GNSS Solutions:

Adaptive antenna arrays, multi-GNSS tropospheric monitoring, and high-dynamic receivers

"GNSS Solutions" is a regular column featuring questions and answers about technical aspects of GNSS. Readers are invited to send their questions to the columnists, **Professor Gérard Lachapelle** and **Dr. Mark Petovello**, Department of Geomatics Engineering, University of Calgary, who will find experts to answer them. Their e-mail addresses can be found with their biographies at the conclusion of the column.

"What is adaptive nulling vs. adaptive beamforming? What are the advantages and disadvantages?"

Adaptive arrays are perhaps the single most powerful antijamming tool in the GNSS systems engineer's toolkit. They can provide anywhere from 15 to 90 dB of jamming rejection depending on the specific architecture used. Their main disadvantage is that they require an array of antenna elements, each spaced about four inches apart (center to center), and thus are physically large.

Two general types of adaptive array antenna are used with GNSS receivers: single-output nulling antennas and multiple-output beam-steering antennas. Most deployed systems are single-output adaptive nulling antennas that operate as an antijamming appliqué. In this way, a GPS receiver need not know to what type of antenna it is connected, be it a fixed or controlled reception pattern antenna (FRPA or CRPA). New development systems tend to emphasize multiple-output beam-steering antennas because of their better performance. However, in order to handle the multiple output channels, a new receiver is required, too. The trend is to integrate the array processing with the GNSS receiver in a single unit.

Figure 1 shows a generic nulling antenna that uses a common set of weights for all GNSS signals. The objective is typically to minimize the output power subject to the constraint that one element be turned ON (top channel in Figure 1). Remaining channels have their output phase and amplitude dynamically adjusted so as to cancel out jammers in the summation process on the right hand side. The resultant is very sharp spatial nulls in the directions of the jammers but, because the GNSS signal's direction of arrival isn't taken into account, a significant possibility arises for low gain in some signal directions. In principle, such an array can independently steer N-1 spatial nulls in the directions of the jammers.

Figure 2 shows the other major adaptive antenna configuration, a multiple-output beam-forming array. Here, the unit generates a unique set of weights for each signal, optimized for that signal. The weight formation process takes into account the desired signal's direction of arrival and, in absence of jamming, will phase the input channels so they coherently add together to create a beam in the direction of the satellite.

Attitude information is typically obtained from an inertial measurement unit and then combined with satellite ephemeris to calculate pointing angles. Like the nuller, the beamformer can independently steer N-1 spatial nulls in the directions of the jammers.

Both the nuller and the beam-former will perform much better (>20 dB) against narrowband jammers — all else being equal. Broadband jammers present a problem in that the degree to which the channels match in terms of phase and amplitude across the band limits null depths. One weight will not be ideal for all frequencies and, so, jamming energy leaks through at some frequencies, thus limiting the cancellation ratio.

Space Frequency Adaptive Processing (SFAP) addresses this issue by dividing the frequency band into multiple, narrow subbands; typically using a fast Fourier transform (FFT). As an example, with a 20 MHz complex sample rate the GPS P(Y) code frequency band might be divided into 128 subbands with 156 kHz center-to-center spacing. SFAP computes weights unique to each subband, applies them, and then takes the aggregate subbands and reconstructs the full band signal using an inverse FFT.

Within each subband, the phase and gain is relatively flat using SFAP, and, consequently, the jammer cancellation is more complete. Against broadband jammers, SFAP improves null depths by upwards of 30 dB compared with non-SFAP approaches. SFAP can be used with either nuller or beamformer configurations but with attendant increased processing requirements for both cases. *Space Time Adaptive Processing* (STAP) is the time domain cousin of SFAP and uses adaptive finite impulse response (FIR) filters to achieve similar effect.

So what are the advantages of nulling vs. beamforming?

- Historically, nulling has been used because of its lower complexity. A 24-channel L1/L2 receiver ideally has a 24-beam adaptive beam-former associated with it; 12 beams for L1 and 12 beams for L2. Contrast this with a nuller configuration which would have one output for L1 and one for L2. The beamformer has a 12x throughput requirement.
- To first order, an N element beamformer provides $10\log_{10}(N)$ higher output signal-to-noise ratio (SNR) compared with a nuller. That is 8.5 dB for a 7-element antenna. In situations where the desired signal's direction of arrival is close to that of a jammer, the beamformer's advantage is even greater as it will try to avoid canceling out the desired signal, while the nuller has no such apprehensions (unless constrained). Furthermore, nullers often cast sympathetic nulls in directions other than those of jammers. Sometimes, this is in the direction of a desired signal and that signal is lost.
- Beamformers tend to yield a fairly broad beam in the direction of the desired signal and lower gain in other directions. Multipath arriving from low gain directions is more strongly attenuated and has less ability to corrupt code and carrier phase observables. Nullers don't provide this performance gain as they don't seek to generate a directional beam.
- Adaptive arrays improve SNR in the presence of jamming and thus permit signal tracking in environments that otherwise would lack code and carrier phase

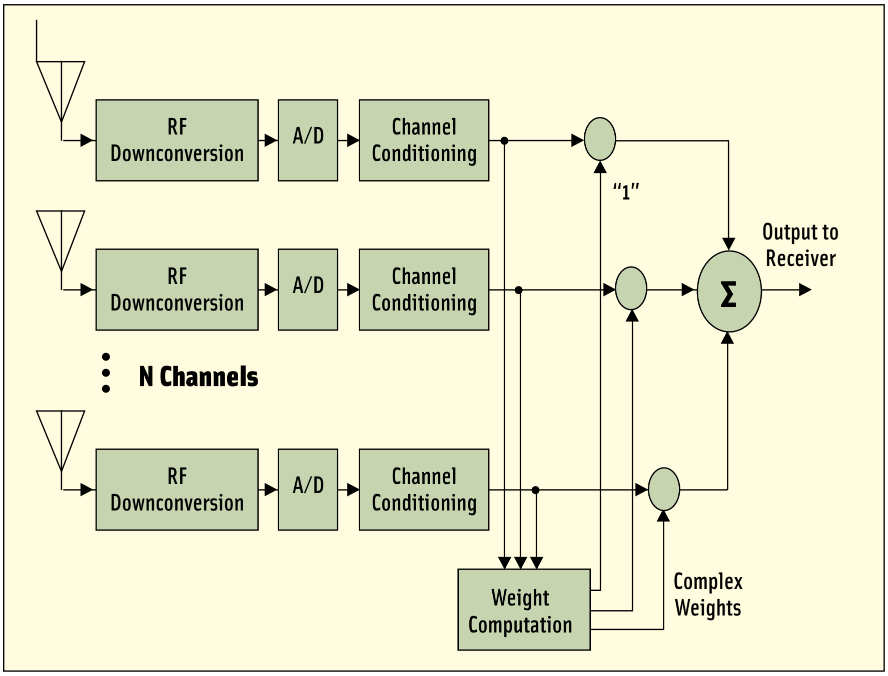

FIGURE 1 Single Output Nuller

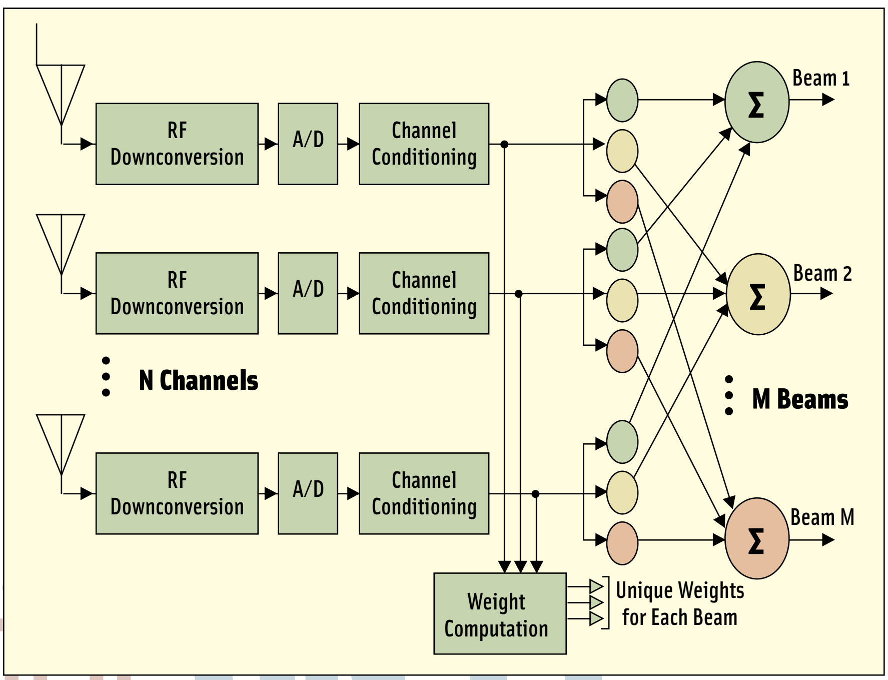

FIGURE 2 Multiple Output Beamformer

observables. This is not without cost though; adaptive arrays can bias code and carrier phase observables. The array antenna is a direction-dependent filter and its distortion effects are also direction-dependent. The distortion is unique for each desired signal and doesn't necessarily "common mode out" in subsequent processing.

In the absence of jamming, the biases are fairly benign. Turn on jammers though and the biases can become large and sustained. Beamformers can show 100-degree carrier phase biases and upwards of one-meter code phase biases. Nullers do even worse. For high precision systems, these errors can be a significant component of the overall error budget and can adversely affect the ability to resolve carrier phase ambiguities in real-time kinematic systems.

Historically, adaptive arrays have been rather expensive, as they are signal-processing and RF plumbing–intensive. With the advent of low-cost, high-performance DSPs and fast, high precision A/D converters, adaptive arrays will find wider application. However, caution should be exercised because they can also be a significant source of measurement errors.

LOGAN SCOTT

Logan Scott, based in Breckenridge, Colorado USA, is a consultant specializing in radio frequency signal processing and waveform design for communications, navigation, radar, and emitter location. He has more than 27 years of military and civil GPS systems engineering experience. As a senior member of the technical staff at Texas Instruments, he pioneered approaches for building high-performance, jamming-resistant digital receivers. He is currently active in location-based encryption and authentication, high performance/low bias adaptive array technologies, and RFID applications. He holds 29 U.S. patents.

How will Galileo benefit the troposphere monitoring community?

L-band RF signals experience propagation delays dependent on pressure, temperature, and humidity in the neutral atmosphere. We can measure this effect using GNSS receivers and extract information about atmospheric properties. Of particular interest are atmospheric moisture measurements, because water vapor is an important greenhouse gas and a major factor in weather systems.

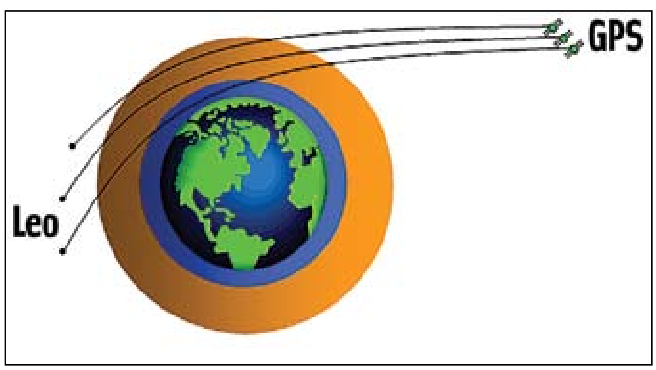

FIGURE 1 Radio occultation technique

Over the past decade, meteorologists have exploited GNSS as an atmospheric remote sensing tool, with applications in weather forecasting and climate change. The availability of Galileo signals, when combined with those from GPS (and/or GLONASS), will enable more accurate estimates of water vapor using ground-based receivers, with higher temporal and spatial resolution. By deploying Galileo receivers onboard low-Earth orbiters, vertical profiles of atmospheric temperature and humidity may be derived with improved accuracy over current GPS-based methods.

A common technique is the estimation of integrated water vapor overlying a ground-based GNSS reference station. By forming ionosphere-free carrier phase observables and reducing other sources of ranging error (e.g., clock and orbit ephemeris) through differential or precise point positioning techniques, we can isolate the wet delay contribution for each satellite slant path. An absolute zenith wet delay (ZWD) is then modeled as the average of all satellite slant delay observations scaled to zenith. In some cases an azimuthal gradient is also estimated.

Many GPS reference networks worldwide currently employ this approach for meteorological applications. For example, the NOAA Earth System Research Laboratory assimilates near real-time estimates of ZWD from hundreds of U.S. reference stations into numerical weather forecasts.

Galileo observations, when combined with those from other systems such as GPS, will provide significant improvements in accuracy and resolution of moisture estimates. A GPS/Galileo approach would effectively double the number of observations available at a given epoch, allowing reliable ZWD estimation over a shorter batch processing interval. A 30–40 percent reduction in ZWD error is expected, as compared with GPS-only methods. Increased redundancy will allow improved detection of outliers, particularly ultra-rapid orbit errors, which are currently a limiting factor in near real-time processing.

Batch processing intervals for ZWD estimation must be long enough to achieve adequate satellite geometry and to allow for a sufficient number of observations to reduce noise and multipath errors. Typical batch intervals are 30 minutes for near real-time processing. We could achieve a temporal resolution of 10 minutes or less, however, for near real-time

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ZWD values using a combined GPS/Galileo (or GPS/GLONASS/Galileo) approach. This resolution would allow new opportunities for detecting and monitoring severe weather such as hail storms, thunderstorms and tornados.

We could also use additional observations in a GPS/Galileo approach to resolve higher-order spatial variations. Directional information about moisture content is of critical importance for regional weather forecasts — which generally have horizontal resolutions of 15 kilometers or less. Azimuthal asymmetries, associated with approaching weather fronts and thunderstorm dry lines, may be identified in the vicinity of a given GNSS reference station.

Ionosphere-free GNSS observations are required input for ZWD estimation. Due to dispersive properties of the ionosphere (where ionosphere range delays are dependent on frequency), a linear combination of dual-frequency GPS observations can currently be used to remove ionospheric effects to the first order. This accounts for more than 99 percent of the total ionospheric error.

We could use triple-frequency observations for Galileo (and modernized GPS) to model the remaining higher order effects and provide more accurate input observables for ZWD estimation. The use of a triple-frequency ionosphere-free observable is expected to further improve accuracy of ZWD values by 20 percent.

Another rapidly developing technique for atmosphere monitoring is based on radio occultations. This method derives information about both troposphere and stratosphere properties. GNSS receivers on board low-Earth orbiters view a GNSS satellite rising or setting behind the Earth's limb (see **Figure 1**).

Successive signals travel through different horizontal layers of the atmosphere with bending dependent on neutral atmosphere properties. By employing differential techniques to isolate atmospheric path delay, we can estimate the signal bending (and therefore atmospheric properties) and derive high-resolution vertical profiles of temperature and humidity.

The radio occultation technique is effective from near-surface troposphere up to stratosphere altitudes of 50–60 kilometers. At the higher altitudes, atmospheric delay is very small and the residual ionosphere errors and observation noise become significant. For Galileo signals, a triple-frequency ionosphere-free observable could be used to reduce the higher order ionospheric effects. Observation noise would also be reduced compared with current GPS combinations of L1 and low-SNR L2 phase measurements. Triple-frequency techniques could also produce more accurate calculations of stratosphere temperatures.

These values are an important factor in understanding ozone dynamics and global climate change. The availability of multiple-frequency Galileo signals will also improve observation quality and humidity profiling at lower altitudes where current methods based on GPS are limited by atmospheric attenuation of the L2 signal.

Overall, the availability of Galileo signals for atmosphere monitoring will improve accuracies of ground-based moisture estimates by as much as 50 percent – through improved observation accuracy, better geometry, and higher temporal and spatial resolution. This will provide significant benefit to the many agencies worldwide currently assimilating, or planning to assimilate, GNSS ZWD observations into weather forecasts. By exploiting Galileo triple-frequency capabilities, improved temperature and humidity profiles may be derived using radio occultation techniques. Applications include global meteorology and climate change studies.

SUSAN SKONE

Dr. Susan Skone (Ph.D. Calgary) is an associate professor in geomatics engineering at the University of Calgary, Alberta, Canada. Her research focuses on global navigation satellite systems. She is actively involved in atmospheric research for GPS applications, and her technical papers have been recognized with a number of awards. She is chair of the Canadian Navigation Society and co-chair of the International Association of Geodesy's Sub-Commission 4.3: GNSS Measurement of the Atmosphere.

Are special GNSS receivers required for high-dynamic applications such as on fighter aircraft?

Yes — high dynamic applications do often require special types of GNSS receivers. When designing a GNSS receiver, many tradeoffs need to be made, and certain design decisions are necessary in order to be able to track during high dynamics.

Several different factors can affect the ability of a receiver to maintain lock on the GNSS signal for a given level of dynamics, including the loop filter characteristics, oscillator phase noise, and oscillator vibration sensitivity. Each of these will be explained separately.

Loop filter characteristics. The loop filter's function is to feed back information from the processed signal to the parts of the receiver that track the incoming signal's carrier and PRN code (the numerically controlled oscillators). Many factors go into loop filter design, but one significant factor for this discussion is the "noise bandwidth." In general, a large noise bandwidth will enable the tracking loops to track under higher dynamics, but the larger the noise bandwidth, the noisier the measurements become. Some more advanced receivers allow the users to set the noise bandwidth (or select from a predetermined range of values). Another significant factor is the order of the loop filter, which along with the bandwidth determines the response of the system to dynamic stress (velocity, acceleration, etc.)

Oscillator noise. The quality of the oscillator within a receiver can become a significant design consideration under high dynamic conditions. An oscillator that is inherently noisy will make it harder for the tracking loops to maintain lock on a signal. In a sense, a noisy oscillator forces the loop filter to operate at a lower noise bandwidth (to mitigate the effects of the oscillator noise), but this is the opposite of what is desired for a high dynamic receiver.

Oscillator vibration sensitivity. Often, vibration is a factor in high dynamic applications. Oscillators can be sensitive to vibration in such a way that their noise appears to increase under certain vibration frequencies. Again, this adds more noise into the system and can keep the receiver from maintaining lock. A GNSS receiver may very well track a particular dynamics profile beautifully when it is sitting on a lab bench hooked up to a simulator, only to find that when the same dynamics profile is experienced in the real world, the receiver loses lock. This is the result of vibration-induced oscillator phase noise, which is not present on the lab bench but is in the real world.

Erratum

In the article on GPS/Galileo antennas by Chris Bartone in the March "GNSS Solutions" column, one of the notes for additional readings about BOC Signals cited on page 23 was incomplete. It should have read as follows: Rebeyrol, E., et al., BOC Power Spectrum Densities, ION NTM 2005, 24-26 January 2005

We should also be note that the ability of the GNSS receiver to maintain lock is not necessarily the only thing that is needed. If GNSS measurements are incorporated into a top-level navigation filter — perhaps along with outputs from other navigation sensors — then it is important that this navigation filter also be tuned for high dynamics. It is certainly possible for the GNSS receiver to maintain lock, while the overall navigation system "fails" in a high dynamics environment. In this case, "failure" would constitute producing unacceptably large positioning errors during certain maneuvers with large acceleration, jerk, and/or higher order dynamics.

Another way to improve receiver performance in high dynamics is to aid the tracking loops with externally generated information about the trajectory. An inertial navigation system (INS) can be useful to this end. Feeding INS measurements into a specially designed GNSS receiver can help the GNSS receiver maintain lock, because most of the dynamics are measured by the INS; so, the tracking loops do not need to work as hard.

In summary, many factors indeed determine GNSS receiver performance under high dynamics. If high dynamic performance is required, then it would be important to use a receiver that is designed for that purpose.

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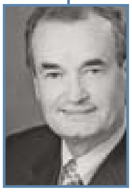

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