BOC or MBOC?

The Common GPS/Galileo Civil Signal Design: A Manufacturers Dialog, Part 2

For the past two years a high-level but quiet debate has been under way that will shape the future of GNSS user equipment. At issue: design of the common L1 civil signal planned for broadcast from future GPS and Galileo satellites. This is the third installment of an exclusive Inside GNSS series in which a US/EU technical working group and GNSS manufacturers have discussed the common GPS/Galileo L1 civil signal design. Should it be a binary offset carrier (BOC) or multiplexed BOC (MBOC)? The choice will determine the direction — and fortunes — of the industry for decades to come.


Global navigation satellite systems are all about timing. In a narrow sense, GNSS is technically a matter of how long the satellite signals take to reach a receiver. In a larger sense, it's about designing global infrastructure systems that may not produce practical benefits for decades to come.

Will the common civil signal be the binary offset carrier, or BOC (1,1) waveform as stated in a 2004 agreement between the United States and the European Union? Or, will it be the multiplexed BOC (MBOC) signal recommended by a technical working group set up under that agreement to examine further refinements to the design? The signal decision involves benefit trade-offs for different types of GNSS receiver designs and will have widespread consequences for the products developed over the next 10, 20, or even 30 years.

Although the math and science underlying the discussion may seem esoteric, there's nothing abstract or theoretical about the consequences of the decision. The selection of a common GPS/Galileo civil signal will profoundly shape the user experience, the engineering challenges, the business prospects and strategies of GNSS manufacturers and service providers, and even the political relations among nations for decades to come.

Our series started in the May/June issue with a "Working Papers" column that introduced the MBOC spreading modulation. Earlier this year, the GPS-Galileo Working Group on Interoperability and Compatibility recommended MBOC's adoption by Europe's Galileo program for its L1 Open Service (OS) signal and also by the United States for its modernized GPS L1 Civil (L1C) signal. The Working Papers column discussed the history, motivation, and construction of MBOC signals. It then showed various performance characteristics that the authors believe demonstrate MBOC's superior performance and summarized their status in Galileo and GPS.

The May/June column also noted, "The United States is willing to adopt for GPS L1C either the baseline BOC(1,1) or the recommended MBOC modulation, consistent with what is selected for Galileo L1 OS." Given this impartial U.S. government position, Inside GNSS believed it would be appropriate and useful to ask a panel of GNSS industry representatives their thoughts on the subject of a common civil GPS/Galileo signal waveform.

In the July/August issue of the magazine, therefore, in an article introduced by Tom Stansell, nine technology specialists from leading GNSS manufacturers began the discussion of technical alternatives, implications for receiver design, and significance for the products that reach the marketplace.

This month four more GNSS receiver designers join the manufacturers dialog, bringing the total to 13 panelists representing the perspectives of 8 manufacturers — CMC Electronics, Japan Radio Company, NavCom Technology, Nemerix, NovAtel, Qualcomm, Rockwell Collins, and SIRF Technology — and 3 independent consulting engineers. Their biographies follow, along with their verbatim answers to questions posed by Inside GNSS.

Pat Fenton, Lionel Garin, Ron Hatch, Toshihiro Kawazoe

The Experts

Pat Fenton, president and chief technology officer, Navitel Inc. Fenton is one of the founding senior GNSS receiver designers of Navitel Inc. He has been heavily involved with the six generations of receivers that the company has produced over the last 20 years. He has also held key positions at ALCATEL, Rockwell, EADS, and Harris. He was the 2001 recipient of the Satellite Industry Award from the Satellite Industry Association. Fenton is the inventor of a new frequency-agile technology that permits satellite navigation receivers to access several satellite constellations simultaneously.

Lionel Garin, chief technical officer, Nemerix SA. In charge of Galileo and GPS development, Garin has been designing GNSS receivers for 30 years, also submitted some comments on the panelists’ discussion, which appear in this section as well.

Ron Hatch, Sr., was one of the founders of NovAtel Inc. Hatch is currently president, general manager, and chief technical officer of NavCom Technology, a John Deere Company, and is currently its director of navigation systems. He has 30 years experience concentrated on high-accuracy applications of satellite navigation at NovAtel and Magnavox. Hatch received a B.S. degree in math and physics from the Seattle Pacific College and is a member of the Institute of Navigation. Hatch has served in a number of positions with the Center for Advanced Navigation (ION) including Chair of the Satellite Division and the 2001–2002, 2002–2003, 2003–2004, and 2004–2005 ION President. He was the 1994 recipient of the Satellite Division’s Award of Merit and the 2000 recipient of the Award of Honor from the Institute of Navigation.

Toshihiro Kawazoe has been with Japan Radio Company (JRC) since 1980, engaged in GPS system analysis and receiver software development. He has also developed GPS receivers for car navigation, with a special focus on improving the positioning performance, improving noise, and improving the software's performance. He has received the B.S. and M.S. degrees from Waseda University in Japan. He is now an assistant general manager of the IRE research and development center laboratory.
The Questions and Answers

Would you expect any performance difference for your products if MBOC code is transmitted instead of BOC(1,1)?

Fenton – Yes, depending on the exact MBOC option used, we would expect between 21 percent to 33 percent reduction in code tracking error due to the increased effective chipping rate and a significant improvement in the detectability and correction of close-in multipath interference.

Garin – Compared to a theoretically achievable performance with BOC(1,1) only, we would lose performance. Compared to the competition who will have to deal with the same signals in space, we won’t be at a disadvantage.

Hatch / Knight – We expect a modest improvement in multipath mitigation under moderately weak signal conditions, such as under foliage.

Kawazoe – We do not expect any advantage from MBOC. Kohli / Turetzky – The biggest difference we would see would be in the availability due to the lower signal strength. However, it’s the same for everyone and if the benefit of higher accuracy for some applications is deemed to be of higher importance, we can still build a very high performance receiver on the BOC(1,1) base.

Do you really care whether GPS and Galileo implement plain BOC(1,1) or MBOC? Why?

Kawazoe – Yes. We prefer BOC(1,1) for easy implementation. Kohli / Turetzky – We don’t have a strong opinion. We can see the benefits of both for different markets. Whatever is chosen, we will build the best receiver for our customers.

Are the GNSS receivers of interest narrowband (under ±5 MHz) or wideband (over ±5 MHz)?

Kawazoe – Our receivers of main interest are narrowband because low cost and jamming robustness are most important for our major customers. Even so, some BOC receivers are wideband because accuracy is more important for these receivers.

Keegan – I have designed receivers that are narrowband (consumer) as well as wideband (Survey) receivers.

Kohli / Turetzky – Our customers have a definite preference for narrowband receivers because they make their system design more robust to interference. As our receivers operate in harsh RF environments and can navigate at extremely low signal levels, keeping interference out lets them utilize our technology to its fullest. Interference in integrated products arises from LCDs, disc drives, and other RF links, and the interfering spectrum can be wideband.

Seyhunlat / Rowitch – The receivers of interest are narrowband. Low cost GPS consumer devices do not employ wideband receivers today and will most likely not employ wideband receivers in the near future. Any technology advances afforded by Moore’s law will likely be used to further reduce cost, not enable wideband receivers. In addition, further cost reductions are expected to expand the use of positioning technology in applications and markets which today do not take advantage of the technology because it is considered by the manufacturers and marketers to be too costly.

Which design parameters are most critical for your products: power, cost, sensitivity, accuracy, time to fix, etc.?

Kawazoe – The most critical design parameter is cost. The next parameters are sensitivity and accuracy. Our main GPS receiver specifications are: power: 88 mA typical at 3.3 Volts, sensitivity: less than -135dBm, accuracy: 10 m 2DRMS typical, and time to fix: 8 sec. typical (hot start).

Kohli / Turetzky – We target different parameters for different target markets. In general, however, availability (a combination of sensitivity and time to first fix) with reasonable accuracy and power are more important than extreme accuracy.

Do you really care whether GPS and Galileo implement plain BOC(1,1) or MBOC? Why?

Kawazoe – Typical products are GPS receivers for car navigation. The total Japanese Car Navigation market was over 4 million units in 2005, and JRC sells about 1.8 million units per year.

Keegan – I have worked with companies in all Market areas from Consumer to High Precision Survey as well as Military.

Kohli / Turetzky – SiRF has a broad array of location and communication products at the silicon and software level that address mainstream consumer markets. Our main target markets are automotive, wireless/mobile phones, mobile compute, and consumer electronics. These markets have a potential size of more than a billion units per year. Although the consumer GPS market is growing very fast, the overall penetration of GPS in these markets is still quite low. Our technology is used in a range of market leading products including GPS-enabled mobile phones, portable and in car navigation systems, telematics systems, recreational GPS handhelds, PDA and ultra mobile computers, and a broad range of dedicated consumer devices. Our customers are global and we currently ship millions of units per quarter all over the world. We focus on providing best in class performance for consumer platforms (availability, accuracy, power, size) at a cost effective price.

Which signal environments are important for your products: open sky, indoor, urban canyon, etc.?

Kawazoe – It is an urban canyon environment.

Kohli / Turetzky – There is not a single most important environment, our products are designed to operate across all environments. The biggest challenge for us and our “claim to fame” is our ability to make GPS work in obstructed environments. The consumer expectation is that location is always available and meeting this expectation is the focus of our innovations. Our technology is targeted to meet the difficult challenges of the urban canyon, dense foliage, and indoor environments.

Which design parameters are most critical for your products: power, cost, sensitivity, accuracy, time to fix, etc.?

Kawazoe – The most critical design parameter is cost. The...
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band BOC(1,1) signal was 30 centimeters, then the expected
the RMS code tracking error of a channel locked to a narrow
increase in RMS tracking error respectively. For example, if
signal strength would result in a 7 percent and 11 percent
the experts

Jerry E. Knight is a principal engineer and manager of advanced
receiver development at NavCom Technology and was previously vice-
president of engineering at SiRF Technology. He has 25 years experi-
ence in the design and implementation of satellite navigation receiv-
ers and signal processing software. Knight received a B.S. degree
in earth sciences from California State College at Hayward and M.S.
degrees in geosciences and computer sciences from the University of
Arizona.

Sanjai Kohli is a technology officer (CTO) of SiRF Technology Inc. Previously, he was the founder and CTO of Trumpan, which
developed semiconductors for mobile video applications. Previously,
he was a co-founder, president, and CEO of WirelessHome (WH), which
developed a point-to-multipoint system. WH was acquired by Proxim/
Western Multiplex in 2001. At Proxim he was the vice-president/gen-
eral manager for the Multipoint Systems Division, responsible for the
Tsunami and Quick bridge product lines. Prior to WH, Kohli was the
co-founder and president, and vice-president of engineering of STaRTon
Technology. At STaRTon he was responsible for the development of the first two
generations of GPS chips and software, including Sirfstar II. Prior to
SiRF, he founded Software Technology & Systems (STS) that devel-
oped smart munitions and spread spectrum technology, serving as its
president and CEO. Kohli holds a B.S. in engineering from the Indian
Institute of Technology—Bombay and an M.S. in system science from
Washington University, St. Louis, Missouri, USA. He has more than 20
published papers and 20 issued patents.

Rioch Keegan is an independent GPS consultant specializing in
receiver architecture and signal processing, including consumer and
embedded GPS. He has been involved in radiolocation receiver
development for more than 30 years, including over 20 years of GPS
commercial receiver development. Prior to becoming a consultant
Keegan was the director of engineering at Magnavox Commercial GPS
technology director for Leica GPS. He holds numerous GPS-related
patents including receiver architectures, multipath mitigation, and
semi-codeless tracking of L2.

The Experts

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satellites without MBOC signals are launched, it will be a
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Kohli/Turetzky
and compact design of GPS receivers.

Kawazo – We expect 12.1 percent and 18.2 percent power
loss will not cause any serious problems. However, we would
like BOC(1,1) to be adopted rather than MBOC for simple and
compact design of GPS receivers.

Keegan – Signal level is sensitivity, and sensitivity is a signifi-
cant part of consumer GPS. So, I believe that this 0.6 dB (or
0.9 dB) is more of an issue with consumer sets than high pre-
cision sets. However, in current consumer applications there
are many places where architectural improvements would
increase the signal-to-noise ratio (SNR) by more than these
amounts, such as better antenna technology, more optimum
signal sampling (sample rate and quantization), closed loop
processing, etc. However, every dB is important.

Kohli/Turetzky – In general, we fight for every tenth of a dB
in every aspect of our system design. Giving up 1 dB in trans-
mitt signal power is a concession, but will be mitigated by
other processing gains. One dB will translate into additional
penetration in a building. This can make a measurable differ-
ence in availability at the consumer level.

Stratton – It is not directly a disadvantage. We will produce
receivers that utilize every waveform that adds value to our
markets. The key factor for us is whether our users would
achieve operational benefits by using modernized signals, and
we do not perceive a difference in user benefit between
these two alternatives.

Studenoy – We develop wideband receivers and maximize
performance as required. We would use all available signals
in the most effective manner possible.

Weir – With today’s technology, a narrowband design is
required in applications where the receiver must have low
cost and low power consumption. If it must also be capable of
operating in poor signal environments, the provider of such
receiver is likely to believe that every decibel counts and
therefore be in favor of a BOC(1,1) signal with its lower RMS
bandwidth making all of the signal power useable. On the
other hand, I would argue that it will probably take a decade
to make MBOC signals available, and in that time improved
technology is likely to make low-cost, high bandwidth receiv-
ers a reality. One must also take into consideration that if
satellites without MBOC signals are launched, it would be
a long time until the next opportunity to improve signal char-
acteristics.

signal strength would result in a 7 percent and 11 percent
increase in RMS tracking error respectively. For example, if
the RMS code tracking error of a channel locked to a narrow-
band BOC(1,1) signal was 30 centimeters, then the expected
tracking errors of the same hardware locked to the respective
MBOC signals would increase to 32.1 and 33.3 centimeters
assuming all other variables remained the same. We do
not see this as being a significant disadvantage. The lower
signal level will also slightly extend satellite acquisition
times and time to first fix.

Garin – The disadvantage will be minor, at this level, as
the fading effects are much more important than the
absolute signal power. On the other side, the advantage
will be immaterial for our current market. Nevertheless,
we support the introduction of MBOC, as the theoretical
penalty is minor, and the practical one will be insignifi-
cant.

 hatch/knight – It is not likely that our company will build
a narrowband receiver.

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If your receivers predominantly are narrowband now, do you believe your customers would benefit from wider bandwidth receivers with better multipath mitigation capabilities? Why or why not?

FENTON – The customers of our narrowband receivers would benefit from multipath mitigation capabilities. However the priority of these customers is cost rather than accuracy. It is more important for them to have a lower unit cost than advanced multipath mitigation technologies. However due to Moore’s law, by the time these signals are available, the cost of adding the increased signal processing to achieve better multipath mitigation may be tolerable.

GARIN – Our today’s typical user will marginally benefit from the widening of bandwidth, when it will be technically and commercially feasible, mainly in line of sight conditions, that still represents a non negligible percentage of the conditions.

KAWADE – Our customers wouldn’t benefit from wider bandwidth because multipath error is reduced with dead reckoning sensors, and the largest position errors occur when only non-direct signals are received, such as in areas with tall buildings.

KEEGAN – The main drivers for Consumer (or narrowband) receivers are cost and power and not accuracy in all but the most demanding environments such as indoors or in urban canyons, in which case improved performance is a desire as long as it does not grossly impact cost or power. However, a multipath environment that could be mitigated by a wideband receiver using conventional multipath mitigation techniques is not the environment experienced indoors or in urban canyons since the signal being tracked is typically a non-line-of-sight multipath signal and not a direct path signal contaminated with multipath. I believe it is unlikely these consumer products will significantly benefit from conventional multipath mitigation techniques employing a wider bandwidth design.

KOHL/TURETZKY – Most of our receiver are narrowband today and we have far more requests for narrower bandwidth than wider. The multipath benefit is outweighed by the susceptibility to interference in most consumer markets.

SHEYNBLAT/ROWITCH – Given that the current performance capabilities of GPS technology meet the needs of consumers and business users worldwide, cost reduction is the remaining critical element needed to achieve wider utilization of GPS and Galileo in the future. This view is shared by most mass-market product manufacturers in the location industry.

WEILL – I believe that customers will undoubtedly benefit from wider bandwidth receivers and that receiver manufacturers will provide more of these products in the not-so-distant future. For example, a major application of narrowband receivers is consumer-level high-sensitivity assisted GNSS handheld receivers, often embedded in a cell phone. Using current technology, these receivers are narrowband in order to reduce cost and power consumption, but this exacerbates multipath errors, which cannot be reduced by differential corrections available in many assisted systems. Compounding the problem is the severe multipath often encountered in urban canyons. Going to a wider bandwidth can significantly reduce these errors, especially in conjunction with newer multipath mitigation technology.
If your receivers predominantly are narrowband now, do you believe your designs will migrate toward wideband receivers in the next 10 to 15 years? Why or why not?

**FENTON** – What’s limiting the choice of processing bandwidth is unit cost and power consumption. Generally, wideband receivers have more complicated ASIC designs with higher gate counts as compared with narrowband designs. The use of these large and more expensive ASIC components along with larger CPU’s required for the multipath processing results in higher unit receiver costs to our customers. Moore’s law may reduce the cost of signal processing to an insignificant amount before these signals are available or during the lifetime of these signals. Larger bandwidths require higher sampling rates and clock rates to the digital sections. These higher rates result in higher power consumption of the receivers. If the customer’s top priority is low power consumption then this will limit the widening of the bandwidth. Traditionally, each generation of electronic components have become more power efficient, so processing wider bands in the future may not increase the power demands beyond tolerable limits.

**GARIN** – Our designs will increase the IF effective bandwidth, first for more accurate measurements, and possibly to accommodate Carrier Phase for the mass market in the next 3-5 years.

**HATCH/KNIGHT** – Future high performance GNSS receivers will trend toward wider bandwidths. Performance of advanced code and phase multipath mitigation techniques is limited by the composite bandwidth of the satellite and receiver filterings. Receiver bandwidth in most existing receivers truncates a portion of the satellite signal spectrum and thereby reduces the effectiveness of advanced code and carrier multipath mitigation techniques.

**KAWAZOE** – There is a possibility to migrate toward a wideband receiver, but the cost reduction and the jamming robustness are the main requirements from our customer, so we suppose that low cost narrowband receivers will continue to be dominant.

**KEEGAN** – One must believe that in 10-15 years the vast majority of consumer GPS receivers will be embedded in mobile handsets. In this environment I don’t believe wideband receivers (as defined here as capable of tracking the BOC(6,1) component) will improve the performance sufficiently to warrant its migration to this market. Other technical drivers would have to change first; such as much better antenna technology that does not impact cost and/or force the user to orient the device much better to line-of-sight conditions (filtering) technology. Unless these change, wideband receivers that only offer 1dB of improved sensitivity will not compete with the lower power and cost of narrowband receivers. Unless these also improve, wideband receivers that only offer less than 1dB of SNR improvement will not compete with the lower power and cost of narrowband receivers. I don’t see a benefit that will cause them to migrate to something that is inherently more costly and consumes more power.

**KOHUI/TURETZKY** – It makes economic sense to develop a wideband receiver in the future, we would do so. However, in our current markets today, we do not see that migration.

**WEILL** – I have little doubt that competitive forces for better positioning accuracy combined with enabling technology will result in a trend toward low-cost high bandwidth receivers for most applications, even those which currently use narrowband receivers.

If your receivers now or in the future are wideband, do you now or would you in the future likely use a form of “double delta” multipath mitigation?

**FENTON** – Possibly. The advanced multipath processing technique that enhances the advantage of the MBOC waveform requires increased software processing demands and is more burdensome to the host CPU. It is envisioned that we would offer a modified Double-Delta style tracking technique for those customers who do not wish to burden their CPU with increased processing requirements. However, due to Moore’s law, by the time these signals become available, the cost of processing the algorithms may not be an issue.

**GARIN** – If the bandwidth was suitable and the patents had expired, we would use some form of double-delta correlator as an add-on but not as the main mitigation technique. We believe that double-delta will be superseded by methods pertaining to estimation theory rather than reference or received signal shaping. There is a misconception that carrier tracking performance won’t be different between C/A code, BOC and MBOC. It is probably true for traditional carrier phase tracking techniques. I would like to emphasize that several Carrier Phase “offset tracking” techniques can capture part of the code multipath performance into carrier phase performance, and will benefit as well from better code multipath performance.

**HATCH/KNIGHT** – Some future multipath mitigation techniques will combine edge differencing techniques like “double delta” with advanced mitigation techniques.

**KAWAZOE** – We would like to use a new method for multipath mitigation, if we are able to invent it.

**KEEGAN** – Double Delta type correlators can help any receiver mitigate multipath contamination and would be a good improvement even for narrowband receivers that actually (closed loop) track the signal. Many of the current consumer receivers do not track very low level signals but make open loop measurements of range in these environments, in which case double delta type correlators really have minimal benefit since there is limited control of the actual “sampling point” of the received signal. Other than intellectual property (IP) issues, there is nothing right now to stop narrowband receivers from benefiting from the Double-Delta type correlators… though the benefit is not as great for a narrowband as compared to a wideband receiver.

Obviously, high precision survey type receivers will employ any and all available multipath mitigation techniques, with IP issues being the limit.

**KOHUI/TURETZKY** – SRF has a number of patented multipath techniques that we would leverage to take advantage of any new signal structure.

**STADTEN** – Our receivers utilize a variety of tracking architectures depending on the specific requirements. Current civil aviation regulations limit the manufacturer’s flexibility to implement multipath mitigation techniques, though “double delta” discriminators are permitted. These limitations are intended to ensure that augmentation systems meet integrity performance under off-nominal conditions (e.g., spacecraft or atmospheric anomalies). The regulations will need to be revisited prior to the certification of receivers using modernized signal waveforms.

**WEILL** – No, Double-Delta techniques have their own limitations and problems. Other techniques exist that are superior to Double-Delta. Vision is one example. We are working on in-house signal processing, but we are not ready for disclosure.

**WEILL** – Double delta may be a reasonable choice for low-cost, narrow bandwidth applications using current technology. If your receivers now or in the future are wideband, do you now or would you in the future likely use a more modern form of multipath mitigation (e.g., Multipath Mitigation Technology (MMT) by Larry Weill, as used by NovAtel in their Vision Correlator)?

**FENTON** – Yes, NovAtel intends to use a modified MMT algorithm specifically designed to take full advantage of the MBOC signal structure and to provide our customers both code and carrier tracking performance at near theoretically maximum performance achievable. NovAtel has exclusive use and sublicensing rights to MMT for commercial GNSS applications and intends to look at sub-licensing opportunities for its Vision technology.

**GARIN** – MMT and Vision have their respective merits in their own market segments, but definitely not in ours, and not in an hypothetical high accuracy mass market. Other generations of MP mitigation techniques are under study and will probably obsolete the current MP methods. I feel it would be short-sighted to try to evaluate today what will be the impact of MBOC on Multipath, looking only at the impact it will have on the methods published as of now. A narrower correlation peak is also of interest in carrier phase multipath mitigation.

**HATCH/KNIGHT** – We will deploy a more modern form of both code and phase multipath mitigation and, of course, will attempt to patent it as we get it out.

**KAWAZOE** – We would like to use new multipath mitigation, if we will be able to invent one which does not conflict with all multipath mitigation methods patented before.
If your receivers now or in the future are wideband, what are the implications of licensing arrangements where there is competition for positioning accuracy? I would like to offer some thoughts on the matter.

The MBOC signal structure is between 2 and 3.5 times larger than the BOC(1,1) signal (or the L1 C/A signal). If the RMS error of a channel tracking the BOC(1,1) signal was 30 centimeters, then switching to an MBOC would result in reducing the RMS error to between 23 centimeters and 21 centimeters, depending on the exact MBOC code chosen (a factor of between 21 percent and 33 percent improvement).

Wideband multipath mitigation technologies also benefit from an effective increase in code tracking signal to noise ratio. These algorithms will be able to detect the presence of multipath sooner with increased signal gain and be able to provide more precise range and phase measurements in the presence of closer-in multipath interference as compared with BOC(1,1).

The wider bandwidth will benefit this incoming accurate mass market.

The real world benefit would be a reduced multipath effect, and we would expect better accuracy in urban canyons. Under poor signal conditions we would not expect high sensitivity or high cross-correlation through MBOC.

As mentioned in the MBOC signal structure should improve the performance of all wideband receivers tracking the MBOC signal that employ these modern multipath mitigation techniques. The more difficult the multipath is to observe (e.g. with very short delays) the more the additional code transitions will help.

For our customers, we would expect some very limited benefit in accuracy under a very narrow set of conditions. When we talk about poor signal conditions, we are talking about -160 dBm and lower.

Accuracy will be better under ideal conditions, but we have not seen validation of the theoretical benefit under realistic conditions. The impact of off-nominal conditions on accuracy, particularly differential GNSS (augmentation system) may be seen.

Impact of atmospheric propagation effects that distort split-spectrum signals, which may impact MBOC differently than BOC(1,1) or C/A.

The edge power provided by the MBOC signal structure is meaningful for a very small fraction of the time and cannot be attained without a redesign of the code generator in our receivers. This will necessitate replacement of all the receivers in our customer base. We do not think the perceived benefits of MBOC are worth the cost.

The extra edge power provided by the MBOC signal structure is meaningful for a very small fraction of the time and cannot be attained without a redesign of the code generator in our receivers. This will necessitate replacement of all the receivers in our customer base. We do not think the perceived benefits of MBOC are worth the cost.
the multipath delay becomes smaller, the ability to distinguish and hence the measure the multipath becomes problematic. More code transitions assist in this case even in high SNR conditions.

STRAUTON – Civil aviation receivers must pass specific test criteria under standard interference conditions to provide a margin for the user and for interference. The ability to maintain carrier track is far more important to accuracy than raw code phase quality in these scenarios. The receiver’s ability to demodulate data in these scenarios is also more critical, since navigation data senescence is a requirement to use the augmentation system. The military user may benefit indirectly from a more jam resistant acquisition signal in cold-start cases; however, the power level devoted to the data channel is all that matters in these cases.

STUDENNY – In Commercial Aviation, the concern is the integrity in applications supporting all phases of flight including CAT-III/III precision approach. As we approach CAT-III precision approach, the bounding probability for a very small position-fix error in the vertical direction and horizontal plane has to be very large (in excess of 99.99999%). Any benefit that the signal-in-space can provide to meet those kinds of requirements is welcome. To answer the question directly, please note that there are various task forces at RTCA, EUROCAE, ICAO, and elsewhere, that are attempting to precisely quantify the various error allocations due to the signal in space, the aviation receiver, the proposed augmentation system, and the aircraft and crew, for all phases of flight, and for precision approach in particular. Please refer to these task forces for more details.

WELL – The receiver bandwidth of an MBOC signal will generally improve MMT multipath performance by the same amount relative to BOC(1,1) under all conditions. Even with a relatively weak direct path signal component, MMT can be effective if the application permits extending the observation time of the signal. This is because its performance in reducing multipath error improves proportionately with increases in the ratio of signal energy to noise power spectral density, or E/N0. (This is not the case for double-delta mitigation.) For example, if the direct path CN0 is 15 dB-Hz (a very weak signal), 10 seconds of signal observation gives an E/N0 of 25 dB-Hz·sec, which is useable by MMT. In some applications 100 seconds of signal observation can bring E/N0 to 35 dB-Hz·sec to give even better performance. Consequently, MMT multipath mitigation can be effective in many cases when the direct path signal is attenuated by foliage or passes through walls. (Note that extended signal observation times with MMT are appropriate only for static applications.) Urban canyons present a more difficult problem if there is total blockage of the direct path component, but then it is unlikely that any method of receiver-based multipath mitigation will work. On the other hand, the future availability of many more satellites could provide enough unblocked direct path signals to obtain positioning enhanced by good multipath mitigation.

As you know, the statistics of real-world multipath are difficult to assess. Based on our real-world experience, how important is effective multipath mitigation to the GNSS community, and specifically in what applications? How important is it to your company?

FENTON – Having good multipath mitigation technology benefits almost all applications. Very few applications have “ideal” antenna locations providing multipath free signals. Most real-world applications suffer from some amounts of multipath. The amount of benefit that the user sees from this technology is inversely proportional to the quality of the RF signal received.

GARIN – Multipath is in my opinion the “last frontier” in the pursuit of better navigation and positioning performance for the GNSS community at large. Building monitoring and surveying will be the principal beneficiaries. For the cell phone and personal navigation device we deeply do care about. For navigation data at sufficient power. During the development of the civil augmentation systems, multipath was seen as a significant issue, but methods were developed to mitigate multipath that were within the reach of current technology. For example, the GNSS signal has a carrier smoothing (i.e., complementary filter) that takes advantage of the high advantage of the L1 carrier phase) to mitigate multipath sufficiently to conduct CAT III landings if the augmentation system is located at or near the airport. In looking at new approaches to this technology, we see no degradation in accuracy as the airplane approaches the runway environment. This is expected because of the frequency separation of the multipath resulting from the airplane’s motion.

STUDENNY – Multipath is an issue, especially for GRAS ground stations. It has to be minimized by whatever techniques are available. A signal with desirable code properties is a great starting point to minimizing multipath effects. The corner example is the L1 C/A code – it has poor multipath rejection properties and requires specialized signal processing to mitigate some of the multipath effects.

WELL – Effective multipath mitigation has always been regarded as important in high-precision applications, where in some cases fixed integer ambiguity estimators. Not only does Multipath Mitigation Technology (MMT) provide cleaner measurement solutions with large errors. Mitigation of this type of multipath is more important for consumer chipsets than the mitigation of multipath-contaminated direct path signals, but I don’t expect MBOC to help with this problem.

KOHLI/TURETSKY – Multipath mitigation can be a clear differentiator in accuracy and our focus is getting the best possible accuracy in obstructed environments, given the constraints of cost, size, and TTFP for consumer applications. Our customers care about “consumer affordable” meter level accuracy to determine streets and house numbers not centimeter level accuracy.

STRAUTON – Having greater multipath resistance is secondary in importance to having a robust and available signal with navigation data at sufficient power. During the development of the civil augmentation systems, multipath was seen as a significant issue, but methods were developed to mitigate multipath that were within the reach of current technology. For example, the GNSS signal has a carrier smoothing (i.e., complementary filter) that takes advantage of the high advantage of the L1 carrier phase) to mitigate multipath sufficiently to conduct CAT III landings if the augmentation system is located at or near the airport. In looking at new approaches to this technology, we see no degradation in accuracy as the airplane approaches the runway environment. This is expected because of the frequency separation of the multipath resulting from the airplane’s motion.

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The wider bandwidth of an MBOC signal will generally improve MMT multipath performance by the same amount relative to BOC(1,1) under all conditions. Even with a relatively weak direct path signal component, MMT can be effective if the application permits extending the observation time of the signal. This is because its performance in reducing multipath error improves proportionately with increases in the ratio of signal energy to noise power spectral density, or E/N0. (This is not the case for double-delta mitigation.) For example, if the direct path CN0 is 15 dB-Hz (a very weak signal), 10 seconds of signal observation gives an E/N0 of 25 dB-Hz·sec, which is useable by MMT. In some applications 100 seconds of signal observation can bring E/N0 to 35 dB-Hz·sec to give even better performance. Consequently, MMT multipath mitigation can be effective in many cases when the direct path signal is attenuated by foliage or passes through walls. (Note that extended signal observation times with MMT are appropriate only for static applications.) Urban canyons present a more difficult problem if there is total blockage of the direct path component, but then it is unlikely that any method of receiver-based multipath mitigation will work. On the other hand, the future availability of many more satellites could provide enough unblocked direct path signals to obtain positioning enhanced by good multipath mitigation.

As you know, the statistics of real-world multipath are difficult to assess. Based on our real-world experience, how important is effective multipath mitigation to the GNSS community, and specifically in what applications? How important is it to your company?

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cost high precision GNSS sets, but I doubt that they will ever be part of consumer chipsets since they only provide mitigation of multipath that accounts for a few meters of phase error in relatively static situations.

**Kohl/Turetzky** – For our markets, near multipath is not the biggest source of error at the signal levels our customers are most interested in. Therefore, the multipath mitigation techniques we would use to protect today’s chipsets would become more significant in the future if GNSS is used in air-port surface applications (i.e., when the airplane is moving slowly), but this requires further study and validation. On the other hand, a more complex signal structure may be more slowly, but this requires further study and validation. On the other hand, a more complex signal structure may be more difficult to certify for safety-critical uses. It is not yet clear whether the certification risks associated with migrating to modernized signals will outweigh their potential benefits.

This is analogous to the situation that exists today, with low-tech (but proven) instrument landing systems still being installed despite the availability of GNSS landing systems, which are dramatically more accurate from the pilot’s perspective.

**Studenny** – The preference is NOT to use unusual or complicated receiver technologies. It is also true that a well designed signal will not require such unusual technologies to reach the required performance levels. A well-designed, wide-band signal allows for simple receiver architectures and designs that achieve very high levels of performance. We believe that having an indigenous GNSS receiver technology is not only applicable to the highest precision sets. As processing becomes cheaper and higher sampling rates become the norm, this type of multipath mitigation will migrate to lower

cost high precision GNSS sets, but I doubt that they will ever be part of consumer chipsets since they only provide mitigation of multipath that accounts for a few meters of phase error in relatively static situations.

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**Civil GNSS Signals at a Crossroads: An Afterword**

In an effort to close the loop between receiver designers and signal experts, we invited additional comments on the discussion presented in the two-part article, “BOC or MBOC?”

We received responses from several U.S. members of the US/ European technical working group that recommended the multiplexed binary offset carrier waveform for the new GPS and Galileo civil signals. (They also were coauthors on the original Working Papers column that introduced the signal proposal in Inside GNSS’s May/June issue.) Javad Ashjaee, president and CEO of Javad, provided a commentary of the original Working Group A (WG A) Recommendations on L1 OS/L1C Optimization, which can be viewed at the GPS and Galileo signal specification websites, respectively <gps>gpsj.org</gps> and <Galileo>http://www.galileoju.com/page3.cfm</Galileo>. Our focus here is on the GPS L1C signal.

Javad Ashjaee, president and CEO of Javad, provided a commentary of the original Working Group A (WG A) Recommendations on L1 OS/L1C Optimization, which can be viewed at the GPS and Galileo signal specification websites, respectively. This response is meant to provide additional information that complements the views presented in the introduction to the article and to explain the background of the L1C process. This process conforms to the general recommendation in the May/June issue of Inside GNSS, the Galileo program has the lead in choosing a common signal modulation that will be used for decades by not only Galileo, but also GPS, QZSS, and possibly satellite-based augmentation systems, and other radio navigation receivers. We understand Galileo decision makers’ need to balance near-term programmatic issues against the longer-term investment in improved satellite-based navigation, and respect their decision process.

In conclusion, we sincerely welcome receiver manufacturers’ views on both BOC and MBOC. The challenge for all of us — signal designers, receiver designers and manufacturers, and decision makers — is to make this decision in the context of applications and receiver technologies that will be relevant later in the next decade and for decades to follow.

We believe the engineering tradeoffs reaffirm that TMBOC, like other aspects of L1C, will provide solid net benefits to future generations of satellite navigation users.

**MBOC is the Future of GNSS; Let’s Build It**

**Additional Comments on MBOC and BOC(1,1)**

**John W. Betz, Christopher J. Hegarty, Joseph J. Rushanan**

**The MITRE Corporation**

As members of the United States team who worked with our European colleagues to design the MBOC spread-spectrum signals, we respectfully offer the following comments on the article entitled “BOC or MBOC? Part 1,” published in the July/August issue of Inside GNSS.

**BOC or MBOC?**

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**MBOC is the Future of GNSS; Let’s Build It**

**Javad Ashjaee**

**JAVAD NAVIGATION SYSTEMS**

If I can say is, I’m glad these guys complaining about MBOC weren’t the ones designing the GPS system — or the new common GPS/Galileo civil signal. What is their basic complaint about MBOC? That it adds complexity and power consumption. But 25 years ago, GPS user equipment weighed 150 pounds and a receiver cost $250,000. If they had based the system design on the state-of-the-art receiver at the time and tried to simplify the system design to accommodate them, they would have said, “We don’t need carrier phase or a second frequency.” They would have been thinking about receivers as if they were carrying an FM radio from those days around in their pocket.

But technology changes. Product design improves. How old is Moore’s Law? Does it apply to the complexity of integrated circuits, with respect to minimum component cost, doubles every 18 months, and yet it’s still going on. The same thing is repeating itself today.

In the early 1980s when we were building the first GPS receivers, we only had 8-bit microprocessors. Multiplying two floating point numbers together was a huge task. I had to write software to simplify the computation of the signals as much as possible, but I never complained about the GPS system design itself.

Now the technology has matured to the point that you see today — single-chip GPS receivers. And yet modern user equipment is based on this GPS system design of 30 years ago.

We should design the system and make it as good as we can. By the time it’s up and running, technology will have advanced a long way in the products that we are building.

Even with the current technology, however, what do the people who don’t want MBOC lose? One decibel. But the new satellites have 3 dB more than we have today.

On the other hand, what do we gain with MBOC? Maybe a little, maybe a lot, depending on who looks at it. MBOC gives us more things to work with. It may help us to get faster RTK by removing multipath in the automatic landing of an aircraft. The people worried about getting GPS signals further indoors are talking about users who may be sitting around drinking wine, not sitting in an airplane that’s landing in the fog. Even if there is an emergency indoor application, it most probably can wait a few more seconds to get a position fix or have a few more meters of error.

The chips that will be designed to fully use this new GNSS system will come 10 years from now. It’s a crime to say that we can’t build the best system for the future because today somebody needs an extra bit of processing power.

One final note: my hat’s off to a dear, long-time friend, Tom Stansell, for a job well done in helping coordinate the BOC-MBOC discussion in Inside GNSS in such an unabashed even-handed way.

**Javad Ashjaee, Ph.D., is President and CEO of Javad Navigation Systems, San Jose, California, USA, and Moscow, Russia.**