Possible accurate time/frequency sources for maserless VLBI?

SETICon04

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ABSTRACT - The SETI League's project ARGUS currently works as a set of independent antennas/receivers, distributed in direction to maximize solid angle coverage. In some cases like wanting to do a follow-up observation with increased sensitivity, it would be desirable to coherently combine signals from several antennas. Since project ARGUS antennas are geographically dispersed, VLBI techniques will have to be used. This paper gives a quick overview of possible synchronization sources available to stations lacking atomic standards or masers.

1. REQUIREMENTS

When combining two coherent signals of equal amplitude, to keep combining losses below 1dB, the phase error must be less than 54 degrees. This is similar to the common optical criterion of 1/8 wavelength or 45 degrees wavefront error. In terms of delay, for example on 1.4GHz, that is cca 100ps or 3cm of path length difference. For a 100 sec integration time, for example, the required accuracy is therefore 1E-12.

On lower frequencies, the requirement gets relaxed proportionally to wavelength, but VLBI gets difficult because of the random delays in the ionosphere, which quickly increase below a few hundred Mhz. Maybe some equivalent of adaptive optics as used by optical astronomers to mitigate atmospheric turbulence ('seeing') could be used here to take the twinkle out of the ionosphere on the lower bands?

Apart from the RF frequency/phase synchronization, there is also the need to synchronize the recording start time, to reduce the amount of searching needed at the central correlating station.

It should be clear that the requirement is only that the stations are that well synchronized among themselves, without the need for reference to some absolute external standard. As long as they are locked to the same reference, the absolute time and frequency accuracy of that reference is less important. More important is its stability (coherence time) because different stations will receive the reference with different delays, therefore the reference must keep the required coherence at least as long as the longest delay difference (including the delay difference of the observed source).

Another question is what loop bandwidth does a reference signal allow in your

locking loop for the local standard (how often the error information is available to adjust it). The needed bandwidth depends on the quality of the local standard. A good local standard needs less bandwidth and opens up more possibilities in the choice of the reference.
Example: you have an old mechanical watch that goes off by about one minute per week (cca 1E-4). Suppose you want your time accurate to one second. Obviously, you will need to set the watch at least 9 times a day! But if you had a good quality quartz watch, accurate to one second in 10 days (1E-6), it would be enough to set it once a week.

A good quartz oscillator will have approx 1E-7 long term accuracy [1]. This means 140Hz error at 1.4GHz, or more than 50000 degrees of phase error each second, limiting possible integration time to a millisecond or so. Obviously, a way of locking the reference oscillators at each station is needed. Big radio observatories normally use hydrogen masers for this purpose, which can achieve 1E-15 on the time scale of minutes [2]. Let's assume that for a large number of small stations, individual atomic standards are not feasible due to economic reasons. What alternatives do exist?

2. A QUICK OVERVIEW OF SOURCES OF ACCURATE TIME AND FREQUENCY

2.1 The Internet

Because of the way data is transferred over the Internet, random delay variations are in the range of seconds, thus many many orders of magnitude too large for this application. Software exists that tries to measure the delay and compensate for it, but the residual errors are still in the millisecond range, millions of times too big.

2.2 The telephone network

Classic analog circuit-switched telephone lines of 30 years ago would be much better suited for time transfer, but today telephone traffic is digitized and suffers unpredictable delays of up to 100ms in various buffers along the way, making it useless. Even in analog systems, SSB techniques were used in trunk lines, so frequency information was lost.
Telecom operators must keep parts of their network highly synchronized, and use atomic clocks for this purpose. I don't know if this synchronization reaches all the way down to the bitrates of the individual digital telephones (ISDN etc). If yes, this would be a possibility for oscillator locking, at least in the limited area of a single operator. However since many (hundreds of) kilometers of cables exposed to environmental variations are involved, random delay variations are probably too big for interferometric purposes.
Even if the synchronization doesn't reach the subscribers, for those living along major microwave trunk links it could be possible to 'steal' the bit clock from these links.

2.3 The power grid

Continent-wide power systems are operated synchronously. But the power network has a complex impedance, so the phase of the voltage will change with varying local loads. Even 1/1000 of a degree at line frequency means 55ns, way too much. As mentioned above, absolute frequency accuracy is not required, but the power line frequency variations can exceed the pulling range of a quality VCXO, making locking impossible.

2.4 Short wave/long wave broadcasts (WWV, DCF, LORAN and similar)

It would be easy to lock to a carrier of an shortwave AM broadcast station and use the modulation as a time marker, but SW reception is usually via ionospheric refraction. Ionosphere is a dynamic system which can induce about a ms of delay variation and a few mHz of Doppler. This is the reason most time services (like DCF77) and navigation systems transmit on long waves, where variations in the ground wave regime are about ten times smaller. However they are still much larger than required for VLBI and have long periods (diurnal), so that the short term stability of a quartz oscillator cannot average them out sufficiently for interferometry. For example, the LORAN system, which uses a special pulsed scheme to separate the ground wave, has a navigation precision in the order of 100 meters, compared to centimeters needed for L-band VLBI.

2.5 Terrestrial VHF and UHF broadcasts

Line of sight propagation of VHF and higher frequencies in the troposphere offers good delay stability. The high power and frequency of AM/VSB TV broadcast carriers make them ideal for high quality locking. The troposphere as a propagation medium introduces some random delay variation, as the refractive index of air changes with temperature and humidity. Refractive index, in PPM over unity is [3]

$$N = 77.6/T*(p+4810*e/T)$$

where p and e are total pressure and partial water vapor pressure in millibar and T is in Kelvin. Plugging in the extremes of weather, this gives cca 200ppm of change, or 20cm per km. In a limited geographical area, the p,e and T values will be correlated, so the relative variation will be less.

According to [4], the amount of multipath delay variation in a single link is

$$dt = 0.7*(d/50)^{1.3}$$

nanoseconds for distance d in kilometers. This would imply a maximum distance of 11km to keep delay variation below 100ps. However these are maximum values, reached only in extreme weather. Most of the time the variation will be maybe 10% of that, making these signals usable within most of their optical visibility coverage area (cca 100km).

The carriers of different TV transmitters are neither coherent nor atomic locked, so carrier locking works only within the area that a single transmitter covers.

By locking to modulation (line frequency, color subcarrier) instead of the RF carrier, the area of possible synchronization can sometimes be extended to the coverage area of the particular TV network - at least that was possible in the days of analog video trunk linking. Digital links almost always include some buffering (convolutional FEC etc), which can introduce unpredictable delay variations. Even with analog links (not many of these remaining) the random delay variations will increase with distance and number of hops. Segments of networks that cover several time zones and use time staggered programing can be totally incoherent. It is worth mentioning that TV networks are sometimes used to distribute accurate absolute time and frequency. This was first proposed 1967 in Czechoslovakia. Later,in the former East Germany (DDR), they used the timing of the state TV network to distribute the national time and frequency standard. Nowadays quite a few European TV stations are locked to atomic standards, but whether this will continue into the digital era remains to be seen.

Besides the sync pulses, the content of the video or teletext data could be used as a coarse time marker for the recordings.

Another excellent possibility for phase locking, at least in the area of a single transmitter, is the bitrate of digital broadcasts.

2.6 CATV networks

CATV networks offer another source of possible reference signals. The problem is that long cables exposed to environmental variation plus the automatic gain and slope compensation circuits can cause random delay variations. At the headend, the signals are sometimes resynced thru frame buffers to relax the linearity requirements on the trunk amplifiers, so the coherence between off the air and CATV version of the same signal can be destroyed. Introduction of digital trunking further complicates things.

Anyway, CATV systems are almost always leaky enough to make radio astronomy work in their vicinity a challenge, and are mostly available only in urban areas with high levels of RFI.

2.7 Cellular networks

Cellular phone networks are well synchronized and cover large areas. I don't know enough about their operation to be able to estimate their suitability for our purposes. The random nature of the traffic could be a problem for a passive user.

2.8 Satellite navigation systems

Satellite navigation systems (GLONASS, GPS) have revolutionized the world of time and frequency metrology. Their main advantages are global availability and absolute reference. However there are some problems when one wants to extract interferometric quality timing from their signals.

These satellites are in non-geostationary orbits, moving at many km/sec relative to the user. That means several kHz of Doppler that changes within hours and is different for each satellite and each user. The correction has to be done based on the ephemeris broadcast by the satellites, which have an error between 35 and 150 cm, depending upon time since upload [5].

Two receivers may not use the same set of satellites, so the errors at the two sites won't be correlated, reducing the quality of synchronization.

Non-geostationary satellites rise and set, so the receiver has to switch between them. Each sat having different ionospheric delay and ephemeris error, this potentially introduces phase jumps, worsening the stability requirements on the local standard, which has to average them out.

The L-band frequency for the navigation sats was chosen as a compromise between ionospheric errors and transmit power requirements on the satellites (with fixed antenna gain, path loss increases with frequency). On 1.5GHz, the ionospheric delay is up to 50ns. Using the ionosphere model broadcast by the satellites, this can be reduced by cca 70%, but that is still a lot compared to the 100ps requirement.

Depending on the water vapor content, the troposphere can add a few ns of extra delay straight overhead [5], and up to a few ten ns on the horizon. This delay is difficult to model, because the troposphere can be granular on a much smaller scale than the ionosphere.

The most popular way of using GPS satellites for locking a local standard are the 1pps (one pulse per second) pulses provided by some commercial receivers. The problem is that these pulses are usually clocked from an internal non-locked clock in the receiver. For example with an 10 MHz internal clock, the peak error will be +-50ns or 29ns RMS assuming a constant distribution (frequency offset / sawtooth phase). To get 0.1ns error, it would be necessary to average cca 1E5 pulses, that is cca one day worth of 1pps pulses. It is questionable if a quartz oscillator allows this long an integration time.

This means that for our purposes it would be necessary to use either spread code locking or RF carrier locking, combined with DDS techniques for Doppler removal, to lock the reference oscillator. None of the low-cost consumer (and even military) GPS receivers offer this option.

Another possibility how to use the GPS system for our purpose could be similar to how Woan [7] used terrestrial broadcasts. Instead of locking the oscillators, one could record the GPS band together with the desired signal, for example in an system that would record the complete bandwidth from 1400 to 1600 MHz. This would make individual receivers very simple, except for the bandwidth. The central station could later offline digitally demultiplex the GPS signals from the desired signals, decode the GPS code and carrier and use these to align the samples from all the stations.

At least for signals close to the GPS frequency band, there is an interesting possibility of turning the ionospheric delay on the GPS signal into an advantage: by using a satellite close to the direction of the desired source, the delays on the source and satellite signals will be similar, possibly canceling out each other to some degree.

2.9 Broadcast satellites

satellite broadcasts from geostationary satellites are probably the best reference for at least relative synchronization, because they move less and slower than other satellites. Although precise orbit ephemeris (of the GPS type) is usually not available for these birds, their movement could be simple enough to be predictable based on simple Keplerian elements (as available on Celestrak or Kelso) and the perfectly predictable Moon and Sun gravitational pull. They are not perturbed by the bumpy gravitational field of the Earth because at their distance from Earth and on the scale of their movement it is virtually smooth. At this height there is also no atmospheric drag. The only unpredictable influences are probably the station keeping thruster firings and maybe solar wind.

Some satellites from the GOES series transmit a special time/frequency beacon on the 70cm band [6]. Because of the intended application, precise orbit data is available for these satellites. However, the 70cm band is prone to relatively large ionospheric delays, and none of these satellites are receivable from Europe.

Of the other geosats, the most interesting are those for radio/TV broadcasting, since they provide strong signals that can be received with relatively small antennas. A good example is 'World Space Radio' [8] which transmits digital radio programming and can be received with a 10x10cm antenna in the areas of coverage, which include mainly equatorial areas (Africa, South America etc), and with a Yagi in Europe. It's bitrate would be a good source of lock, but the L-band carrier could be subject to too much ionospheric variation, about the same as GPS.

Almost ideal are the TV broadcasts in the 11GHz band, where ionospheric effects are virtually nonexistent. Some of the (analog) TV signals are locked to atomic standards, providing an absolute reference, too. I did some experiments measuring the relative phase of the color subcarriers of pairs of satellite TV channels [9]. The accuracy of the atomic-locked stations without Doppler correction was cca 1E-9. For baselines up to a few 1000 km (within the limits of the satellite coverage) the

Doppler's are correlated, so the relative accuracy between two stations is probably ten times better. Using simple Keplerian orbit calculations, it would be probably possible to correct the Doppler down to 1%, giving the required 1E-12 accuracy for 100 sec integration on 1.4GHz.

One big advantage of this approach is that the recording stations can be kept simple, just doing the recording with a simple locked time base. All the required Doppler and other corrections could be done later off-line at the central correlation facility.

The analog TV broadcasts are slowly being phased out, so the future of color subcarrier locking is questionable. Digital satellite TV offers one potentially very good locking source: the bitrate. I haven't yet dismantled any digital TV receivers (they are still too expensive for my budget :-) so I'm not sure if the bit clock can be picked out easily. The problem is probably that they don't use an analog PLL for clock extraction. In a DPLL the phase jumps in discrete steps, making DPLL's useless for our purpose. This would mean that one would have to construct his own receiver with analog bit clock extraction. (no need to decode the data, thankfully) I'm not sure about the absolute accuracy of the bit rates. In 'classical' digital TV, sampling was coherent with the analog video source, so if this was atomic locked, so was the bit rate. But satellite TV broadcasts are MPEG, and the whole production line can be digitized, with no atomic locked analog time base in the background. Let's hope that despite the 'computer guys' taking things over, the bitrates are at least good enough for relative synchronization. Otherwise at least one reference station with atomic standard would be needed, which would record clock rate deviations for later correction.

3. CONCLUSION

Of all the available synchronization sources, only three seem to offer the required accuracy and loop bandwidth: terrestrial VHF/UHF broadcasts, the navigation satellites and the broadcast satellites. The first solution has the advantage of simplicity, but is probably useful only over limited geographical areas, in the order of 100km. The navigation satellites offer potentially high enough precision - but to realize it would probably require hardware that is not commercially available at low cost. The broadcast satellites could provide very high precision with relatively simple hardware, but it remains to be seen what the current digital revolution will bring in terms of signal stability.

4. REFERENCES

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