERY CLOSE TO A SIGNAL LINE OF THE OSCILLATOR.**

- **SUCH TYPES OF ACTIVE PROBES HOWEVER BEING VERY EXPENSIVE AND THEREFORE SELDOM AVAILABLE.**

# 10.c) MOST COMMON WAY TO DETERMINE THE FREQUENCY ?

- MOST COMMONLY BEING REGULAR PASSIVE TYPE OSCILLOSCOPE PROBES AVAILABLE AND NEED TO BE USED.
- AS DISCUSSED EARLIER IS THIS BRINGING A PROBLEM OF UNKNOWN CAPACITANCE ADDED TO THE CIRCUIT.
- THE WAY WE CAN DO THIS IS BY ADDING A KNOWN CAPACITOR IN SERIES TO THE OSCILLOSCOPE PROBE.
- BY USING A 1pF CAP IN SERIES TO THE PROBE HAVING A CAPACITANCE SOMEWHERE BETWEEN 9 AND 20pF WE WILL END UP WITH A TOTAL OF 0.9_pF.
- THE DIGITS AFTER THE DECIMAL POINT BEING NOT CONSIDERABLE AND WE CAN SIMPLY SAY WE ARE ADDING IN TOTAL A CAPACITANCE OF 1pF.
- PREFERABLY IS THIS CAP ADDED TO THE OSCILLATOR OUTPUT IF KNOWN.



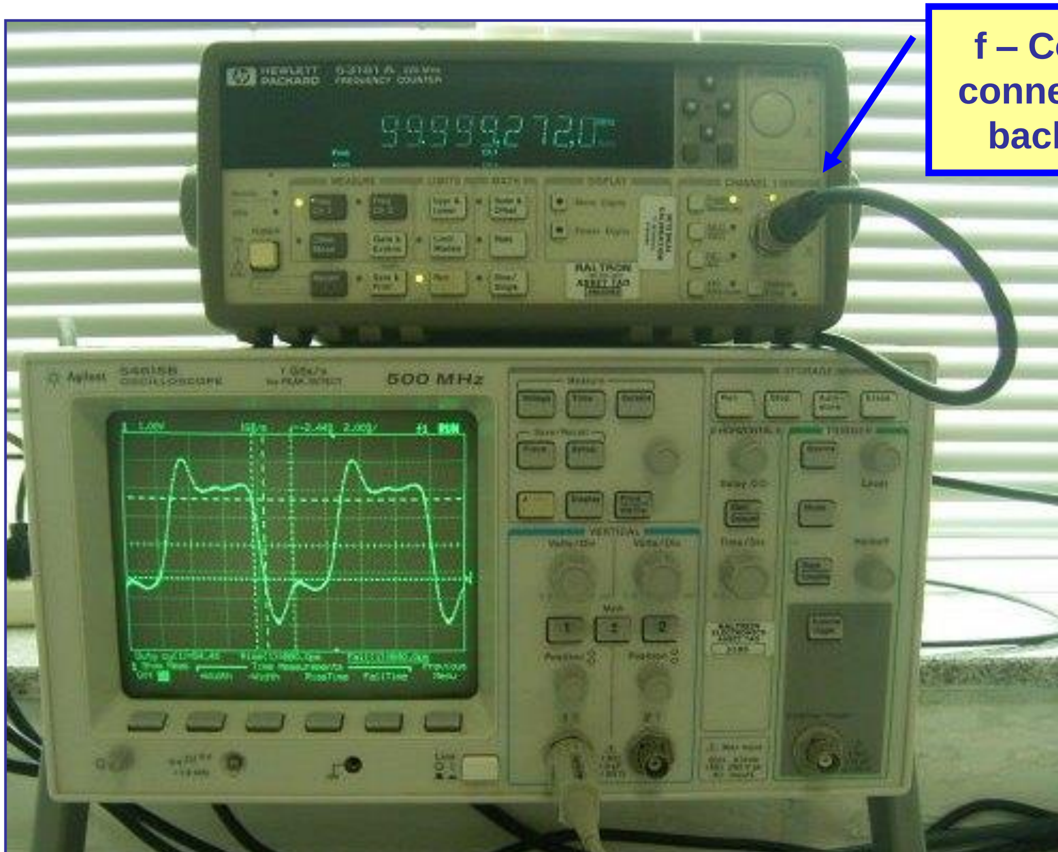

SCHEMATICS 3

# 10.c) HOW TO DO THIS PRACTICALLY ?

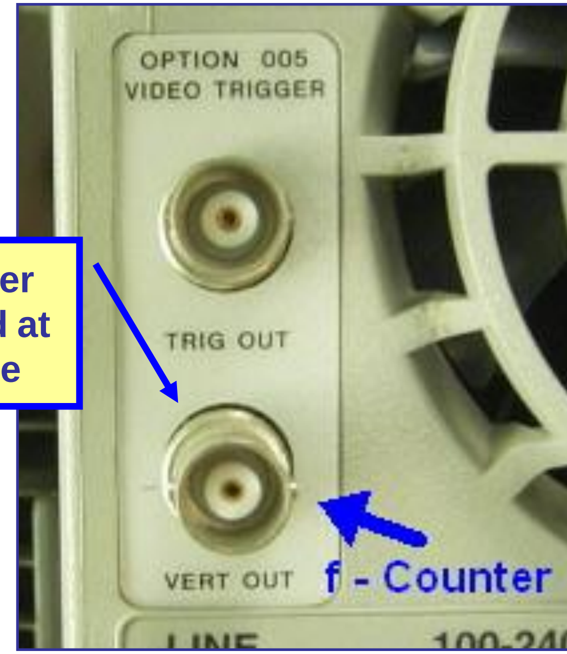
- IN ORDER TO EASILY ACCESS THE CAPACITOR CONTACT WITH THE PROBE WE MOUNT THE CAPACITOR UPRIGHT LIKE A "TOMB STONE".
- PREFERABLY DO WE SOLDER THE 1pF "TOMB STONE" CAP AT THE SOLDER JOINT OF THE LOAD CAPACITOR. THE CRYSTAL PADS ARE NOT ADVISABLE TO BE USED SINCE THE CRYSTAL MAY BE CHANGED SEVERAL TIMES FOR TESTING PURPOSES.
- BE AWARE OF THAT MEASURING THRU THE 1pF CAP YOU DAMP THE SIGNAL AND MAY ALSO DISTORT THE WAVE SHAPE.
- THEREFORE IS THIS CAP TO BE USED FOR FREQUENCY MEASUREMENT ONLY WHILE FOR WAVE SHAPE CHECKS TH PROBE TOUCHES DIRECTLY INTO THE CIRCUIT.

# 11. THE TEST SETUP ?

- USE AN OSCILLOSCOPE WITH A FREQUENCY RANGE AT LEAST 5 TIMES THE ONES TO BE MEASURED – BETTER 10 TIMES. THE f–COUNTER SHALL BE CONNECTED TO OSCILLOSCOPE.




f – Counter connected at back side




- AT THE BACK OF THE OSCILLOSCOPE IS A SIGNAL OUTPUT CALLED "VERT OUT" – THIS SHALL BE USED TO CONNECT THE f–COUNTER.

# 12. PREPARATION OF FREQUENCY CORRELATION CHECK

- ASK YOUR CRYSTAL MANUFACTURER TO PROVIDE YOU SAMPLE UNITS WITH ELECTRICAL TEST DATA. THESE DATA SHALL CONTAIN AT LEAST:
  - THE LOAD FREQUENCY AT THE DESIRED LOAD CAPACITANCE.
  - THE CRYSTAL UNITS RESISTANCE RR (or Rs which you can consider the same)
  - THE STATIC CAPACITANCE C0 AND THE MOTIONAL PARAMETERS AS C1 AND L1.
  - VERY USEFUL IS THE TRIM SENSITIVITY "TS" (then you don't have to calculate it).
- ASK YOUR CRYSTAL MANUFACTURER TO PROVIDE YOU AVERAGE CRYSTALS IN REGARDS OF RESISTANCE RR, DO NOT USE UNKNOWN OR UNSTABLE CRYSTAL UNITS.
- DO NOT USE CRYSTAL UNITS YOU MAY HAD REMOVED FROM OTHER BOARDS, THOSE MIGHT HAVE BEEN IMPACTED BY THE HEAT DURING REMOVAL.
- ASSEMBLE THE CRYSTAL UNIT TO THE TEST BOARD, IF YOU INTEND TO TEST SEVERAL UNITS ON SAME BOARD YOU MAY NOT SOLDER THE WHOLE SMD CRYSTAL ON BUT TILT THE LEADS SLIGHTLY OUT AND SOLDER THE LEAD ENDS ONLY, THIS KEEPS THE SOLDER PADS ALIVE FOR A LONGER TIME AND SEVERAL SOLDER SESSIONS.
- MAKE SURE YOU HAVE PROPER CONNECTION.

# 13. EVALUATION OF TEST RESULT

- **OUR CRYSTAL MANUFACTURER PROVIDED UNITS WITH ELECTRICAL TEST DATA. ONE OF THE UNITS WITH BELOW DATA WE ARE GOING TO USE:**
  - **THE LOAD FREQUENCY AT 18pF FL = 2.0 ppm ( 27,000,054Hz ).**
  - **THE STATIC CAPACITANCE C0 = 3.1 pF**
  - **THE MOTIONAL CAPACITANCE C1 = 11.2 fF**
  - **THE TRIM SENSITIVITY "TS" = 12.6 ppm/pF.**
- **CRYSTAL WAS ASSEMBLED TO THE TEST BOARD AND FREQUENCY MEASURED USING METHOD 10.c) – FREQUENCY WAS FOUND TO BE 26,999,720 Hz**
- **THIS IS GIVING US A DEVIATION TO THE FREQUENCY THE CRYSTAL MAKER MEASURED AT 18pF OF –334 Hz OR IN OTHER WORDS -12.4 ppm.**
- **CRYSTAL DATA SHOW US TS = 12.6 ppm, WE JUST NEED TO COMPARE THIS AND WE CAN SEE THAT OUR DEVIATION IS ALMOST THE SAME WITH -12.4 ppm.**
- **THE NEGATIVE RESULT OF -12.4 ppm MEANS THAT THE LOAD CAPACITANCE ON BOARD IS HIGHER AS WHAT THE CRYSTAL WAS MEASURED AT ≈ 19 pF.**
- **REMEMBER WE ADDED THE 1pF "TOMB STONE" CAP – SO THE ACTUAL LOAD CAPACITANCE ON BOARD IS 18 pF AND THEREFORE CORRECT.**

# 13. EVALUATION OF TEST RESULT – ANOTHER BOARD

- **WE USE A CRYSTAL WITH SAME DATA AS ABOVE (just for easiness now).**
- **THE FREQUENCY ON BOARD WE DETERMINED TO BE 27,001,210 Hz.**
- **THAT IS A DEVIATION OF 1,156Hz OR 42.8 ppm.**
- **WE COULD DO HERE SAME EVALUATION AND JUST DIVIDE OUR DEVIATION BY THE CRYSTALS "TS" IN ORDER TO GET THE LOAD DEVIATION.**

$$\boxed{CL_{DEV} = \frac{f_{DEV}}{TS}} \quad \boxed{CL_{DEV} = \frac{42.8}{12.6}} \quad \boxed{CL_{DEV} = 3.4}$$

- **THE DEVIATION IS 3.4 pF, OUR FREQUENCY ON BOARD WAS HIGHER AS THE CRYSTALS ORIGINAL FREQUENCY, THIS TELLS US THAT THE LOAD CAPACITANCE ON BOARD IS LOWER FOR 3.4 pF → 18 – 3.4 = 14.6 pF.**
- **REMEMBER THAT "TS" IS NOT A LINEAR FUNCTION AND THEREFORE THE FREQUENCY SHIFT OVER LARGER DISTANCE MAY INACCURATE WHEN CALCULATED AS ABOVE.**
- **FOR A MORE PRECISE CALCULATION WE NEED TO USE A MORE COMPLEX EQUATION THAT INCLUDES THE CRYSTAL PARAMETERS AND THE LOAD OFFSET AS WELL.**

# 13. EVALUATION OF TEST RESULT – ANOTHER BOARD (cont.)

- **THE EQUATION FOR THE EXACT CALCULATION OF THE ACTUAL LOAD ON BOARD IS:**

$$CL_{BOARD} = \frac{-2 \times \Delta f \times C0 \times (C0 + CL_{XTAL}) + C1 \times 1000 \times CL_{XTAL}}{2 \times \Delta f \times (C0 + CL_{XTAL}) + C1 \times 1000}$$

- **THE PARAMETERS ARE:**
  - **$CL_{BOARD}$ THE ACTUAL LOAD CAPACITANCE ON BOARD [pF].**
  - **$\Delta$f THE FREQUENCY DEVIATION WE HAVE DETERMINED BETWEEN CRYSTAL AND BOARD MEASUREMENT IN [ppm]**
  - **CRYSTAL'S LOAD CAP $CL_{XTAL}$ = 18pF, CRYSTAL'S C0 = 3.1 pF AND C1 = 11.2 fF.**

$$CL_{BOARD} = \frac{-2 \times 42.8 \times 3.1 \times (3.1 + 18) + 11.2 \times 1000 \times 18}{2 \times 42.8 \times (3.1 + 18) + 11.2 \times 1000}$$

$$CL_{BOARD} = 15.1$$

- **THE RESULT IS THAT THE <u>ACTUAL LOAD CAPACITANCE ON BOARD IS 14.1 pF</u> CONSIDERING THAT WE ADDED 1pF "TOMB STONE" CAP.**
- **PREVIOUSLY WE HAD ESTIMATED 14.6 pF BY USING SIMPLY THE CRYSTALS "TS" – SO WE WERE 0.5 pF OFF WITH THAT METHOD.**