Santa Clara Valley Solid State Circuits Chapter Technical Meeting held on November 16, 2005
(These are Floyd Gardner lecture notes. Dan Oprica has made the transcription.)

Floyd Gardner

"PLL history: a personal point of view."

- Dan Oprica asked me to talk about history of PLL.
- Don't know much about history.
- Decided to talk about my own experience: maybe that would illuminate some aspects of broader history.
- Quick overview. Will expand upon any particular adventure upon request.

Schooling

- 7 years in three universities.
- Finished in summer 1953.
- Was taught vacuum tube technology: never heard mention of transistors.
  (Thought 1st transistor article was April's fool joke; explained as back-to back point contact diodes). While packing to up to leave University of Illinois, I met incoming students for summer course in transistors: the first university course in the country.
- Graduating after 7 years at Universities, my education was just starting. Would have to continue indefinitely.
- Never any mention of PLLs in those years.

1950s

- In 1950s PLLs were unimaginably exotic and mysterious.
  People would ask: "What does it mean to lock phase?"
- Noise rejection properties of Narrow Band PLLs seemed somehow magical.
- Set-up demo:
  Input signal immersed in noise. Signal couldn't be seen on the scope, only noise.
  Output from the VCO shown on another scope: nice clean sine wave, maybe some visible jitter.
- Magic!
- Of course, just narrow band pass filtering of noise, but without using conventional band pass filters.

Tracking Filters

- First six years worked for two companies that built “tracking filters”.
- Tracking filters (TF) were PLLs taking input from standard communications receivers (RXs).
- These were intended for tracking target returns of CW radars. Narrow Bandwidth rejected noise; permitted lock to weak signals.
- Phaselocking allowed tracking of changing frequency of signal.

Tracking filters Features:

- Type-3 PLL to accommodate target acceleration (changing Doppler shift).
  (Type-3 means that there are three integrators in the feedback loop).
- Switchable loop bandwidth (BW): 3Hz-3kHz in ½ decade steps. (Learned: DO NOT switch the filter capacitor). Could not lock in 3Hz BW due to excessive phase noise).
- Two-phase (complex) input and Phase Detectors to enable tracking through zero Doppler shift.
- Built with vacuum tube technology; transistors were not feasible for practical equipment.
- PDs used hybrid transformers to form sum and difference of signal and VCO inputs.
  Vector sum and difference applied to pair of vacuum tube detectors whose outputs were differenced to develop error signal.
- Balance to suppress DC offsets was difficult: required several hours of technician labor for each unit. PD signal levels were about 100V.
- VCO used current-controlled saturable inductor to tune to needed frequencies.

Sputnik

- Tracking filters were ready when Sputnik was launched. Setup an antenna in a parking lot, connected to RX, connected to TF.
- Received frequency changed across each overhead pass because of changing Doppler shift. TF tracked changing frequency with narrow BW to produce excellent sensitivity.
  Type-3 PLL could follow changing Doppler with small tracking error.
- Great excitement in company at this accomplishment, achievable at the time only by a few who happened, by chance, to be prepared.

DOVAP Transponder

- In late 1950s, led a project to build a DOVAP transponder.
- DOVAP was a CW range-sum tracking system (ellipsoidal contours of constant range sum) used for missile tracking.
- Uplink a CW signal at approximately 450MHz.
  Transponder doubled frequency to 900MHz for downlink.
- Large change in Doppler shift over the target trajectory. Fixed-tuned transponder required enough BW to encompass entire shift. Narrow Band PLL tracks Doppler shift: major improvement in sensitivity.
- Employed frequency discriminator for fast acquisition lock.
- Transistor circuits, except for front-end RF amplifier. Needed tube because no transistor had adequate HF capability in late 1950s.
- Major challenge: obtain near-constant phase shift (2-3 degree variation over amplitude dynamic range). Devised AGC amplifiers with small phase shift and tested setup to measure phase shift.

State of the art, 1950s

- Very few PLL workers in 1950s.
- Some work on TV synchronization: horizontal, vertical, color.
- Massive concentration of talent at Jet Propulsion Laboratory;
  Working on receivers for Deep Space missions (spacecraft and earth station)
  People like Viterbi, Lindsey, Simon, Stiffler, Tausworthe, Jaffe, Rechtin and many others.
- Main thrust was narrow bandwidth for working deep into noise. Loop BW order of 10Hz.
- RXs built with vacuum tube technology. Predated transistors.
- Tube DC amplifiers were generally not satisfactory. Passive loop filters were widely employed. Narrow BWs required large time constants. Some receivers occupied two rack drawers: one drawer for electronics and one drawer for high-value, high quality capacitor (e.g. polystyrene) for loop filter
- Much concern over leakage (don't use electrolytic capacitors) and dielectric soak (stress-caused polarization of dielectric; don't use oil filled capacitors).
- JPL team was responsible for establishing sophisticated theory of Narrow Band PLLs: mainstream work and crucial at the time, but of highly specialized interest today.

PLL Transponders

- Early 1960s consulted for Resdel Engineering on PLL transponders contract for NASA Huntsville.

PLL Course

- NASA requested Resdel to provide one-week training course on PLL transponders.
- Expanded request to two weeks, on subject of PLLs in general.
- Resdel asked me to prepare the course. Prepared course. Spent two weeks in Huntsville.
- Subsequent PLL courses at NASA-Houston, Goddard, and Wallops Island.

Book

- Realized that course notes were basis for a book.
- Sent notes and prospectus to various publishers. Wiley offered a contract.
- After further hard work, 1st edition of "Phaselock Techniques" was published in 1966. (2nd edition in 1979; 3rd edition in 2005).

Later 1960s

- Worked on a couple of PLL transponders.
- Encountered false locking and leakage signals. Hard to understand at the time, hard to eradicate.
- Discussed in 2nd and 3rd editions of Phaselock Techniques
- IC PLLs began to appear in this time frame. They were not very good: relaxation oscillators had large phase noise, poor frequency accuracy. Active phase detectors were not well balanced; had substantial DC offset. (Unusable for narrow band applications, my interests at the time.)

1972-73: Two extended consulting engagements in Europe

First engagement: AEG Telefunken in Ulm Germany

- PLL transponders for Helios project (Joint effort between NASA and European partners).
- RX had threshold about –160dBm. Much trouble generating test signal accurately at such low level. (Someone once left some screws off of the generator case - 20 ft away from RX - and we couldn't reduce input power enough to make RX lose lock. For a few minutes, the RX sensitivity seemed miraculous, until we figured something was very wrong).
- Transponders originally suffered from false locks; fixed that by simplifying IF filter and by suppressing some sneak paths that don't appear on schematic.
- RX also plagued by PD offsets caused by spurious signals leaking around the unit. Spurs so weak that only the receiver itself was sensitive enough to detect them. No lab test instrument came close. Spurs eventually suppressed to tolerable levels by meticulous care in shielding, isolation, filters, grounding coaxial outer conductors at shield, feedthroughs etc. Very educational.

Second engagement: 8 months at European Space Agency in Holland

- Synchronization studies for Satellite Digital Communications.
- Mostly synchronization, not PLL.
- Recommended feed-forward synchronizers after becoming aware of hang-up effect.
- Phase acquisition can be very slow in PLL.
- Others discovered hang up. I provided explanation.
- European Space Agency required burst acquisition with high probability of success with 30-symbol preamble. Impossible with PLL. Easy with quenched feed–forward synchronizer.
- Stay in Holland was forerunner of numerous study contracts over the years, mainly related to Synchronization and to Satellite Digital Communications. Led to studies of digital implementation of RX functions.
- ESA sponsored my work on:
    - digital timing recovery
    - phase and frequency detectors
    - digital interpolation for timing adjustment
    - phase jitter effect of frequency quantization
- Very satisfying work – getting paid to learn new things!

Returned to U.S. in 1973 (Los Angeles).

- Moved to Palo Alto in 1974.

Lockheed as Client

- Conducted experimental study of PLL FM demodulator's threshold behavior, based on FM clicks.
- Found only about 2dB threshold improvement over conventional discriminator and then only if PLL BW is optimal.
- Optimum PLL BW is a tradeoff between too narrow, with cycle slips (indistinguishable from FM clicks) caused by fast excursions of modulation, or too wide, with cycle slips caused by noise.
- Effects are strongly nonlinear. A linear analysis to minimize phase fluctuations fails to predict the sharp optimum.

PFDs (Phase/Frequency detectors) and CPs (charge pumps)

- PFDs appeared in early 1970s.
- Motorola and RCA were among the pioneers.
- Motorola had the bipolar IC 4044 that included a PFD and a peculiar CP.
- Motorola literature described PFD in 16 (32?) states, most of which were transient or forbidden. Today's three-state description was developed later.
- Never did understand Motorola CP.
- Literature on CPs was sparse and uninformative. Specifications talked of PD gain of e.g. 0.45V/rad. Little or no clue that CP shuts off for most of the cycle when PLL is locked.
- Several clients were using PFD/CPs. Having trouble; called on me for help.
- Put 10Mohm scope probe on loop filter. Stupefied to see large shift in static phase error. Realized I didn't understand CP PLLs.
- Mulled over problem. Gradually developed a model and made analysis.
- Published it in IEEE Trans. Comm., vol. COM-28, pp. 1849-1858, November 1980. Revised and corrected version in 3rd edition of "Phaselock Techniques".

4046

- First IC PLL I worked with.
- Near complete PLL: 2 PDs (one PFD, one XOR), lock detector, voltage-switch CP, VCO.
- Needed only external loop filter (LF) and, maybe, external divider.
- Voltage-switch CP has severe nonlinearity at LF voltages away from equilibrium (UP gain very different from DN gain, except at LF reference voltage).
- Newer literature shows current-switch CPs, almost exclusively. Much preferred to voltage-switch.
- Active filter (with opamps) maintain low voltage at CP output. Minimizes effect of nonlinearity of voltage-switch CP. (Nonlinearity not fatal flow necessarily. May be acceptable in some applications. But linear analysis is no longer applicable).
- Keep fast pulses out of opamp; put ripple filter ahead of opamp, which goes into slew-rate limiting on HF inputs.
- PFD is supposed to produce automatic frequency acquisition. But, what if frequency uncertainty range is greater than VCO electronic tuning range?
    - Arrange monitors on VCO control voltage to actuate switches on RC range setting elements of frequency dividers. Switch tuning range if control voltage comes too near to the edge.
    - Allow ample hysteresis to avoid switching chatter.
    - Auto range switching is especially important today because of wide tolerance on actual frequency of integrated VCOs.
- 4046 and successors had 1uA spec on CP leakage at elevated temperature. To avoid static phase error leakage current must be much less than CP current. 1uA leakage implies approximate 1mA CP current. Large pump current implies large C in loop filter for small BWs. 4046 was not well suited for small BWs, but was very popular nonetheless.

Synthesizer PLL ICs

- Numerous ICs contain one or more PFDs plus programmable counters, plus CPs plus lock detectors. Loop filters and VCOs were not included until recently.
- Usually marketed as "PLLs", but are incomplete.
- Made for low-cost synthesizers.

1980s, 1990s

- Worked mainly on Digital Communications system development and analysis.
- Strong emphasis on digital implementation.
- Particularly algorithm analysis and invention
- Heavy involvement in Simulation of Data Transmission.
  Co-author of a book and simulation program on the subject.
- PLL work incidental as part of synchronizers.
- Gradually removed from circuits, as ASICs become more common.

Recent years

- Spent several years writing 3rd edition of "Phaselock Techniques".
- Deleted 1/3 of previous edition, but 3rd edition is ½ again as long.
- Greater depth in old topics.
- Much new material on phase noise, digital PLLs.
- Revised choices for characterization of PLLs.
- Published in 2005.

Current activity

- Partly retired after 45 years as consultant.
- Taking on small tasks where my experience is strong.
- Exploring a paradox related to phase noise.
  - Spectrum of phase noise is typically represented as a mix of white, flicker (1/f), Wiener (1/f^2) and 1/f^3 components.
  - Performance of PLL is measured by untracked phase noise variance-- the integral from f = 0 to infinity of the product of phase noise spectrum multiplied by magnitude-squared of loop error transfer function.
  - The Wiener component integrates satisfactorily for any PLL; the flicker and white component integrate OK if a high-frequency cutoff is imposed.
  - The 1/f^3 component requires a true type-2 PLL (two ideal integrators inside the loop) to give a finite result.
  - In a type 1 PLL, the integral is unbounded – the variance is infinite.
  - That predicts that a 1st order PLL, or any type-1 PLL (i.e. ALL analog PLLs, since a perfect analog integrator is not achievable in active RC networks) cannot remain locked, contrary to common experience with millions of analog PLLs.
  - Previous work has suggested that in finite observation time T, the variance grows slowly as ln(T).
- I am working on this issue, trying to establish approximate formulas that quantify the behavior.