GPS Modernization and GNSS Handout

Slide 1	GPS, put in place with amazing speed considering the technological hurdles, is now critical to all sorts of positioning, navigation and timing around the world. It's that very criticality that requires the modernization. The oldest operational satellites in the current constellation were launched in 1997. It is not surprising that there are plans in place to alter the system substantially. What might be unexpected is many of those plans will be implemented entirely outside of the GPS system itself. GNSS, the Global Navigation Satellite System is here. New capabilities are available. Today there may be more than 30 navigational satellites above your horizon.
Slide 2	The GPS system is one component of the worldwide effort known as the Global Navigation Satellite System (GNSS).
Slide 3	Another component of is the Galileo system administered by the EU.
Slide 4	A third is the GLONASS system of the Russian Federation. There is one more global system.
Slide 5	The Chinese BeiDou Satellite Navigation and Positioning System and there are regional systems
Slide 6	The Japanese Quasi-Zenith Satellite System (QZSS)
Slide 7	The Indian Regional Navigation Satellite System (NAVIC) aka (IRNSS).
Slide 8	There are also ground-based real-time augmentation systems (GBAS) and space-based augmentation systems (SBAS) deployed by the United States, Europe, Japan, China. The US WAAS, the European Geostationary Navigation Overlay Service (EGNOS), the Japanese Multi-functional Satellite Augmentation System (MSAS); India's GPS And Geo-Augmented Navigation (GAGAN) system and Russia's System for Differential Corrections and Monitoring (SDCM). Several more are in development.

Slide 9	One effect of GNSS is the substantial growth of the available constellation of satellites, the more signals that are available for positioning and navigation, the bet-ter. Just considering the global systems, GPS has 30 operational satellites, GLONASS adds 22, GALILEO adds 22 and Beidou adds 44. There are 118 global satellites available now. Considerably more than we had in the early days.
Slide 10	The objectives of this cooperation are interoperability and compatibility. Compatibility refers to the ability of U.S. and foreign space-based positioning, navigation, and timing services to be used separately or together without interfering with use of each individual service or signal.
Slide 11	One example of the scope of this increased horizon in global positioning is illustrated by the name change of the International GPS Service to the International GNSS service, IGS. It is a federation of 200 worldwide agencies that generate information on the GPS & GLONASS systems.
Slide 12	Looking at GPS Modernization
Slide 13	The oldest satellite in the current constellation was launched in the 1997. If you imagine using a personal computer of that vintage today, it is not surprising that the system is consistently updated.
Slide 14	Let’s start with Block I.
Slide 15	Block I demonstrated the viability of GPS by broadcasting the codes on L1 and L2. The C/A civilian code on L1 and the P code on L2 similar to today, but some things have changed.

Slide 16	For example, the orbital inclination of these satellites relative to the equator was 63° back then instead of the inclination of 55° which has been used in all the subsequent blocks.
Slide 17	The Block I satellites were powered by 7 1/4 square meters of solar panels and they also had three rechargeable nicad batteries. They had a design life of 4 1/2 years. Some operated for double that, but none are on orbit today
Slide 18	The Block I satellites needed frequent help from the Control Segment. They could operate independently for only 3 1/2 days, and in the early days there were fewer monitoring stations around the world.
Slide 19	Today there are 6 Air Force and the 11 National Geospatial-Intelligence Agency (NGA) monitoring stations and there have been other improvements in the Control Segment.
Slide 20	Every GPS satellite is now tracked by at least 3 of these monitoring stations all the time. They collect range measurements, atmospheric information, satellite's orbital information, clock errors, velocity, right ascension, and declination along with pseudorange and carrier phase data.
Slide 21	These data are sent to the Master Control Station (MCS) where problem diagnosis and solution are more reliable now due to the redundant observations of satellite anomalies. The Master Control Station needs this constant flow of information because it provides the basis for the computation of the almanacs, clock corrections, ephemerides, and other components that make up the Navigation message.
Slide 22	Once the message is calculated, it needs to be sent back up to the satellites from through the ground antennas at the four stations collocated with them.

Slide 23	The new stations also improve the geographical diversity of the Control Segment, and that helps with the MCS isolation of errors, like separating clock error from ephemeris errors. A hard thing to do in the past but now testing shows the improved modeling of the augmented clock corrections and ephemerides in the Navigation message contribute to an increase in the accuracy of autonomous GPS of 15% or more.
Slide 24	Another modernization program is coming. The Operational Control System (OCX) will facilitate the new GPS signals like L5, L2C, L1C and the continuing GPS III program.
Slide 25	Those are some of the improvements since Block I. However, there are features of the Block were carried over into future GPS Blocks, like satellites exceeding their design life, onboard nuclear detonation detection sensors and atomic frequency standards – also known as clocks.
Slide 26	It was clear from the beginning that GPS would only work as required if atomic clocks, were onboard, a tall order. The first 3 Block I satellites carried 3 rubidium clocks. Unfortunately, they stopped working after about a year in space.
Slide 27	Equipment was added to keep the frequency standards at a constant temperature during flight and a cesium frequency standard was added to subsequent satellites in this block. One of the largest errors in GPS can be attributed to the satellite clock bias
Slide 28	The onboard satellite clocks are independent of one another. The rates of these oscillators are more stable if they are not disturbed by frequent tweaking and adjustment is kept to a minimum.
Slide	Block II was next. There were some improvements.

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Slide 30	The uploads to the Block II satellites from the Control Segment were encrypted. That was new. They could be without contact with the Control Segment for up to 14 days. First launched in 1989 they weighed twice as much as the Block ones and often exceeded their 7.3 design life. One of them operated for 17 years and was taken out of service in 2007. None of the Block II satellites are in the constellation today.
Slide 31	Moving right along. Block IIA
Slide 32	19 Block IIA satellites were launched between 1990 and 1997
Slide 33	These satellites could operate without contact with the Control Segment for 6 months.
Slide 34	GPS satellites are stabilized by reaction wheels. There are usually 3 zero momentum wheels aligned to the X, Y and Z axes – with a 4^{th} at an odd angle for redundancy. Their good points include precision control and no consumables. Their bad points include added mass, gyroscopic effect and the fact that left alone they would accelerate continuously until they were useless so the excess momentum is periodically dumped on instructions from the Control Segment.
Slide 35	Selective Availability (SA) was included in both Block II and Block IIAs.
Slide 36	The signals from the Block II/IIA and IIR satellites were intentionally degraded periodically. Selective availability was implemented on the C/A code by disrupting the satellite clock frequency from time to time starting in April of 1990. Surveyors using methods that relied on the carrier phase observable were not significantly affected by Selective Availability, but code measurements were. It was ended Tuesday, May 2, 2000 at 4:00 UTC.

Slide 37	Two Block IIA satellites were equipped with Laser Retro-reflector Arrays (LRA). The retro-reflectors facilitated satellite laser ranging (SLR) and provided a valuable independent validation of the satellite's orbit.
Slide 38	Block IIAs were expected to have a design life of 7.3 years which they exceeded, but none of the Block IIA's are operational today.
Slide 39	9 Block IIR satellites are operational though.
Slide 40	The first launch of the Block IIR satellites in 1997 was unsuccessful, but the next one succeeded.
Slide 41	Block IIR satellites can determine their own position using inter-satellite crosslink ranging, called AutoNav.
Slide 42	AutoNav means autonomous navigation and it involves use of reprogrammable proces-sors onboard to do autonomous fixes in flight. They can operate in that mode for up to 6 months and still maintain full accuracy. The Control Segment can also change their software while the satellites are in flight.
Slide 43	With a 60-day notice they can move them into a new orbit
Slide 44	Some of the Block IIR satellites also have an improved antenna panel that provides more signal power. Despite their differences Block IIA and the Block IIR satellites are very much the same in some ways. For example, the carriers they broadcast.

Slide 45	The GPS satellites still broadcast the same fundamental legacy GPS signals on L1 and L2 as they have since the beginning – now joined by a new L5 carrier - but what about the codes on those carriers?
Slide 46	They are modulated onto their carriers by a method that was originally developed by the military during World War II - CDMA, Code Division Multiple Access.
Slide 47	First let's see how the zeroes and ones of the military P(Y) binary pseudorandom noise code get onto the L1 carrier. See the blue carrier? It's the rather pointy sine wave here. Watch for the moments when the value of the code chips change from 0 to 1, or from 1 to 0. See, when that switch is needed there is an instantaneous reverse of the phase of the carrier wave at the black centerline in the middle, that's the zero-crossing. It flips180º. Well, except when the number stays 1 or 0 and does not switch then there is no change in phase of the carrier. Like there where it stayed on the 1 for two chips. See the red square wave at the bottom? It just showed two zeroes there. The code chips are created every microsecond. This is a rate of 10.23 MHz **.** The GPS fundamental clock rate. F_0 This whole method is called binary phase shift keying (BPSK).
Slide 48	Now, let's look at the civilian C/A code. Again switching from 0 to 1 and from 1 to 0 is accomplished by phase changes of 180º in the carrier wave, the green line here. In this example the 180º phase flip happens once when the carrier is at the zero-crossing. That is because there is 1 C/A code chip for every 10 P(Y) code chips. This is a rate of 1.023 MHz. That is 1 tenth of the GPS fundamental clock rate. Notice that the black dashed square wave for the C/A code is perpendicular with the red P(Y) code square wave.
Slide 49	Each satellite has its own unique C/A-code. The code has 1023 chips a millisecond before it repeats. The length of its chip is 960 feet. Typically, the very best you can do is

	resolve a chip to ~1% of its length in this case 9.6 ft.
Slide 50	The Precise code or P(Y)-code is encrypted. It is on L1 and L2 has a chipping rate that is ten times faster than the C/A code at 10.23 million chips per second. The P(Y)-code has a code length of about a week, approximately 6 trillion chips, before it repeats. The length of its chip is 96 feet. 1% of that is about a foot.
Slide 51	The transmitted message is recovered by correlating the received signal with the PRN code available at the receiver.
Slide 52	The rate of all of the components of GPS signals are multiples of the standard rate of the oscillators. The fundamental clock rate is 10.23 MHz.
Slide 53	For example, the GPS carriers are L1: 154 times Fo, or 1575.42 MHz, L2: 120 times Fo, or 1227.60 MHZ, and L5: 115 times Fo, or 1176.45 MHZ.
Slide 54	Here is a new feature. Some Block IIR satellites carry Distress Alerting Satellite System (DASS) repeaters. These DASS repeaters are used to relay distress signals from emergency beacons to the search and rescue satellites to a local user terminal to a mission control center to dispatch a rescue vehicle. These repeaters were part of a proof of the concept of satellite-supported search and rescue effort that was completed in 2009.
Slide 55	Block IIR-M
Slide	In the current constellation there are 7 Block IIR-M satellites on orbit and operational. They broadcast two new codes. L2C is a civilian signal on the L2 carrier where there

56	was none before. Making a dual frequency mitigation of the ionospheric delay using codes possible. The other is the new military code, the M code. Also note that anti-jam flex power was introduced. Maybe this is a good time to talk a bit about how to think about signal power.
Slide 57	First, please note that a change in 3 decibel Watts is an increase or a decrease of 100% in power.
Slide 58	That means that a 3 decibel decrease indicates a halving of the signal strength, but A 3 decibel increase is a doubling of the signal strength.
Slide 59	So, a signal of -163 dBW has half the power of a signal of -160dBW and a signal of -157 dBW has double the power of a signal of -160dBW.
Slide 60	The minimum power received from the P(Y) code on L1 by a GPS receiver is about -163 dBW and the minimum power received from the C/A code on L1 is about -160dBW. Makes sense because they are transmitted 3 decibel Watts apart at the start of their trip to Earth. The P(Y) code on L1 leaves the satellite at +23.8 dBW (240 W) and the C/A code on L1 leaves at +26.8 dBW (479 W). So, the difference between the power of the transmitted GPS signal and the received signal is 186 to 187 dB.
Slide 61	There is an atmospheric loss and a polarization mismatch loss, but the biggest loss by far happens in the approximately 20,000 km between the satellite and the receiver
Slide 62	Then there is also the spreading of the GPS signal in space as described by the inverse square law.

Slide 63	The intensity of the GPS signal varies inversely to the square of the distance from the satellite. By the time the signal makes that trip and reaches the GPS receiver it's pretty weak and is easily degraded by vegetation canopy, urban canyons and other interference.
Slide 64	Speaking of power there are several new signals available to you now. So, I'd like to introduce a diagram that is useful in illustrating how the new signals differ from each other and from legacy C/A and P(Y). The Power Spectral Density Diagram helps in understanding signal differences.
Slide 65	I'll start with those familiar codes the C/A and P(Y). This PSD diagram helps illustrate these two signal's powers per bandwidth.
Slide 66	In GPS and GNSS literature the PSD diagram is often represented with the frequency in MHz on the horizontal axis with the power represented on both perpendicular axes in dBW/Hz , which is decibels relative to one Hertz per Watt. The C/A code and the P(Y) codes on the L1 signal, are both centered on the frequency 1575.42 MHz and they are spread over approximately 20.46 MHz, 10.23 MHz on each side of the center frequency. The horizontal scale shows the offset in MHz from 1575.42 center frequency. The other scales show the decibels relative to 1 Watt per Hertz (dbW/Hz). Ok, ok, why don't we just express the power of the signals like a light bulb, in just simple Watts? Wouldn't that be easier?
Slide 67	Well, expressing GPS signal power expressed that way would be as one tenth of a millionth billionth of a watt. It's a bit exhausting.
Slide 68	Now there is, of course, it is much more convenient to express the number this way. However, this does not give us a way to express the power of the signal over a particular portion of its bandwidth. That's the really useful information. A step toward that is showing the power in decibel Watts. That can be done with this formula.

Slide 69	Doing the calculation, it shows that the one tenth of a millionth billionth of a Watt is -160 decibel Watts.
Slide 70	Ok, the signal has power -160 dbW. It also has bandwidth. Let's find out how much power there is over just one tenth of the C/A codes 20.46 MHz bandwidth. What is it over just 2.046 MHz of the signal?
Slide 71	Using this formula and presuming that the 10^{-16} W power is evenly distributed. We calculate that using 2.046 MHz, one tenth of the C/A codes bandwidth, you would receive just -223 dbW/Hz It's a good thing it's a spread spectrum signal.
Slide 72	Let's look at the new signal introduced by the Block IIR-M L2C. This is the first of several new signals available to you now. So first I'd like to introduce a diagram that will be useful in illustrating how are the new codes are different from the legacy C/A and P(Y) codes on L1 and L2.
Slide 73	The L2 signal diagram used to look like this. We have been using the L2 carrier centered on 1227.60 MHz since the beginning of GPS of course, but in the past, it only carried one code, the encrypted military P(Y) code.
Slide 74	But things have changed. A new civilian code L2C, first announced back in March of 98, and a new military signal, the M-code.
Slide 75	Here is L2 as it was from the Block II satellites with P(Y) only. Here is L2 carrier as available on Block IIR-M and subsequent blocks with both the M-code and L2C.
Slide	The M code is broadcast on both L1 and L2 and will eventually replace the P(Y) code. There was consideration given to raising the power of the P(Y) code to accomplish the

76	same end, but that strategy was discarded when it was shown to interfere with the C/A code. Then there was another interference concern from an entirely different direction.
Slide 77	In 2001 The U.S. State and Defense departments threatened to cease all satellite navigation cooperation with Europe unless the Galileo's planned Public Regulated Signal (PRS) was moved away from the M-code frequencies. Then Deputy Secretary of Defense Wolfowitz wrote a letter to EU member states who were also in NATO saying-
Slide 78	"I am writing to convey my concerns about security ramifications for future NATO operations if the European Union proceeds with Galileo satellite navigation services that would overlay spectrum of the global positioning system (GPS) military M-code signals." The problem was that unless things changed DoD could not jam Galileo's PRS without jamming their own M-Code reducing the US militaries navigation ability. The European Commission stuck for a time to its preferred modulation option – Binary Offset Carrier, or BOC, 1.5 – rather than the US choice, BOC 1.1
Slide 79	However, on February 25, 2004 the EU executive opted to use the latter for Galileo's free signal and an agreement was signed.
Slide 80	The agreement fixed BOC(1,1) here as the baseline for both Galileo and GPS future OS (Open Service) signals. The EU, meanwhile, was glad that "the Americans agreed to renounce a veto right on the future development of signals. A crucial US concession was that "they cannot decide to jam our system", he added.
Slide 81	Perhaps it would also be useful here to briefly represent implementations of the Binary Offset Carrier as used on both the Galileo PRS and the GPS M code. It differs from the binary phase shift key (BPSK) used with the legacy C/A and P(Y) signals.
Slide 82	The M-code was designed to share the same bands with existing signals, on both L1 and L2, and still be separate from them. See those two peaks in the M-code? They represent a split-spectrum signal about the carrier. This allows minimum overlap with the

	maximum power densities of the P(Y) code and the C/A code, which occur near the center frequency. An important characteristic of BOC modulation is the M-code has its greatest power density at the edges, that is at the nulls, of the L1. This architecture both simplifies implementation at the satel-lites and receivers and also mitigates interference with the existing codes.
Slide 83	So here are some characteristics of the M-code , , , , ,
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Slide 85	Just as a reminder a signal of -158 dBW has double the power of a signal of -161dBW. Also, the M code improves the military anti-jamming efforts through flexible power capability, more about that later.
Slide 86	Since the C/A code is susceptible to waveform distor-tion, narrow-band interference and has marginal cross-correlation properties. L2C is not a copy the C/A code.
Slide 87	It contains two distinct PRN sequences: CM (for Civilian Moderate code) is 10,230 bits in length, repeating every 20 milliseconds. CL (for Civilian Long code) is 767,250 bits, repeating every 1.5 seconds. Each signal is transmitted at 511.5 kHz.
Slide 88	Here is how these two codes are used.
Slide 89	First there is acquisition of the CM code with a frequency locked or Costas loop.

Slide 90	Next there is testing of the 75 possible phases of CL.
Slide 91	Acquisition and tracking of CL is done with a basic phase-locked loop. A good thing because the phase-locked loop improves protection against continuous wave interference. A welcome benefit as L2C's power is actually weaker than C/A by 2.3 dbW, even so the stability of the lock on the long data-less CL is improved by nearly 6 dB. We have a better lock there because the squaring Costas loop used on CM, C/A and P(Y) is not used with CL.
Slide 92	Now these two codes multiplexed together to form a 1.023 Mbps signal.
Slide 93	L2C alter-nates between chips of the CM code and chips of the CL code. Chip-by-chip multiplexing.
Slide 94	In practice this means L2C is easier to keep separate from the background.
Slide 95	OK. Great so what does all that mean in English? GPS positions can be acquired with more certainly and lock maintained more surely in marginal situations
Slide 96	It also means increased stability and improved tracking in obstructed areas like urban canyons because L2C has better tolerance to interference.
Slide 97	It means fewer cycle slips
Slide 98	What else? Well, before L2C we had just one civilian code C/A on L1.

Slide 99	So, there was no way to remove the second largest source of error in a code-phase position, the ionospheric delay.
Slide 100	But with two civilian signals, two on L1 (C/A), L1(L1C) and one on L2 (L2C) it becomes possible to effectively model the ionosphere using code phase
Slide 101	And there's more – a new navigation message called CNAV. Here's a short reminder on the importance of the navigation message receivers acquire from the satellites.
Slide 102	The Legacy navigation message has been a mainstay of GPS since the beginning. It carries information about the location of the GPS satellites called the ephemeris and data used in both time conversions and offsets called clock corrections.
Slide 103	It also communicates the health of the satellites on orbit and information about the ionosphere.
Slide 104	It includes the location of other satellites in the constellation, called almanacs that provide a GPS receiver with enough little snippets of ephemeris information to calculate the coordinates of all the satellites in the constellation with an approximate accuracy of a couple of kilometers
Slide 105	Some aspects of the information included in the NAV message deteriorates with time. In the past when there were only six tracking stations it was possible for a satellite to go unmonitored for up to two hours each day and that translated into the rate of change in the three-dimensional position of a GPS receiver of approximately 4 cm per minute.

Slide 106	But, as mentioned earlier, there is a new network in place and every satellite in the GPS constellation is monitored continuously from at least three stations. The new augmented Control Segment has improved modeling. The accuracy of clock corrections and ephemerides in the Navigation Message are substantially better now.
Slide 107	Remember that the L2C Civilian Moderate code carries data? The message that it carries includes an improved Navigation code called CNAV.
Slide 108	The legacy Navigation message is still around and is known by the acronym NAV. Its Master Frame contains 25 frames, or pages, of data. Each of the 25 frames is 1500 bits long and is divided into five subframes.
Slide 109	Each of the five subframes contains 10 words and each word is comprised of 30 bits. In other words, each of the five subframes has 300 bits and since there are 5 of them in each of the 25 frames the entire NAV message contains 37,500 bits. At a rate of 50 bits-per-second after a cold start it takes 12 1/2 minutes to receive the entire message.
Slide 110	CNAV is more compact than the legacy NAV. A receiver can get first fix faster. CNAV can support 32 satellites using only 75% of its bandwidth with a fraction of its packet types and can grow to accommodate 63 satellites. CNAV is also more flexible. For example, there could be a packet with differential correction data like an SBAS. In fact, there is a packet assigned to the time offset between GPS and GNSS, more about that later. An unhealthy satellite can be flagged, that is just the sort of quick access needed to support safety--of-life applications. CNAV has Forward Error Correction (FEC) capability in which data are sent giving the receiver the ability to detect errors at the single bit level and correct them without the need to have the data retransmitted. There are actually four new NAV messages coming into play; L2-CNAV, CNAV-2, L5-CNAV and one military message, MNAV.
Slide 111	

Slide 112	Now, let’s look at the new carrier L5.
Slide 113	An IIR-M satellite SVN 49 demonstrated L5
Slide 114	It is centered on 1176.45 MHz, 115 times the fundamental clock rate.
Slide 115	Two codes in quadrature like L1. The basic structure of L5 is familiar but it is using Quad Phase Shift Key (QPSK). Note that the in-phase (L5 I) signal carries a complex flexible data message and the other; the quadraphase signal (L5 Q) is data-less. Both have equal power and are multiplexed.
Slide 116	Both parts of L5 have the same chipping rate as the fundamental clock rate. Remember this is the same rate as the restricted P(Y) code. The fast rate means better measurement resolution and improved multipath protection
Slide 117	So L5 only has civilian codes. It is stronger and faster than C/A. , that reduces interference. Its bandwidth is about 20 MHz, a processing gain, and it incorporates Forward Error Correction (FEC).
Slide 118	It is also in a band designated by the International Telecommunication Union for the Aeronautical Radionavigation Navigation Services (ARNS) so it will not be prone to interference with ground based navigation aids. Aircraft can use L5 in combination with L1 C/A to improve ionospheric correction and signal redundancy.
Slide	Here’s an interesting use of L5. This is a L1 and L5 dual-frequency smartphone like

119	those being sold by Samsung, OPPO, Realme, iQoo, Huawei, Vivo, Xiaomi and others – promoted as delivering decimeter absolute accuracies.
Slide 120	In other words, it may be possible for an autonomous code-phase receiver like that phone to deliver much better than its usual 3-10m positional accuracy. Its capability just might increase to a sub-meter range.
Slide 121	But why did it take the advent of L5 for the phone suppliers to roll-out dual frequency devices? After all, L1/L2 dual-frequency receivers GNSS receivers have been achieving high levels of accuracy for a very long time. Why wait for L5 and not build L1 C/A and L2C dual frequency code phase phones? It is likely that much of the tech on L1 and L2 was locked up in patents so it took L5 coming along for dual frequency phones to appear.
Slide 122	For example, some of them use the Broadcom chipsets that tracks these signals on these 5 constellations: GPS—L1 C/A + L5 Galileo—E1 + E5a QZSS—L1 + L5 GLONASS—L1 BeiDou—B1 Their new chip will add Beidou 3 to the list.
Slide 123	However, please note that L2C and L5 are not yet considered fully operational. When they are - cross-correlation with the P(Y) code will probably be ended. In other words, receivers that exploit characteristics of the encrypted military P(Y) signal at the L2 frequency to achieve dual-frequency capability will no longer have that option . Everyone should expect to utilize L2C and L5 at that point.
Slide 124	Here is an important announcement from the 2019 Federal Radionavigation Plan. The US Government commits to maintaining the existing GPS L1 C/A, L1 P(Y), L2C, and L2 P(Y) signal characteristics that enable codeless and semi-codeless GPS access until at least two years after there are 24 operational satellites broadcasting L5 with fully

	functional navigation messages. . . estimated to occur in 2027. (This) “will allow for the orderly and systematic transition of users of semi-codeless and codeless receiving equipment to the use of equipment using modernized civil-coded signals.” “ . . . 24 operational satellites broadcasting L2C will be available by 2020, with the corresponding ground segment control capability available by 2023 . . . Civilian users of GPS are encouraged to start their planning for transition now.”
Slide 125	Block IIF
Slide 126	The first Block IIF satellite was launched in 2010. Today there are 12 Block IIF satellites on orbit and operational. They broadcast all of the previously mentioned signals including L5. They also carry the Distress Alerting Satellite System repeaters.
Slide 127	The Block IIF satellite's launch vehicles can place the satellites directly into their intended orbits so they do not need the apogee kick motors their predecessors required.
Slide 128	Block III
Slide 129	First launched in 2018 there are 4 Block III satellites on orbit. They offer more power, accuracy and better anti-jamming capabilities. Spacecraft life will extend to 15 years. The GPS III effort also involves new ground stations, additional civilian and military navigation signals, and improved availability.
Slide 130	The broadcast of the M code will change in an interesting way. It will continue to be radiated with a wide angle to cover the full earth just as in the Block IIR-M satellites, but the Block III M code will also have a rather large deployable high-gain antenna to produce a directional spot beam.

Slide 131	The spot beam will have approximately 100 times more power (-138 dBW) compared with (-158dBW) the wide-angle M-code broadcast. It will have the anti-jam (AJ) capability to be aimed to a region several hundreds of kilometers in diameter. A side effect of having two antennas is that the GPS satellite will appear to be two GPS satellites occupying the same position to those inside the spot beam
Slide 132	Block III satellites have cross-link capability to support inter-satellite ranging. Several satellites can be updated from a single ground station instead of requiring each of them to be in the range of their own ground antenna.
Slide 133	Each Block III satellites will have three enhanced rubidium frequency standards (clocks) and a fourth slot will be available for a new clock, i.e., a hydrogen maser.
Slide 134	Block III satellites have on-board Laser Retroreflector Arrays (LRA) (aka retro-reflectors). The satellite laser tracking available with this payload provides data from which it is possible to distinguish between clock error and ephemeris error Similar LRA are planned for the Russian (GLONASS) and European (GALILEO) systems too.
Slide 135	Codes available from earlier blocks are all broadcast with increased power from the Block III satellites. the M code, L2C, L5, the P(Y) code and the C/A code
Slide 136	But GPS III's new L1C civil signal makes it the first GPS satellite broadcasting a signal shared directly with other international global navigation satellite systems, like Galileo, improving connectivity for civilian users.
Slide 137	It is also interoperable with the Japanese Quasi-Zenith Satellite System. The Indian Regional Navigation Satellite System (NAVIC), and China's Beidou system. It is broadcast at the same frequency as the original L1 C/A, but it delivers 40% greater power.

Slide 138	It includes a pilot signal and a data signal. L1C will be easier to receive in obstructed areas such as forests and urban canyons because the pilot gets 75% of the power and the data signal get 25%.
Slide 139	Let's talk about GNSS
Slide 140	Here today there are 27 GNSS satellite above a 10° mask angle at 10:30 am.
Slide 141	GLONASS, the Russian Federation's System
Slide 142	The complete GLONASS system contains 24 satellites spread over three orbital planes at the altitude of 19,100 km about 1000 km lower than the orbit of GPS satellites. The orbital planes are inclined 64.8 degrees toward the Equator.
Slide 143	The original GLONASS satellite was the Uragan. First launched in 1982 with an intended life-span of 4 years. None of these are on orbit today.
Slide 144	A nearly full constellation of 24 or so GLONASS satellites was achieved in 1996 but by 2001 the system was in poor health. Only about 7 healthy satellites remained on orbit and they were only expected to last about three years.
Slide	Since then, GLONASS has been rebuilt and modernized. The constellation has been brought to full worldwide 24-hour coverage.

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Slide 146	The current GLONASS constellation
Slide 147	First launched in 2003 the GLONASS M satellites has improved antennas and an extended lifetime of 7 years. These satellites added a second civil code to the system and are the majority of satellites in the current GLONASS constellation.
Slide 148	There are 3 of the new K satellites in the constellation too.
Slide 149	The first was launched in 2011, the second in 2014 and the 3rd October 25th of 2020.
Slide 150	They are the first unpressurised GLONASS satellites which reduces their mass. They add a third civil frequency known as L3 and have a 10-year service life, 3 years longer than the M. They will eventually replace the M satellites.
Slide 151	There will be three types of the K satellite K1, K2 and KM. A GLONASS-K2 will likely be launched in 2022. The GLONASS-KM is in the research phase and will be launched around 2025.
Slide 152	The original objective was a system providing 100 meters accuracy to civilians, a deliberately degraded standard signal. The military signal was to provide 10-20 meter. That changed in 2004, the Federal Space Agency, FKA, announced a plan to provide high-precision code solution to all users.
Slide 153	GPS, Galileo and BeiDou use Code Division Multiple Access, CDMA. Remember that this means all the users receive the same frequency bands. The transmitted message is recovered by correlating the received signal with the PRN code available at the receiver. For example, each GPS satellite broadcasts its own completely unique segment of the C/A code but they all send the code in the same frequency bands. The frequencies are

	the same. The codes are all different. From most of GLONASS satellites the codes are the same. The frequencies are all different.
Slide 154	In the method is known as FDMA, Frequency Division Multiple Access each GLONASS satellite broadcasts the same code but at its own unique frequency.
Slide 155	GLONASS L1
Slide 156	In GLONASS L1 has a range of frequencies centered on 1602 MHz. Each GLONASS FDMA satellite has the same code, but its own frequencies. There can be up to 25 channels of L-band signals with each channel separated from the others by 0.5625 MHz.
Slide 157	Here is the GLONASS L1 band shown with the other nearby signals
Slide 158	GLONASS L2
Slide 159	L2 is centered on 1246 MHz. Each channel is separated from the others by 0.4375MHz.
Slide 160	Here is the GLONASS L2 band shown with the nearby GPS signals
Slide 161	GLONASS L3

Slide 162	L3 broadcast by GLONASS K is centered on 1207.14 the same frequency as Galileo/BeiDou signal E5B and in the Aeronautical Radio Navigation Service (ARNS) band.
Slide 163	Of course, GLONASS-K and M satellites continue to transmit the existing FDMA signals in the L1 and L2 bands.
Slide 164	But there is also a CDMA open service signal emanating from GLONASS today.
Slide 165	It is centered at 1202.025 . The 3 K satellites in the constellation and the M satellites launched since 2014 are capable of transmitting a CDMA signal on L3 called L3OC. It has a familiar structure a data component and a pilot component. They have equal power and are in phase quadrature with each other.
Slide 166	There are plans for the GLONASS K2 satellites to feature a full suite of modernized CDMA signals in the existing L1 and L2 bands in 2022.
Slide 167	There are also some changes in FDMA too. Russia recently agreed to alter the architecture a bit. GLONASS will assign the same frequency to satellites that are in the same orbital plane but are always on opposite sides of the Earth thereby using half as many bands
Slide 168	In fact, there are many efforts underway to improve the GLONASS accuracy. The stability of the satellites on-board clocks has improved. The GLONASS Navigation Message will include the difference between GPS time and GLONASS time, which is significant.

Slide 169	There are no leap seconds introduced to GPS Time, GALILEO Time or BeiDou Time. They are always 19 seconds and 33 seconds from International Atomic Time, respectively.
Slide 170	However, things are different in GLONASS . Leap seconds are incorporated into the time standard of the system. Therefore, there is no consistent integer-second difference between GLONASS Time and TAI.
Slide 171	The epoch and rate of Russian time, relative to UTC (SU – Soviet Union) is monitored and corrected periodically by the Main Metrological Center of Russian Time and Frequency Service (VNIIFTRI) at Mendeleevo, Moscow.
Slide 172	The GLONASS Ground Control Center and Time Standards are located in Moscow. The telemetry and tracking stations are almost entirely located within the former Soviet Union territory , except for a station in Brasilia, Brazil. There are efforts to increase the number of available tracking facilities.
Slide 173	EU's system GALILEO
Slide 174	The European Union's civilian controlled Galileo system has 22 useable satellites on orbit higher than the GPS constellation at 23,616 km above the Earth. The full constellation will include 30 satellites in 3 planes, 10 in each plane.
Slide 175	GIOVE-A [Galileo In Orbit Validation (IOV) Experiment – A] and GIOVE –B were launched in 2005 and 2008 respectively. They were retired in 2012.
Slide	4 more validation satellites were launched. 3 are currently useable.

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Slide 177	However, the most recent FOC satellites were launched on 7/25/2018. Galileo is on its way to Full Operational Capability (FOC).
Slide 178	There are now 22 Full Operational Capability (FOC) satellites on orbit.
Slide 179	GALILEO has four carriers E5a, E5b, E6 and E2-L1-E1..
Slide 180	E5a and E2-L1-E1 overlap the existing L1 and L5 GPS signals.
Slide 181	Galileo's E5b overlaps the GLONASS L3 signal. The interoperability with GPS and GLONASS is helped by the signals being centered on the same frequencies.
Slide 182	
Slide 183	Here are all the GALILEO signals modulated onto the carriers using CDMA. There is a pilot, data-less as well as a data component broadcast in quadrature in them all. The pilot signal enhances correlation and allows longer integration.

Slide 184	Galileo has defined five levels of service that will be provided by the system. They include the Open Service (OS), which uses the basic signals and is quite similar to GPS and GLONASS. The OS is free and available for timing and positioning applications.
Slide 185	The Safety of Life Service (SOL) is along the same line but provides increased guarantees including integrity monitoring, meaning that users are warned if there are signal problems. SOL will be a global service and will include both a critical level service and a less accurate non-critical level
Slide 186	Both SOL and OS are on the E5a, E5b and E2-L1-E1 carriers. Their availability on separate frequencies presents the ability to ameliorate the ionospheric bias.
Slide 187	The Public Regulated Service (PRS) is encrypted and is meant to assist public security and civil authorities.
Slide 188	PRS will be provided on E6 and E2-L1-E1. Applications include emergency services, law enforcement, intelligence services and customs.
Slide 189	The Search and Rescue Service (SAR) is intended to enhance space-based services and improve response time to distress beacons and alert messages. Galileo is another constellation in the COSPAS-SARSAT effort already mentioned in the discussions of GPS and GLONASS. In the Galileo application the user receives a notification that help has been dispatched
Slide 190	Other services such as the Commercial service will follow when Full Operational Capability (FOC) is achieved.

Slide 191	It will offer unique and custom applications.
Slide 192	Galileo's ground segment has two centers; one at the Fucino Control Centre in Italy and one at the Oberpfaffenhofen Control Centre in Germany.
Slide 193	There is also a network of sensor stations which provide data to the centers through the dedicated data dissemination network. This network is located in areas controlled by European nations.
Slide 194	The uplink and telecommand stations communicate the calculated integrity, time and other information back up to the satellites.
Slide 195	More satellites and improved ground control segment have decreased the Galileo range error.
Slide 196	Beidou, China's system is named after the Big Dipper.
Slide 197	There are 3 orbital categories. First, geostationary - GEO
Slide 198	There are currently 7 of these satellites on a GEOSTATIONARY ORBIT (GEO)
Slide 199	Above specific meridians of East Longitude such as 58.75°, 80°, 110.5°, 140° and 160°.

Slide 200	Which supplies good regional coverage
Slide 201	Second, the medium earth orbit - MEO
Slide 202	There are 27 of these satellites in the MEO – MEDIUM EARTH ORBIT
Slide 203	They are in three planes inclined at 55° relative to the equator with the nominal altitude of 21,528 km and nominal period of 12 hours 53 min which supplies good global coverage.
Slide 204	Finally, the inclined geosynchronous orbit - IGSO
Slide 205	There are 10 of these satellites in the IGSO – INCLINED GEOSYNCHRONOUS ORBIT
Slide 206	These satellites on have the altitude of 35,786 kilometers and an inclination of 55° to the equatorial plane.
Slide 207	The evolution of BeiDou's coverage.

Slide 208	There are currently 44 operational BeiDou satellites.
Slide 209	The BeiDou Radio Navigation Satellite Service (RNSS) has 3 legacy signals; B1, B1-2, B2 and B3. These bands overlap Galileo on E2-L1-E1, E5b, and E6 respectively. BeiDou's modulation method is quadraphase shift key (QPSK), CDMA.
Slide 210	The BeiDou Radio Navigation Satellite Service (RNSS) has 5 new global signals; B1C and B1A, B2a, B2b, B3A. Those in the blue font are open. Those in the red font a restricted. These bands overlap GPS L1 and Galileo on E2-L1-E1: GPS L5 and Galileo E5a: Galileo E5b, and Galileo E6 respectively.
Slide 211	The future BeiDou is expected to support two services: The Radio Navigation Satellite Service (RNSS) and the Radio Determination Satellite Service (RDSS). The RDSS will include a 2-way short message service capable of handling10 million messages/hr. using 3 GEO satellites across this area.
Slide 212	There will be a **global** message service using inter-satellite crosslinks with a capacity of 200,000 messages/hr. using 14 MEO satellites.
Slide 213	The Radio Navigation Satellite Service (RNSS) will also include a Satellite Based Augmentation Service (SBAS). The network includes 150 reference stations, information from these stations is processed in the BeiDou Control/Ground segment and the resulting corrections are sent to the BeiDou GEO satellites which broadcast them via the D2 NAV message to the BeiDou user's receivers. It also includes ionospheric corrections and clock corrections to other GNSS systems.
Slide	The BeiDou Control/Ground Segment is comprised of a Master Control Station (MCS), two Upload Stations (US) and a network of 30 widely distributed Monitoring Stations

214	(MS). The MCS is responsible for the operational control of the system, including orbit determination, navigation messages and ephemerides which are based on the China Geodetic Coordinate System 2000 (CGCS2000) which is within a few centimeters of ITRF.
Slide 215	Japan's QZSS system
Slide 216	The system's nickname Michibiki, means guide. The first demonstration satellite was launched in 2010 and more satellites were launched in phase two. They follow the same asymmetrical figure-8 ground track in the region.
Slide 217	The satellites inclined, geosynchronous and highly elliptical orbits are designed so they are always be available at high elevation angles almost directly overhead in Japan, Oceania and East Asia. It is an augmentation system that assists where obstructions such as urban canyons block GNSS signals. It has also offered Sub-meter Level Augmentation Service (SLAS) and Centimeter Level Augmentation Service (CLAS) since 2018.
Slide 218	Today the constellation includes 2 additional quasi-zenith satellites, QZ-2 and QZ-3 and 1 geostationary satellite, QZ-4 which orbits at the equator.
Slide 219	The 4-satellite constellation will increase to 7 satellites in the future
Slide 220	QZSS transmits 6 signals; L1-C/A, L1C. L2C, L5, L1-SAIF and LEX. The first 4 on the list are the familiar GPS signals. The others are unique to QZSS.
Slide 221	L1-SAIF (Submeter-class Augmentation with Integrity Function) is broadcast at the L1 frequency and provides a sub-meter correction signal with GPS.

Slide 222	LEX(L-band Experiment) signal is an experimental high precision signal for real-time positioning compatible with Galileo E6 signal. 3 cm horizontal and 6 cm vertical RMS errors at 35 seconds first fix has been reported utilizing regional corrections only valid in Japan. Another type of correction messages on the LEX signal known as MADOCA-LEX has wide-area validity and is being tested. Here are some RMS errors and convergence times for kinematic PPP using MADOCA-LEX products on a fixed point.
Slide 223	India's GNSS. Formerly IRNSS, now known as Navigation with Indian Constellation or NAVIC, a Hindi word for sailor or navigator.
Slide 224	When fully developed the NAVIC constellation will provide position, navigation and timing service in this region approximately 1500 kilometers around India
Slide 225	It is comprised of 7 satellites . They have a 10-year design life.
Slide 226	They are continuously visible to the Indian 21 station control segment including the Master Control Center (MCC) at Hassan and the Satellite Control Facility at Bhopal.
Slide 227	NAVIC provides a public Standard Positioning Service and an encrypted Restricted Service on the L5 with a 24 MHz bandwidth and on the S band with a 16.5 MHz bandwidth. The Standard signal is BPSK modulated at I MHz and the Restricted Service will use Binary Offset Carrier.
Slide 228	The NAVIC includes 3 geostationary (GEO) satellites located at 32.5°E, 83°E and 129.5°E.
Slide	There are also 2 pairs of satellites in geosynchronous orbit with an inclination of 29°. The small inclination is appropriate to covering India's low latitudes.

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Slide 230	IRNSS-1A was launched in 2013. Its clock failed. 1B and 1C were launched in 2014. The fourth 1D satellite was on orbit in 2015, the fifth, sixth and seventh all in 2016. The 1H launch failed and 1I reached orbit in 2018. They all carry a rubidium clocks, corner cube retro-reflectors for laser ranging and a C-band transponder.
Slide 231	The US Congress formally acknowledged NAVIC as an allied system in the 2020 National Defense Authorization Act (NDAA) meaning that the system will be on a par with Japan's QZSS and Europe's Galileo allowing U.S. military and government users to utilize them all.
Slide 232	