Carrier Frequency Shift Tracking for LEO Satellite Transmissions

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Introduction

Since the 20th century, Global Navigation Satellite Systems (GNSSs) have provided military personnel and civilians with position and timing information via a system of satellites in Medium Earth orbit (MEO), about 2,000 kilometers above the earth. The Global Positioning System (GPS), a GNSS owned and operated by the the United States Air Force, services the United States military as well as providing countless personal devices with location information across the country. As such, the heavy ramifications of losing GPS functionality makes the system a high-risk target for jamming or attack by the country's adversaries. In a GPS-denied situation, brought about by an attack or by environmental conditions obscuring the signal, an alternative solution to GPS may be required to obtain a position fix.

Team Caribbean Green's senior capstone project, sponsored by Cambridge, MA's Draper, implements a position-tracking system that eliminates the need for GPS data by tracking the Doppler shift of the carrier frequency of satellites in Low Earth Orbit (LEO). LEO satellites can consist of amateur radio craft, research probes, weather satellites and many more types of satellites, numbering in the hundreds compared to the 31 operational satellites that make up the GPS cluster[1]. Since the system tracks frequency shift, data demodulation is irrelevant, making the pool of usable satellites much larger and increasing the likelihood of being able to obtain a position fix at any given time in the absence of GPS.

Impact of Modulation Scheme

Satellite Database

The project group has narrowed down a database of usable LEO satellites for the general vicinity of the test location (Somerville/Cambridge, MA). Listed in this database is the intended carrier frequency and modulation type for approximately a dozen satellites, whose modulation schemes range from pure sine wave transmission to more complex modulation schemes.

LEO Modulation Types

The system the team is designing depends on successful carrier recovery; i.e., monitoring the carrier frequency in order to able to accurately track its Doppler shift over time. From a receiver standpoint, the most convenient signal type for this situation is a continuous wave (CW) transmission, which is a pure sinusoidal transmission at the carrier frequency. Many of these transmissions are sourced from "beacon" broadcasts, which do not transmit data but assist in locating the data-transmitting signal[2]. Since the carrier manifests clearly here, there is no need to isolate it from any modulation scheme and it is easily tracked through Fast Fourier Transform (FFT) or Phase-Locked Loop (PLL) methods, discussed later in this paper.

Naturally, not all carriers are easily isolated like those of CW transmissions; most waves are transmitting data on the carrier with a certain modulation scheme. Some examples from the team's assembled database include:

- Automatic picture transmission (APT): data undergoes a 256-level amplitude modulation on a subcarrier, and is then frequency modulated onto true carrier
- High-resolution picture transmission (HRPT): Binary phase-shift keying (BPSK) or Quadrature phase-shift keying (QPSK) in the range of 1.6 GHz to 1.7 GHz
- Audio frequency-shift keying (AFSK): Digital data symbols are represented by

changes in the frequency of the carrier signal[3]. Specialized for audio.

The spectra of these signals will, of course, no longer contain only the carrier frequency; in fact, it is in many cases not even among the strongest signals present. As a result, any receiver hoping to track the Doppler shift of the carrier frequency will have to attempt one of a few different strategies to isolate the carrier from the data.

Carrier Recovery Strategies

Fast Fourier Transform Tracking

Perhaps the most straightforward way to track a frequency shift over time would be to take the Fast Fourier Transform of the signal, using a discrete algorithm to transform a set of N time-domain samples into magnitudes at N divisions of the frequency range (determined by halving the sampling rate) in the frequency domain. For CW signals or signals with a prominent carrier (such as Dual Side-band AM transmissions), seeing the Fourier Transform of the signal will allow processing software to simply isolate the peak/impulse in frequency that constitutes the carrier frequency, and note the shift in that peak over time.

The quality of results obtained by this method will increase with raising the frequency resolution of FFTs taken (done by increasing N), and with increasing how many times the transform is calculated every second. In this sense, this is a 'brute-force' means of obtaining better results, as the only solution to sustaining faster, higher resolution FFT performance is to throw more processing power at the solution. In situations where computational power is limited (especially in a portable computing setup as in the intended final form of this solution), this method proves unsustainable, leading to a need for a more elegant solution.

In a 2003 paper[4], Yang et al. suggest a novel method for improving on FFT carrier recovery using a Kalman filter to track phase differences while the FFT tracks frequency changes. After an FFT of decent (but likely not perfect) precision makes an initial estimate of the frequency offset, a nonlinear phase estimate loop is used to estimate and track carrier phase. This one-step Kalman filter loop makes an estimate of the phase and uses the error between predicted phase and measured phase to continuously modify it. This open-loop solution is an alternative to the more popular, PLL/Costas-loop based closed loop solutions, discussed next in this paper.

Phase-Locked Loop

The phase-locked loop is a feedback system involving a phase detector (PD) and a voltage-controlled oscillator (VCO), which responds to changes in phase and frequency between its current output (often tuned to a desired frequency like an intended carrier). In carrier recovery systems, it allows the receiver to better ascertain how much frequency and phase shift a signal has experienced.

The following diagram describes the main functional blocks of a PLL:

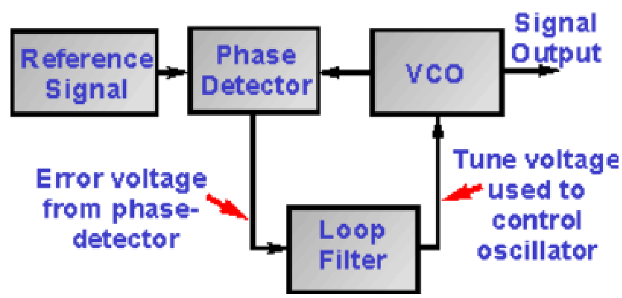

Image credit: radio-electronics.com[5]

The difference between a reference signal and the current output is converted into an error voltage by the phase detector, which is filtered by a tunable loop filter that removes unnecessary high-frequency noise and effectively determines how drastically to tune the oscillation of the VCO in response to the error voltage. Through continuous feedback, a system like this can be used to lock phase and frequency with a reference carrier.

Multiply-Filter-Divide Algorithm

Another means of recovering the carrier frequency is the multiply-filter-divide (MFD) algorithm, which applies a nonlinearity like a squaring or quadratic function to the input signal, in order to affect various frequencies unevenly and increase the relative isolation of the carrier in the frequency domain. The result of squaring the input, for example, will create a harmonic of the carrier frequency at 2 times the received f_c which can be used to drive a PLL tuned to $2f_c$. The phase detector (PD) output of the PLL gives a measure of phase and frequency mismatch between the VCO output signal and the input signal, allowing

the user to discern the frequency mismatch. Due to the multiplication process, the mismatch in frequency will be exaggerated and potentially easier to measure by a system monitoring frequency shift.
The algorithm proceeds further to allow users to reclaim the original intended frequency of the carrier by powering the VCO with the PD output and dividing the frequency by two; going this far, though, is not our intended application of the method as it is chiefly a means to undo frequency and phase shift. The MFD method of carrier recovery proves straightforward to analyze mathematically, but it is often more difficult in a real implementation because the phase offset between receiver and transmitter will be tough to control; additionally, the specificity of the filters required to isolate measured harmonics of the carrier frequency will reduce how well a given system can be applied to an array of different frequencies[6].

Costas Loop

The concepts at play in the PLL are modified to create the Costas Loop, a device for carrier phase recovery from signals whose modulation schemes suppress the carrier, including BPSK and QPSK. The system relies on two feedback loops tracking in-phase and quadrature (I/Q) samples in parallel from a shared VCO which is shifted 90 degrees in phase for the quadrature loop. At the end of each path, the I and Q outputs are put through a multiplier, which is sent through a loop filter whose output is fed to control the VCO.
The division of the system into I/Q tracking loops has the end result of making the Costas loop error voltage twice that of the standard PLL at small frequency deviations, making the loop particularly well-suited for tracking the Doppler shift of satellite transmissions[7].

Conclusion

Though basic frequency shift analysis tools like the FFT or PLL may not alone have the power to detect the relatively precise Doppler shifts in frequency that Team Caribbean Green's system depends on measuring effectively, they do become the building blocks of more complex methods of isolating the received frequency that will allow for savings in computation speed.
While the project as implemented focuses primarily on CW, BPSK and QPSK satellites, for which the MFD algorithm proves easy to implement in software, adapting to other modulation schemes can require a different strategy. Through a potentially hardware- or software-based implementation of an MFD algorithm or Costas loop, there are many effective ways for a project with similar needs to measure frequency shift to high precision at high frequency, without simply increasing computational power only to satisfy the needs of a high-speed, high-point count FFT.

References

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