A Simpler 122 GHz Transceiver

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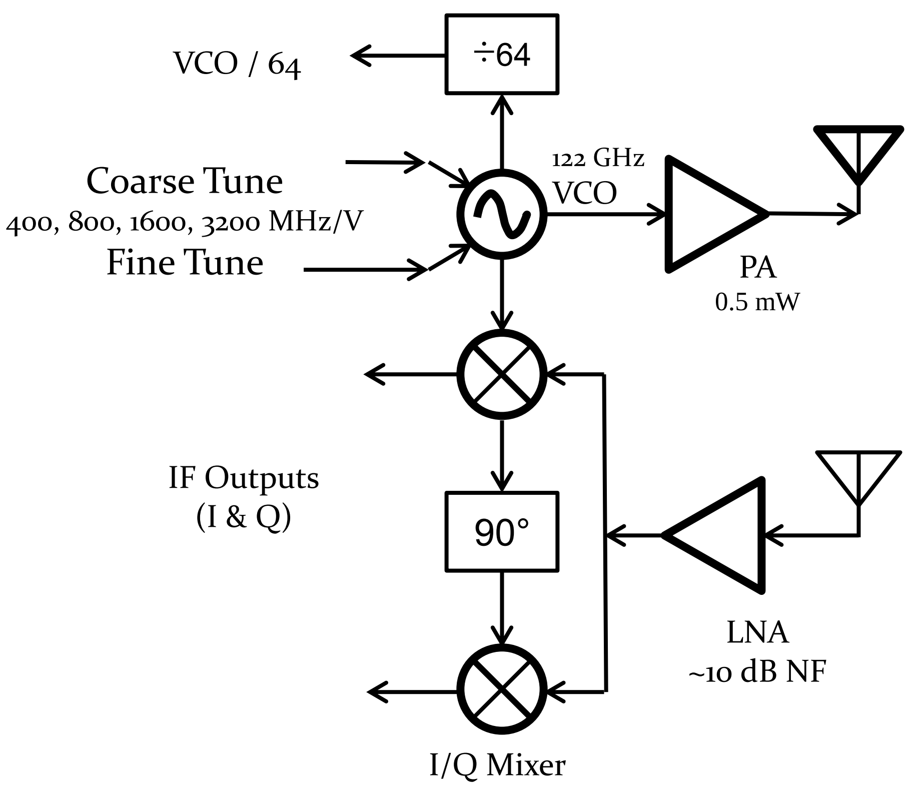
Until now, it hasn't been that easy to build rigs for millimeter wave frequencies. Typical designs involved frequency multiplication chains and diode mixers and multipliers carefully inserted into waveguides [1, 2].

Thanks to new technology and new markets, sensor chips are now available for the 24 and 122 GHz ISM bands, which are also ham bands. This paper will describe a communications application of the Silicon Radar TRX120 transceiver [3]. The TRX120 was designed for FMCW and Doppler radar sensor applications in the 122 GHz ISM band such as liquid level or tool depth sensing and for target range and speed sensing for quadcopters, bike riders and golfers, etc.

Decades ago, X-Band Gunn diode oscillator-mixer modules built for motion sensing and speed trap radar applications became available to hams [4], which led to the second spurt of ham activity on the 10 GHz band (after post-war klystrons and before today's narrow band CW/SSB rigs). Perhaps these new ISM band sensors will enable more hams to tackle 122 GHz.

The Silicon Radar TRX120 Chip

The TRX_120_001 transceiver is fabricated in silicon-germanium (SiGe), which enables high cutoff frequency, moderate cost, transistors that can be used to build oscillators, mixers and amplifiers. Here's a simplified block diagram of the part:



The part includes these important blocks:

- Local Oscillator (voltage controlled, moderate phase noise, div64 sampling output for PLL)
- Transmitter PA (-3 dBm typ, 0 dBm max)
- Receiver LNA (approximately 10 dB DSB NF)
- 90 degree LO phase shifter
- Active I and Q channel mixers (0 – 200 MHz IF; total Rx conversion gain of 10 dB)

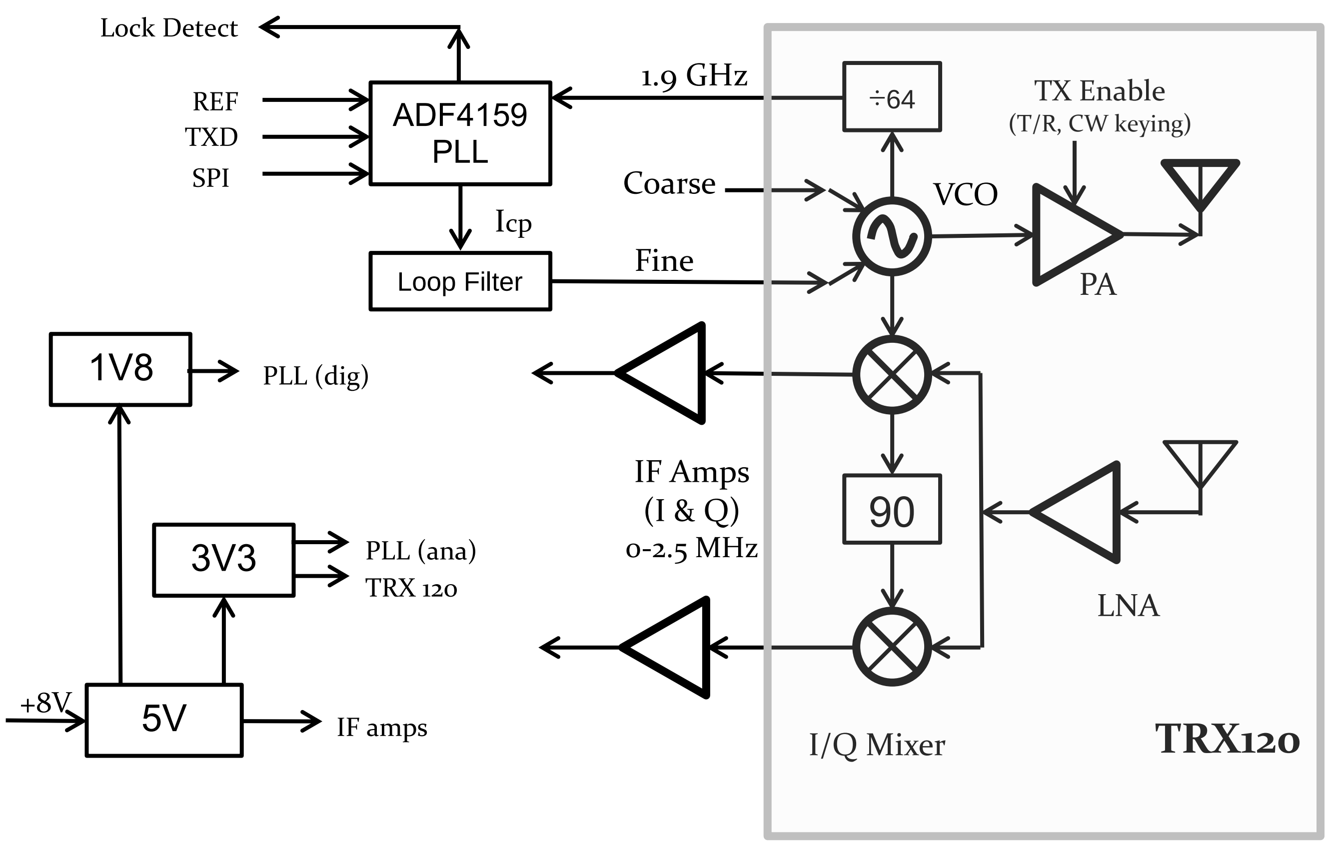
The PA output power is a bit less than some diode multipliers, but the LNA should deliver better performance than simple diode mixers. Now, for something a bit out of the ordinary, we also have:

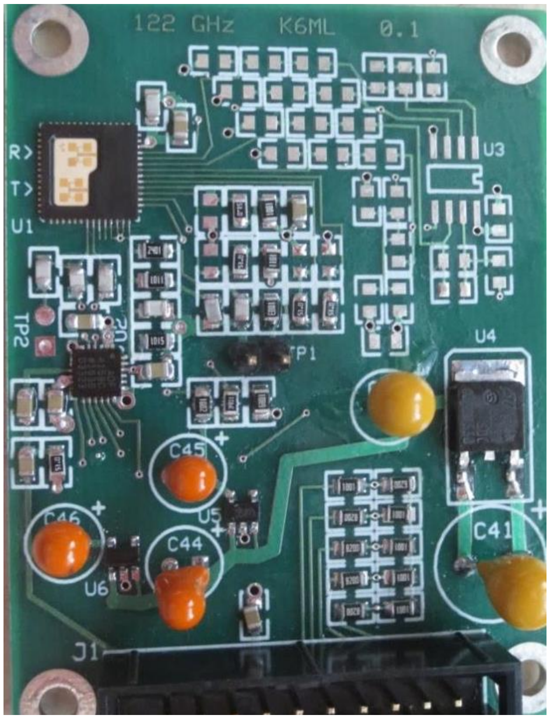
- In-package Rx and Tx antennas wire bonded to the chip die (each a 10 dBi gain 2x2 patch array)

The 8x8 mm QFN package has an open window over the antennas. Because the 122 GHz signals and antennas are all connected inside the package, it is relatively straightforward to design a PCB for the part. The highest frequency pins on the chip are the differential div64 sampling output (1.9 GHz). The next highest are the IF outputs, typically in the MHz range.

Board Design

A 122 Ghz transceiver front end was designed on a 1.9" x 2.5" four layer FR4 PCB using the TRX120:





PCB Photo (left). About 1.5x actual size.

Note that the Rx and Tx antennas are visible in the TRX120 (U1, upper left).

An ADF4159 (U2) phase locks the div64 VCO output to an external reference (typically 10 MHz).

Low noise regulators (U5, U6) provide power to the PLL and transceiver.

A LT6321 dual channel low noise op amp provides matched I and Q IF channels (U3, not yet stuffed in this photo).

Synthesizer. The ADF4159 is used as a fractional-N synthesizer programmable in steps as fine as 40 Hz at 122 GHz when a 10 MHz reference is used. The ADF4159 supports FSK and PSK as well as FMCW ramps. It can be used for radar sensor applications as well as for communications.

Modulation

It does not seem possible to amplitude modulate the part. There is a PA transmit enable pin, which may be useful for half duplex T/R switching to reduce self-desensing of the receiver. This pin might also be useful for on-off keying (“CW”), but a quick test showed that the pin did not kill all transmission, at least not enough for good keying at very close range (perhaps LO leakage was heard during key up).

So we are left with angle modulation. A microphone and simple audio amp can frequency modulate the PLL reference. The PLL has a TX DATA pin which can be used for FSK or PSK modulation (at rates up to at least 20 kbaud, assuming a 100 kHz loop filter bandwidth). FSK can be used for Morse Code or RTTY operation. In addition, the PLL frequency can be changed by one or two register writes, so software m-ary FSK is possible (e.g., WSJT, Domino and other digital modes).

Duplex Modes

Taking a leaf from the Gunnplexer Cookbook [4], it’s possible to build a full duplex “SiGePlexer” around this design. A NBFM receiver (perhaps the IF stage of an old HT or one of the single chip IFs) would be connected to one of the IF outputs and the transmitter would FM the reference. Station “A” would always tune their LO to frequency “X”. Station “B” would always tune their LO to frequency “X” plus or minus the IF frequency. Both stations can transmit and receive simultaneously. This will work best with the in-package lower gain antennas (see later discussion on high gain antennas).

Half duplex operation involves adding an IF offset to the LO frequency when changing from transmit to receive. Greater range using higher gain antennas should be possible in this mode.

IF Receive Output

The TRX120 IF pins support frequencies from baseband to 200 MHz. Depending on the feedback resistor selection, the LT6321 op amp can support a similar range, but as the gain is increased, the useful bandwidth decreases. This design sets the gain at about 30 dB, which supports a 2.5 MHz IF. A simple QRP receiver kit or any handy HF receiver can be used as the IF when connected to either I or Q output.

It's also possible to connect the IQ output pair as baseband or low kHz IF input to a 'sound card' style SDR software running on a PC or a DSP enabled microcontroller. The Doppler shift of a moving target is about 370 Hz for each mph of target speed, which is a virtue for a radar, but can become a problem for communications, especially when a direct conversion or low IF architecture is used. LO leakage and multipath reflections from nearby moving objects (the operator moving about, cars passing by, even tree leaves fluttering in the breeze) can cause QRM and warbling in these IF ranges.

My plan is to use double conversion hardware with a first IF of 2.5 MHz, which avoids Doppler effects up to a 6750 mph target speed. The 2.5 MHz IF will be filtered and down sampled, maintaining the IQ relationship and using the same reference oscillator as the front end, then fed into low IF (12 or 24 kHz) SDR such as the UI board of the mcHF SDR [5]. I/Q phasing in the software (Weaver method image rejection) should cancel most of the front end noise at the undesired 122 GHz image frequency, delivering within a fraction of a dB of the TRX120 DSB NF spec.

Results So Far

Phase Noise. PLL simulations showed that with a 20 MHz phase detector frequency (internally doubled 10 MHz reference) and about 100 kHz loop filter bandwidth, close in phase noise should be set by the OCXO reference's phase noise plus 82 dB due to 12,300x frequency multiplication. Above the loop bandwidth, the TRX120 VCO will set the phase noise. Adding 36 dB to the datasheet div64 output PN plot to correct for the factor of 64, the typical VCO PN is approximately -90 dBc at 1 MHz offset). Low noise voltage regulators were used in attempt to achieve these predicted results.

Initial phase noise measurements showed around -57dBc @ 1 kHz offset and -75dBc (measurement limit) at 500 kHz offset using a 10 MHz OCXO with a -150 dBc @ 1KHz spec.

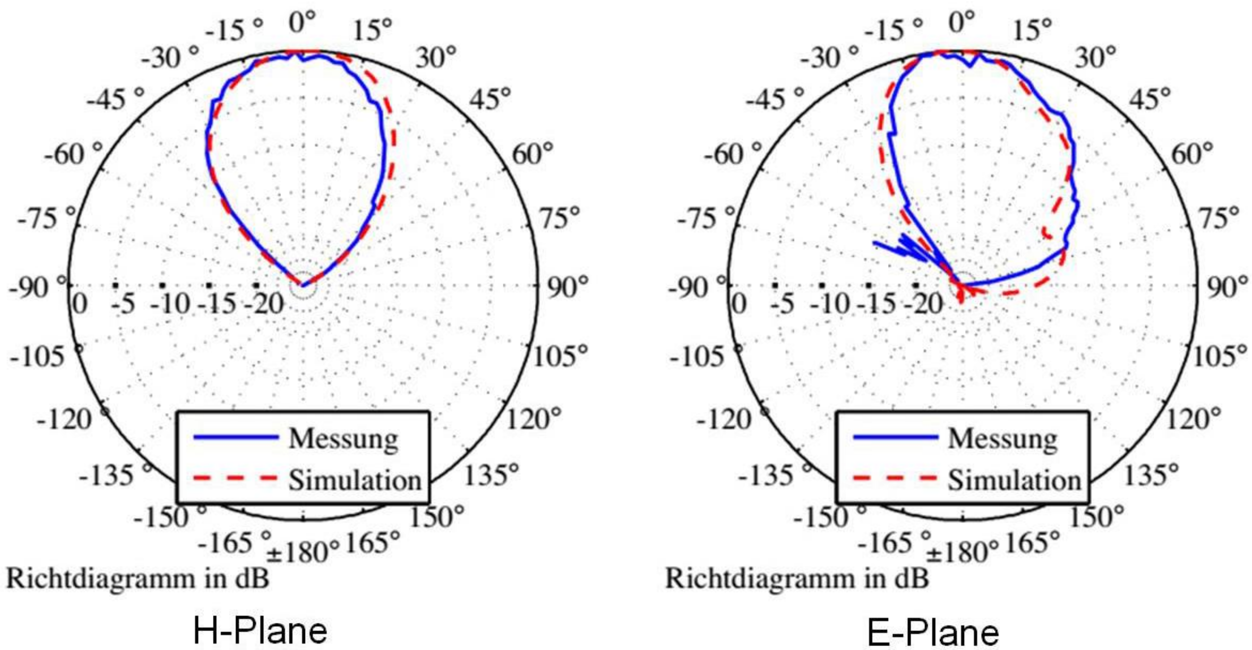
Tuning Range. Testing showed that the VCO's unlocked center frequency varies about 1 GHz as the chip warms up. This drift is greater than the entire 750 MHz ham band, but is still on the order of 1%, so not that shocking for an on die LC oscillator. This means that wide locking range is needed to support the full band while also dealing with the VCO tolerances. In the current PCB, this is done by using 2.4 GHz/V VCO gain (PLL 'fine' tunes the VT1 and VT2 pins) and a fixed 'coarse' bias voltage (VT0 and VT3 pins). Another approach would be to use less VCO gain for a narrower lock range (and potentially lower phase noise) along with firmware to vary the coarse voltage to re-center the VCO on the target frequency using occasional loop lock margin testing.

But is it a radio? One transceiver board was set up as a beacon transmitter sending a CW carrier and FSK CW (Morse Code ID). A second transceiver board was set up as a receiver using a FT-817 as the IF at 2.5 MHz. During a quick test at press time, using just the on chip antennas, signals were 599+ at a range of 120 feet. The received carrier tone was good (T9). Even 80 Hz FSK shifts were clearly distinguished, so there is hope that they can be demodulated with good error rates.

Feeding a Dish Antenna

If the PCB is mounted at the focal point of a 2 foot dish reflector, the gain will be ~55 dBi (assuming ~50% efficiency), or ~45 dB more than the internal 2x2 patch array. If both stations use a 2 foot dish, the system budget improves by 90 dB and significant DX becomes possible.

Matching feed to dish f/D. The first issue is the antenna pattern of the on chip antenna, which is now the dish feed. How well does it illuminate the dish? As already mentioned, the good news of the in-package antenna is that there are no 122 GHz signals to route and no 122 GHz antennas to design. The not so good news is that the antenna design is fixed by the TRX120 designers. Here is the antenna pattern from the datasheet:



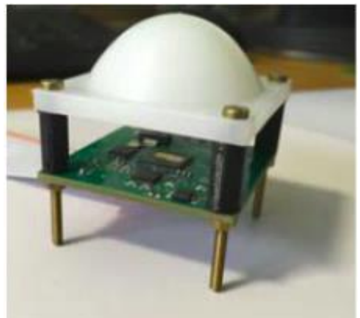
red – simulated, blue - measured

The -10 dB beam width is about 80 degrees, which would significantly under illuminate a typical prime focus dish and slightly over illuminate a typical offset dish. Dishes with surfaces designed for use at millimeter wavelengths are usually prime focus. So, finding a dish that is well matched to this feed (in surface quality and/or f/D) will be difficult; we can expect to sacrifice another 3 to 6 dB (maybe more) using an available surplus dish. Of course, it's possible to design and make a Cassegrain subreflector to match the dish to the feed (another project!).

As a side note, Silicon Radar has a new part [6] in the works (TRA_120_002) that will have **on die** antennas instead of **multi-substrate in package** antennas. The new antennas will be single dipoles instead of the higher gain patch array, which should give a wider beam and a better match to a prime focus dish, but antenna pattern data has not been released yet.

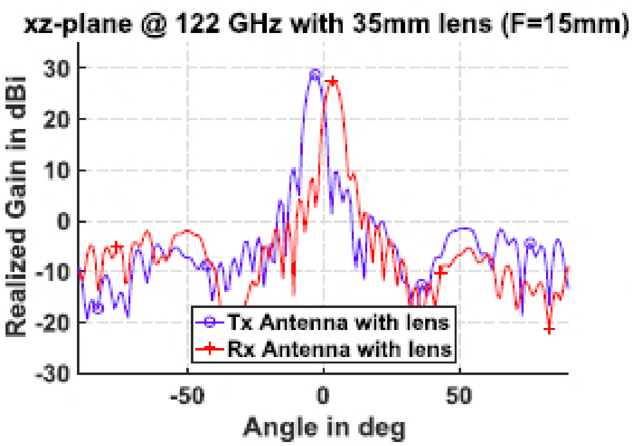
Tx / Rx Beam Skew. But there is a more significant issue. The bad news about the in-package antennas is that there are two of them (one for Rx, one for Tx), not one. This is not a significant issue when the gain is low, but starts to become a problem as the gain is increased (either by adding a lens for moderate gain or a dish reflector for higher gain).

First, note that the ‘focal point’ for the following plots is the dot midway between the two antennas, **shown in the die photo at left**. The antennas are separated by ~3.0 mm in x and ~0.7mm in y.

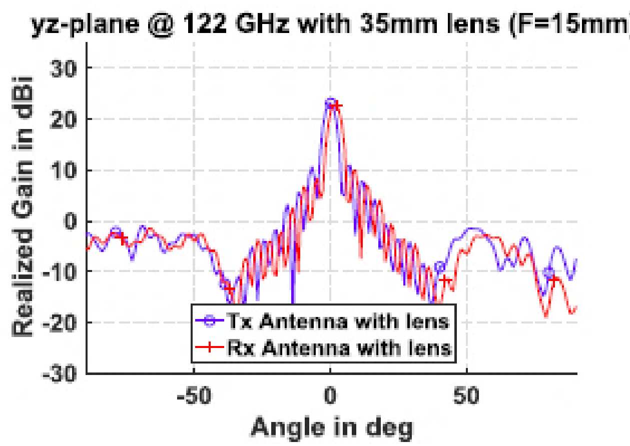


Next, in the following plots from [7], the gain has been increased to about 30 dBi with the addition of a **plastic lens in front of the package (center photo)**. As a result the beam width has narrowed enough to reveal the Tx / Rx beam skew issue caused by the antenna separation.

Separate measurements of the Rx and Tx antenna patterns are shown below for the x axis (a) and for the y axis (b). In each plot the left hand peak is the Tx (blue) pattern and the right hand peak is the Rx (red) pattern:



(a)



(b)

Plot (a) shows that the x axis separation is enough so that with the extra lens gain, the Rx peak is significantly displaced from the Tx peak. Plot (b) shows the effect of the y axis separation is proportionally less bad, but it still can be seen. This Tx / Rx pattern skew problem will only get worse with another 15 dB of dish reflector gain. For a 2 foot dish, it is estimated that the x axis Rx peak is anywhere between the Tx first null (most unfortunate!) and the Tx first side lobe.

Conclusion: The chip must be moved 3 mm in x and 0.7 mm in y when switching between transmit and receive if we want full performance and accurate dish pointing.

System Design: Frequency, Aiming and Path Loss

Of course, higher gains mean narrower beam widths (a quarter degree for a 2 foot dish at 122 GHz) and thus require better pointing accuracy. Higher operating frequencies use higher reference multiplication factors (12,300x for 123 GHz and a 10 MHz reference), which lead to greater frequency errors. A +/- 20 ppB reference can be +/- 2.5 kHz at 123 GHz.

One solution (besides rifle scopes and atomic clocks) can be found on the Silicon Radar webpage [8]. The 24 GHz TRX_024_06 transceivers have a nearly identical architecture to the TRX120 parts. The main difference is that they require an external antenna. A second PCB design that substitutes the TRX24 for TRX120 and adds a 24 GHz antenna can be mounted alongside and offset from the 122 GHz PCB. The same mechanism that moves the TRX120 for proper feed position between Tx and Rx can also move either the TRX24 or TRX120 into position when bands are changed, resulting in a dual band transceiver with common dish alignment. It's 5 times easier to point a dish at 24 GHz than 122 GHz.

Frequency errors are also 5 times greater at 122 GHz than at 24 GHz. Once again it's easier to find the other station at 24 GHz. If each station uses the same reference for 24 and 122 GHz, any frequency delta observed at 24GHz will be proportionally greater at 122 GHz and can be calibrated out for that QSO pair.

Finally, the 24 GHz parts have 7 dB more power out and 6 dB lower noise figure. And according to [9], there is a lot more atmospheric absorption loss at 122 GHz, about one "S" unit more for each 12 km at a dew point of 25 deg F. So, the system budget on a DX QSO can be 40 to 80 dB better at 24 GHz.

Using such a dual band system, the link can be established much more readily using a 24 GHz pilot signal. Stations can switch to 122 GHz once good signals are heard on 24 GHz and be on frequency and very close to target bearing.

I am debugging the TRX24 PCB and have started to design a common IF board (band switching, 2.5 MHz LPF and sampling down converter and amplifiers with SDR interface).

Conclusion

As we go to press, the jury was still out [10], but at least a short range 122 GHz radio is possible with these parts. If they can be successfully mated to a dish, they could make a simple radio capable of greater range which would enable more 122 GHz activity.

References

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10. Look on the proceedings CD for updates and additional info.