Micro-Jump Screening Station for GPS User Equipment

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BIOGRAPHIES

Larry Vittorini holds a BSEE from Purdue University and an MSEE from Arizona State University. He has spent the past 8 years as a GPS staff systems engineer for the Integrated Navigation Products group of Rockwell's Avionics & Communications Division, specializing in high antijam GPS[1] receiver design and GPS frequency standard technologies. Larry recently developed a revolutionary new low cost, high precision externally compensated frequency standard (TSXO[2]) for precision military GPS using a new frequency standard design co-developed with Rakon Ltd.. He has a total of over 15 years experience in systems and RF design for missile and satellite systems.

ABSTRACT

It has been known many years that AT quartz crystals exhibit isolated temperature induced frequency jumps on the order of 1-100 ppb and sometimes up to 1 ppm. These jumps have been found to be disruptive to the carrier and sometimes the code tracking loops used in precision GPS UE[3] equipment and may, if severe, cause temporary loss of satellite tracking.

A considerable effort is in progress in the industry to isolate the causes of frequency jumps and eliminate the problem at the source. Unfortunately, these efforts have yet to produce conclusive results.

Rockwell has devised an interim solution in which each Time Compensated Clock Oscillator (TCCO) used for GPS UE is prescreened over temperature for frequency jumps and rejected if jumps larger than 5.4 m/sec (18 ppb) are found. The test set also allows statistical data collection of the MJ's so one may construct a histogram and CDF of measurable jumps which can allow SPC methods to be applied with respect to this component. The test set is fully capable of evaluating 16 oscillators simultaneously and is based on hardware and software from the Rockwell PLGR[4] GPS set being manufactured for the US Department of Defense. A discussion of the rejection criteria will be included since a single 20 msec jump out of a 3 hour temperature test is sufficient to cause unit rejection.

This paper gives a general description of the test set along with the accompanying temperature chamber and control software used to handle the huge volume of data which must be processed. There is also a discussion of GPS tracking loop basics for the reader to appreciate the magnitude of the problem.

Finally, statistical data is presented from the test results that have been collected from over 2,000 production TCCO's. The data will show a histogram of micro-jumps as a function of the magnitude of the jump. Statistics will also be collected for all units to allow a comprehensive view of large number statistics vs. individual unit statistics.

TOPICS OF DISCUSSION

- **Introduction to Perturbations**
- **The GPS User Clock**
- **UE Clock Sensitivity Summary**
- **Motivation to screen for M-J's**
- **UE M-J Detector & Compensation**
- **Description of M-J ATE Screening Station**
- **M-J Screening Station Development Issues**
- **M-J Screening Station Results**
- **Summary**
- **Conclusions**

[1] *GPS - Global Positioning System*

[2] *TSXO - Temperature Sensing XO*

[3] *UE - User Equipment*

[4] *PLGR - Precision Lightweight GPS Receiver*

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INTRODUCTION TO PERTURBATIONS

- **Perturbations have 2 basic forms:** ***fast and slow***
- **Fast type often referred to as:** ***Micro-Jump***

Definition:

- Abrupt frequency change manifested as a step change
- Detectable at sample rates > 10-50 hz
- M-J magnitude can vary widely in AT crystals
  - *Peak magnitudes :* ***300 ppb (90 m/sec) and higher***
  - *Average magnitude observed:* ***10 ppb (3 m/sec)***
- Not related to coupled modes like Activity Dips
- Anecdotal evidence suggest SC cuts suffer as well
  - *OCXO M-J likelihood diminished due to fixed temp*
  - *Perhaps smaller in magnitude than AT's (1-2 orders)*
  - *Comparison available for SC-OCXO*
- Can cause GPS tracking loop Loss-of-Lock (LOL)
  - *Carrier &/or code loop - dependent on loop design*

Cause(s):

- No general consensus from author's experience
- Contributors include both physical and electrical effects:

PHYSICAL

  - *crystal blank surface contaminants*
  - *crystal blank contour*
  - *crystal blank lattice blemishes*
  - *mount configuration, base plating*

ELECTRICAL

  - *Crystal drive level*
    - Drive level sweep screening shows promise
  - *Crystal load capacitance / changes*
- Relative contributions of these 2 sources ?

  - no consensus author has observed

- **Slow type referred to as: Activity Dip(s) {AD}**

Definition:

- Slow frequency change usually manifested as a step
  - *Detectable at sample rates 1 hz*
- Have observed > 0.5 ppm shifts but < 0.1 ppm typical
  - *Large disparity observed between manufacturers*
- May have multiple instances vs. temp sweep
- Normally **won't** cause GPS carrier tracking loop LOL

Cause:

- Principally due to coupled mode oscillations
  - *Differing temperature coefficients of other modes a possible contributor*
    - Manifested via running sweep at different temp gradients & variable temperature sweep range
- Possible other less likely contributors include some of the same physical & electrical effects described for M-J's:

PHYSICAL

  - *crystal blank surface contaminants*
  - *crystal blank size & contour*

ELECTRICAL

  - *crystal drive level*
  - *crystal load capacitance / changes*
- Anecdotal evidence suggests ADs are less prevalent in SC cuts. Possible Reasons are:
  - *Higher Q than AT's (~10X)*
  - *Other inherent properties of doubly-rotated cut*
  - *Lower sensitivity to drive level variance*

THE GPS USER CLOCK

- **Local clock provides synchronization for a GPS radio to track any/all satellite signals**
  - Tracks the carrier & underlying spread spectrum code
- **Initial freq only offset affects signal acquisition**
- **Tracking sensitive to sudden changes in frequency**
  - Sufficient magnitude & rate will cause tracking LOL
- **GPS has two types of tracking loops**
  - Carrier loop trks either L1 (1575 Mhz) or L2 (1226 Mhz)
    - *Sensitivity to M-J's dependent upon:*
      - Loop type, order & bandwidth
      - Design has N=3 FLL w/ 6 hz BW & ARCTAN detector
      - Tracking SNR (C/N_o)
  - Deltaranges (phase) passed to KF[5] form velocity est.
    - *Frequency shift is interpreted as a velocity change*
      - Affects all 3 axes (x/y/z)
      - Affects all GPS tracking channels

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[5] *KF - Kalman Filter*

- The code loop tracks either of two PRN codes:

  C/A code (1.023 Mhz) - civilian use, Gold code

  P/Y code (10.23 Mhz) - military use
- Sensitivity to M-J's dependent upon:
  - *INS (or other) aiding quality*
  - *Loop type, order and BW*
    - Current std design a 1st order E-L DLL w/ 1 hz BW
  - *Tracking SNR*
- Code loop is less sensitive than carrier loop
  - *P/Y code has 1/2 chip (15 m) tracking limit which implies 15 m/sec (50 ppb) limit on M-J's*
  - *C/A code 10X less sensitive since has 150 m chip length (0.5 ppm)*

UE CLOCK SENSITIVITY SUMMARY

- **Tracking Reliability**
  - Carrier LOL when frequency error exceeds detector BW
    - *Detector BW a fctn of PDI [6] interval (coherent)*
      - GPS normally tracks with a 20 msec PDI (50 hz data)
    - *Lower PDI (5 vs. 20 msec) yields more BW at expense of C/N_0*
      - Lose 6 dB in tracking threshold for shorter coherent integration interval. e.g., 10log(5/20) = -6 dB
    - *Code loop LOL occurs when predicted code phase & rate drop correlation power below tracking threshold*
  - Velocity Accuracy
    - *Dependent upon accuracy of clock frequency estimate*
    - *Clock freq estimate based on carrier loop deltaranges*
    - *Velocity error reduction dependent upon detection*
      - Force KF to weights error into clock term and not as an actual HV [7] dynamic event

CLOCK TYPES EMPLOYED IN GPS UE TODAY

- **Two principal types of clocks employed in GPS:**

  Internally Compensated (IC)

  Externally Compensated (EC)
- **IC clocks output a compensated freq either via:**
  - Temperature Control
    - *OCXO (Oven Controlled XO)*
    - *DHXO (Directly Heated XO)*
    - *Double oven (D-OCXO)*
  - Temperature Compensation
    - *Analog*
      - TCXO (Temperature Compensated XO)
    - *Digital*
      - TCCO (Time Compensated Clock Oscillator)
      - MCXO (Microcomputer Controlled XO)
  - Hybrid techniques combining above two methods
- **EC clocks free run at their natural frequency but must be compensated via an <u>open loop</u> correction inside the radio**
  - Reference frequency crystal free runs (not pulled)
    - *Can be either an AT, SC or other cut*
  - Open loop correction has 3 general requirements
    - *Radio must have an NCO [8] to utilize this technique*
    - *Temperature can be sensed via a variety of means*
      - IC temperature sensor
      - Y-cut crystal as a temperature sensor
      - Dual-mode crystal operation
    - *An open loop correction is formed via curve fit*
      - Fit can be LS [9] or other suitable model type
      - Characterizes Freq vs. Temperature
      - Generally cannot account for perturbations
  - Open loop correction formed & applied to NCO in radio
- **Results from two types of oscillators presented**
  - TCCO is freq std in GEM III®[10] GPS radio (**Type IC** [11])
    - *Digital correction using a PLL technique*
      - SC crystal serves as the reference
      - VCO function performed by an AT crystal @ 10.95 Mhz
  - TSXO (Temperature Sensed XO) (**Type EC** [12])
    - *Co-developed by author & RAKON, Ltd. NZ*
      - Reference fctn performed by an AT crystal @ 10.95 Mhz

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[6] *PDI - Pre-Detection Integration*

[7] *HV - Host Vehicle*

[8] *NCO - Numerically Controlled Oscillator*

[9] *LS - Least Squares (curve fit of order N)*

[10] *GEM III - (GPS Embedded Module) is a registered trademark of Rockwell International, Avionics & Communications Division*

[11] *IC - Internal Compensation*

[12] *EC - External Compensation*

MOTIVATION TO SCREEN FOR M-J'S

- **Customer burn-in on GEM III® GPS UE was failing an unaided operation specification (1995)**
  - Traced cause to frequency standard-TCCO
    - *Caused velocity spikes in 3 velocity states of KF*
      - Spec which radio was failing (more on this later)
      - Interpreted as velocity change in vehicle
      - Less important for aided (GPS/INS[13]) case
  - At worst, causes carrier loop LOL
    - *20 msec PDI track limit equivalent to 8 ppb or 2.4 m/sec (1 σ) @ L1 (1.6 Ghz)*
      - Must budget a portion for other dynamics
  - Code loop generally more robust against shifts
    - *Easier to trk code @ 10.23 Mhz vs. carrier @ 1.6 Ghz*
      - 1/2 cycle shift @ 1.6 Ghz is < .005 of a chip @ 10.23 Mhz
    - *Code rate more important - loss of correlation power*
      - 1 hz code loop, 1/2 chip @ 10.23 Mhz = 15 m/s (50 ppb)
  - Screening plus a UE SW mod detects M-J's
    - *GEM III®: 5 chnl GPS rcvr in SEM-E form factor*

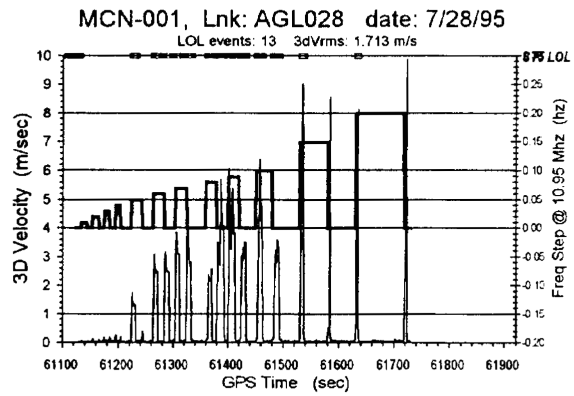
UE M-J DETECTOR & COMPENSATION

- **Software mod desensitized rcvr to M-J's**
  - Carrier loop expects 180° shift for BPSK bit transitions
    - *Bit error threshold set @ 90°*
      - Data Demodulator declares bit error if phase shifts > $\lambda/4$
  - Frequency shift: **Detection**
    - *Difference PDI=5 & 20ms deltaranges computed*
    - *Compute μ and σ of deltarange difference*
      - Freq shift is the assumed cause if $\mu >> \sigma$
  - Frequency shift: **Compensation**
    - *Pass PDI=5ms detector output to tracking loop*
      - Provides 4X improvement in BW
      - Minimum 32 ppb BW (50 hz @ 1.6 Ghz)
  - KF adaptation minimizes velocity error spikes
    - *Freq jump detected in carrier tracking loop*
      - Adjust clock frequency process noise upward (~100X)
      - Wts clk error heavily which reduces/eliminates DR[14] "bump"
    - *Transition to normal clock process noise after 1 cycle*
- **Result in 6 dB loss in coherent tracking threshold**
  - Loss: 10 log(20/5) = 6 dB
- **<u>Not a permanent solution to M-J problem</u>**

IMPROVED UE TRACKING LOOP RESULTS

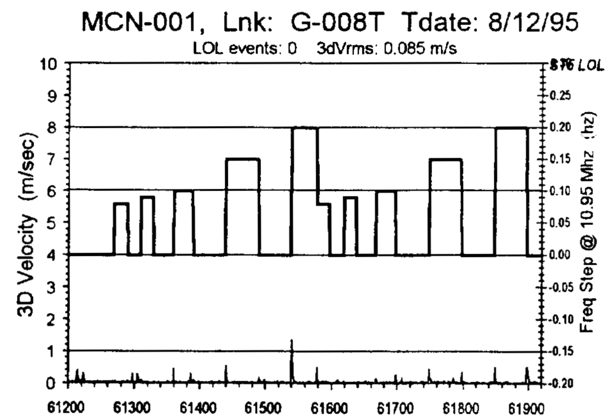
- **Freq step simulated with HP synthesizer**
  - Conversion: 0.2 hz @ 10.95 Mhz = 18.3 ppb (5.5 m/sec)
- **Evidence of LOL for even small steps (see Fig 1)**
  - As small as 4.6 ppb (1.4 m/sec)
- **Both negative & positive shifts cause LOL**

Figure 1 Original SW Link @ 32 dB-hz



- **The new link produced no LOL events for steps up to 18.3 ppb (or 5.5 m/sec).**

Figure 2 New SW Link @ 33 dB-hz



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[13] *INS - Inertial Navigation System*

[14] *DR - delta range, effectively carrier phase*

M-J SCREENING STATION (M-J SS) DESCRIPTION

See Figure 3 for block diagram of M-J Screening Station.

- **Initiated factory M-J screening project in Jan 96**
- **Objective was to monitor TCCO M-J performance and set up suitable screenimg limits**
- **Before screening initated, TCCO M-J failure rate estimated to be ~25% in GEM III® burn-in**
  - Represented > 80% of TCCO defect rate for GPS radio
- **Utilizes PLGR GPS radio as the detector hardware**
  - Developed modified test SW based on UE M-J detector
  - M-J detector part of PLGR in GPS carrier loop
    - ◆ *Fail any unit with a single MAX M-J > 5.4 m/s*
      - ▲ 5.4 m/s = 18 ppb @ 1575 Mhz
      - ▲ Limit based on data showing sensitivity begins at this level
- **Screens up to 16 TCCO units simultaneously**
- **Sweeps a temperature cycle from -55 to +105 °C**
  - Currently running @ 2°C/min gradient
- **Station on line starting Jul 1996**
  - Data shown includes from July 1996 to May 1997

M-J SCREENING STATION DEVELOPMENT ISSUES

- **TCCO's are tested with cover unsoldered**
  - Allows rework to replace VCO crystal
- **Testing showed no significant difference in results with cover soldered on permanently**
  - Measurement consistency a top priority
    - ◆ *Chamber airflow regulation proved most significant factor to repeatable, reliable measurements*
- **System Checkout**
  - Utilized a synthesizer generating known steps to check for measurement accuracy
  - Correlation with GEM III® burnin test
- **System Statistical Tools**
  - Summary data file provided for each unit
    - ◆ *Unit ID*
    - ◆ *Min M-J detected*
    - ◆ *Max M-J detected*
    - ◆ *Mean & Standard Deviation of all M-J events*

M-J SS DATA: TEST STATION CORRELATION

- **Data shows high correlation btwn two tests: > 99%**
  - Screening limit can be adjusted in M-J SS to ensure no units exceeding the limit are passed
  - **Single excursion past limit fails unit**

See Figure 4 for chart of M-J SS vs. GEM III burnin correlation results.

TCCO M-J SCREENING RESULTS

See Figures 5 & 6 for PDF & CDF results, respectively.

- **Have screened > 2,000 TCCO's thru April 1997**
  - Screening throughput rate averaging ~250 per month
  - Screening limit set to 5.4 m/sec (18 ppb) limit
- **Screening yield is currently 71%**
- **TCCOs post screened in GEM during burn-in**
  - Currently reporting < 1% FR[15] for exceeding M-J limit
  - Other TCCO failures contribute approximately 7%
- **There results are counter to the actual data which suggests only 80% pass the burnin limit (see fig 6)**

M-J COMPARISON : TCCO VS. TSXO AT BURNIN

See Figures 7 & 8 for PDF & CDF results, respectively.

- **TCCO data can be compared to TSXO**
  - TSXO has a free-running AT oscillator as the reference
  - Uses same basic crystal as TCCO VCO
    - ◆ *10.95 Mhz fundamental*
- **PDF data suggests largest jumps <u>not due to AT</u>**
  - TSXO drop-off to < 0.1% of jumps > 30 m/sec
    - ◆ *30 m/s = 100 ppb or 0.1 ppm*
  - TCCO still has > 1 % @ 80 m/sec (0.27 ppm)

SUMMARY

- **M-J screening process is successful**
  - TCCO rejection during burnin ↓ by 24X
    - ◆ *Post screened (burnin) FR estimated at < 1% now*
- **Max M-J ↓ by > 2/3 @ 95% confidence level**

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[15] *FR - Failure Rate*

- Max M-J reported for ATE screen: **42 m/s (140 ppb)**
- Max M-J for UE Post-Screen: **13 m/s (43 ppb)**
  - *Data is counter to reported 99% M-J yield @ burnin*
    - Max should be no larger than 6 m/sec - needs further investigation

■ **Failed units can be rescreened after replacing VCO (AT) crystal**

- Reduces TCCO scrap rate
  - *No data available on retest yield*
  - *Improved data collection will allow tracking this statistic in the future*

■ **Comparison with TSXO data suggests large TCCO M-J's caused by other than AT crystal**

- May be an anomaly due to small sample space
  - *90 TSXO's vs. 2,000 TCCO's*

CONCLUSIONS

■ **Further use of statistics may enhance yield**

- If limit set at 99.9% of Normal distrib yield 20%
  - *Yield improves from 71% to 86%*
- Max values per screening appear to be "fliers"
  - *i.e., very low probability of occurrence (< 0.1%)*
- May be due to component other than AT VCO crystal
  - *TSXO data shows no M-J's over 30 m/s (100 ppb)*

■ **Station allows CPI[16] in SPC[17] to improve yield**

- Monitors progress/degradation in M-J performance
- Provide feedback to vendor of crystals
  - *Alert to yield improvements from process changes*
  - *Alert of "lost recipe"*
    - i.e., unintentional process changes degrading M-J performance

■ **Further work is necessary to establish M-J SS and GEM burnin data correlation**

■ **More study of M-J causes may further improve manufacturing process-related mechanisms**

REFERENCES

1. L.D. Vittorini & B. Robinson, "*Application of Low Cost Frequency Standards for Commercial & Military GPS*", 47th Annual Symposium on Frequency Control, 1993

[16] *CPI - Continuous Process Improvement*

[17] *SPC - Statistical Process Control*

Figure 3 Micro-Jump Screening Station Block Diagram

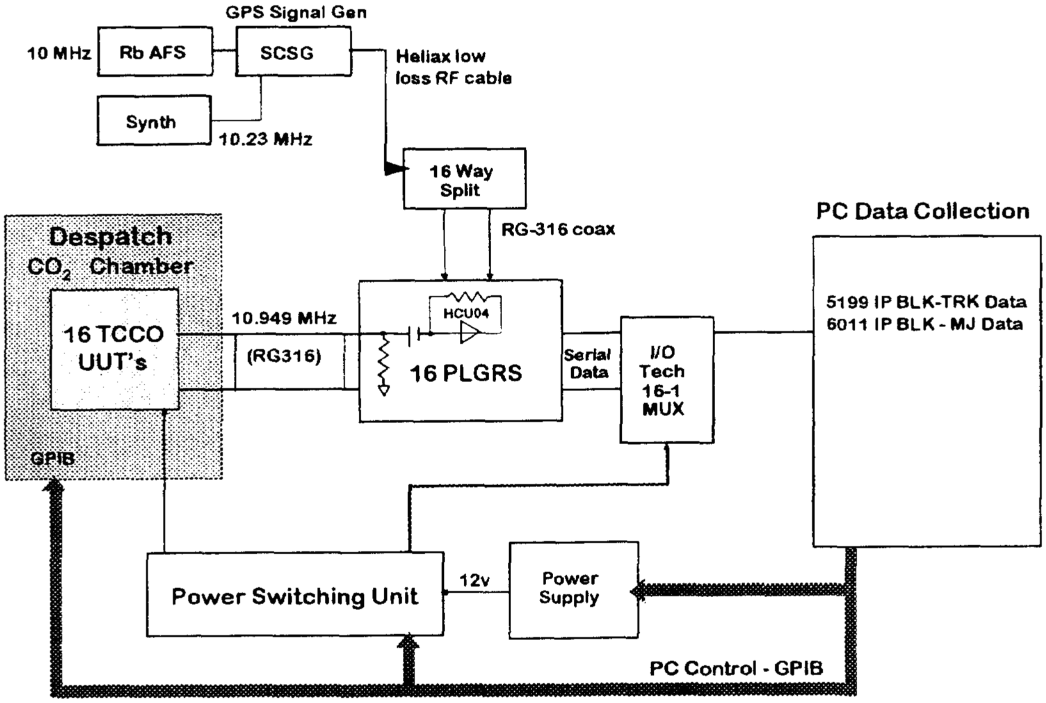

Figure 4 MJ Screening Station Correlation

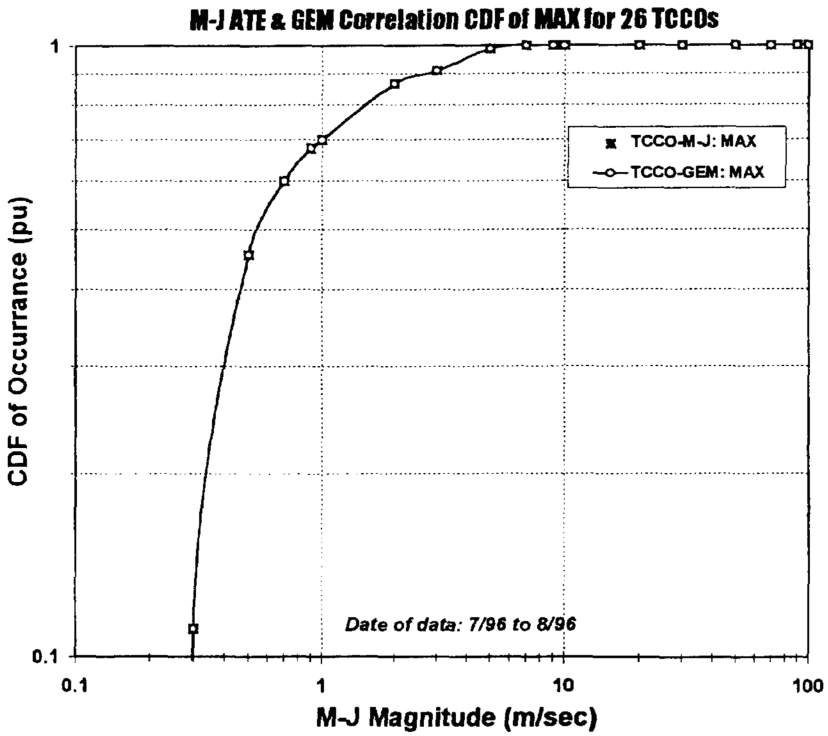

Figure 5 Histogram (PDF) of MAX Micro-Jumps

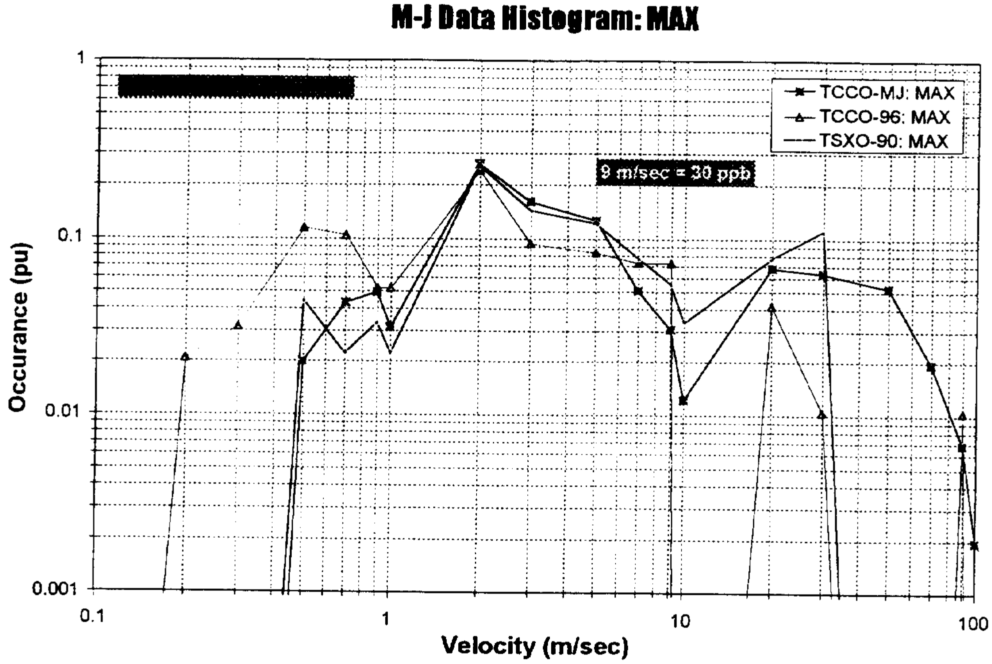

Figure 6 Cumulative Distribution (CDF) of MAX Micro-Jumps

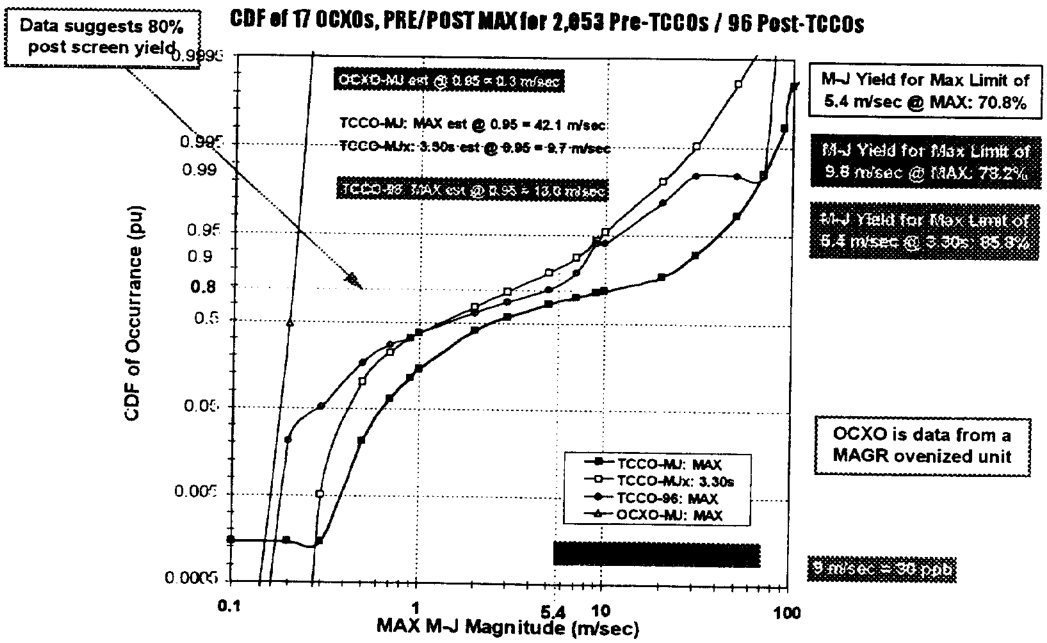

Figure 7 Histogram (PDF) of 3.30σ Micro-Jumps

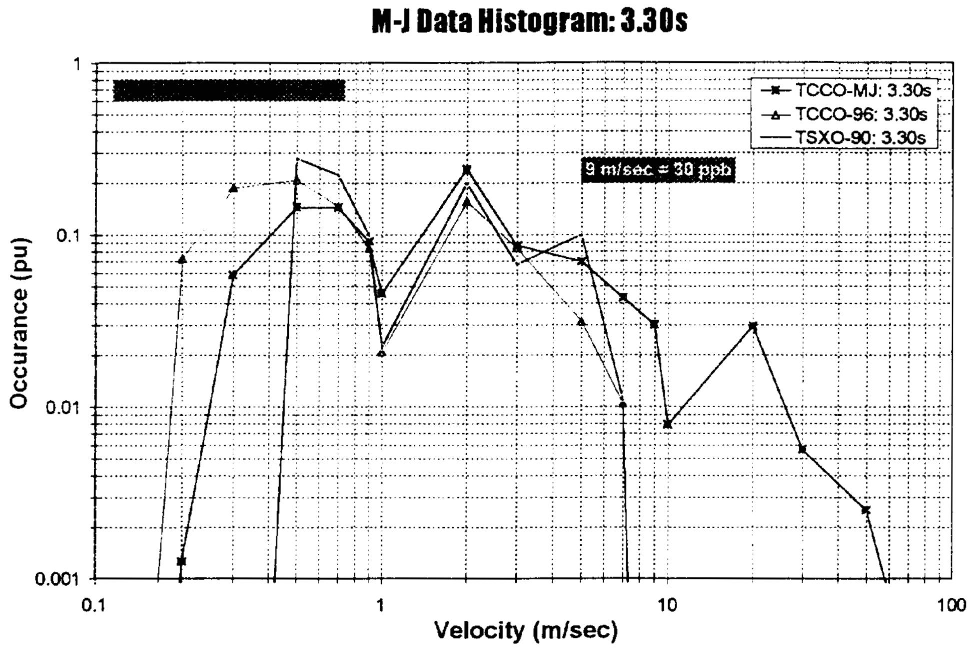

Figure 8 Cumulative Distribution (CDF) of 3.30σ Micro-Jumps