LiDAR, IMU, GNSS and Cameras in Terrestrial Mobile Mapping Systems (MMS)

Slide 1 LiDAR, IMU, GNSS and Cameras in Terrestrial Mobile Mapping
Slide 2 One of the reasons that terrestrial mobile mapping began is that such systems are uniquely fit for purpose. In other words, by mounting the sensors necessary to solve a mapping particular problem on a common platform and synchronizing their data streams these systems eventually evolved to where they could produce -
Slide 3 - a whole mapping solution from one integrated process. An approach that avoided the errors and inefficiencies attendant with post-mission integration of disjointed measurements.
Slide 4 Early days
Slide 5 The development process starts in the 1980s. Here is one of the first mobile mapping systems from that time.
Slide 6 Alain De Taeye of TomTom remembers, "In 1989, . . . our Tele Surveyor. . . was a big Mercedes van with all big cameras on, very prehistoric. You should have seen that. The people who drove it around even had to sleep in that car, otherwise the cameras would be stolen. That car was driving according to a map-
Slide 7 "- and we were able to view the images on 6 screens. We had images from 4 cameras, from 1 map, and also a screen with alphanumeric data, the street names and so on."
Slide 8 And they were not alone. In that same year development started on this GPSVan mobile mapping system at the Center for Mapping of The Ohio State University. It integrated a GPS receiver, a gyro-based inertial system, a wheel counter, a digital stereo-vision system, and color video cameras It collected data at highway speeds from which digital road maps and highway inventories were created. The Center for Mapping also came up with a pretty good definition of a Mobile Mapping System-
Slide 9 A Mobile Mapping System is: "a moving platform, upon which multiple sensor/measurement systems have been integrated, to provide three-dimensional near-continuous positioning of both the platform and simultaneously collected geo-spatial data".
Slide 10 A big leap in mobile mapping development took place in 2003 when the Defense Advanced Research Projects Agency (DARPA) announced its Grand Challenge. The goal was to encourage the development of vehicles capable of autonomously navigating desert trails and roads at high speeds. The first one began on March 3, 2004 but the 142-mile course -
Slide 11 - was too difficult for the field.
Slide 12 The best only traveled 7.4 miles.
Slide 13 The second was on October 8, 2005.
Slide 14 The winning vehicle was built by a team from Stanford and known as Stanley. It was among five finishers.
Slide 15 - It's sensor stack included 5 laser scanners mounted on top of the car-
Slide 16 -that were used to generate a point cloud of the road ahead.
Slide 17 The DARPA 2007 Urban Challenge was different. It was a 60-mile race held at the former George Air Force Base, California in a simulated urban environment that included other self-driving and human driven cars. It had a 6-hour time limit. Six cars finished within that time.
Slide 18 It was won by Boss a system developed by researchers and students from Carnegie Mellon, General Motors, Caterpillar, Continental, and Intel.
Slide 19 Boss integrated a combination of 17 different sensors that included light detection and ranging (LiDAR), RADAR and GPS fused with inertial data. to provide a full 360-degree field of view around the vehicle sensor fields overlapped for redundancy. Mobile mapping vehicles have become a pretty familiar sight today because-

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Slide 20	You sure see lots of them now.
Slide 21	Seems like everywhere you look-
Slide 22	-there is some kind of mobile mapping vehicle driving by. It's a good idea to realize that these vehicles are mostly robots.
Slide 23	Maybe not exactly like this guy but robots nonetheless.
Slide 24	They detect the world around themselves with their sensors-
Slide 25	-and as we have seen the variety of instruments carried on mobile mapping vehicles can vary extensively but there are 4 that are usually present.
Slide 26	Mobile Mapping Components
Slide 27	Multi-directional cameras, LiDAR, GNSS receiver and Inertial Measurement Unit (IMU). There are often other instruments in place but we'll talking about these 4.
Slide 28	Let's talk about cameras first. Facilitated by the better resolution, color acquisition, and radiometric quality especially the anti-blooming, reduced cross-talk of charged couple device (CCD) camera technology the importance of imagery in mapping is increasing.
Slide 29	The cameras are definitely the eyes. Here is a typical array: 4 - 20-megapixel cameras.
Slide 30	Each of these has calibrated optics, a 12 Hz Frame Rate -
Slide 31	-a 12-bit dynamic range. The dynamic range is the range of contrast, the number of brightness levels the camera can deliver. For example, a 4-bit camera has (2^4) 16 shades whereas a 12 bit has (2^{12}) 4096 shades -
Slide 32	Which is much better at delivering good visual acuity, detail in shadows and highlights.
Slide 33	The camera array records images front, right, left and rear and for a comprehensive view of the environment they have a horizontal field of view of 105 degrees and a vertical field of view of 150 degrees. This is just one configuration.
Slide 34	There are also panoramic 360°cameras and many systems also acquire their imagery as a video stream-
Slide 35	-and frame grabbers integrated with high-speed computer buses and processing hardware have become a standard commodity, but what about the incorporation of the camera work into the overall data stream?
Slide 36	To do the photogrammetry and determine 3-D coordinates of objects visible in multiple CCD camera images you need to know the specific information about each camera's orientation at the moment of exposure, both the exterior and the interior parameters.
Slide 37	To know the exterior orientation, you must have the position of the camera perspective center at moment the exposure is made. Here T_x, T_y, T_z indicate the position of the camera projection center in world coordinate system. You also need the camera's orientation at exposure time. There are 3 parameters for each image. Here is the rotation matrix that defines the camera orientation with angles α, β and γ. The objective of all this is to take the coordinates of the point of interest from the camera coordinate system is (X', Y', Z') and put them into the 3D world coordinate system X, Y, Z. However, these exterior parameters are constantly changing so they must be determined on-the-fly using the actual measurements of the combination of GNSS and the IMU, more about that later.
Slide 38	To know the interior orientation, you have to have the interior geometry of the camera meaning that you need to know the parameters linking the pixel coordinates of an image point with the corresponding coordinates in the camera reference frame. Said another

	way the interior orientation parameters are the coordinates in pixel of the image center, or the principal point in u, v, the focal length f and any parameters used to model lens distortion.
Slide 39	Lens distortion is a deviation from the ideal projection considered in a pinhole camera model. A pinhole camera is considered the ideal camera. It has no lenses, of course, so there is no lens distortion and it has a nearly infinite depth of field in which nearly everything appears in focus. So, lens distortion is any deviation from the ideal pinhole camera model
Slide 40	When a lens is distorted straight lines in the scene do not remain straight in the image. Examples of lens distortions are barrel distortion and pincushion distortion. The process of correcting the image displacements that occur due to elements of the camera's interior orientation is called *camera calibration.*
Slide 41	The imagery from the digital cameras can be used to color points in a LiDAR point cloud to aid visualization, classification and processes such as automated sign extraction. LiDAR point clouds which contain intensity values via return signal strength give an indication of target reflectivity. However, intensity values vary from system to system and can even differ due to scanning geometry, multiple returns and material type so colorization can enhance their usefulness
Slide 42	Georeferenced images can enable users to create linework and annotations directly on the images linked to the point cloud rather than in the point cloud itself.
Slide 43	It is good to remember that there is parallax in imagery even with calibrated cameras which can lead to offsets between the point clouds and the images -
Slide 44	- and since a camera is a passive sensor the quality of the image will vary depending on exposure, camera focus and lighting conditions. Yes, these cameras have to be tough. They're on a moving vehicle at speed in fair weather and foul, extreme temperatures, rain, snow -
Slide 45	and in the face of flying debris and insect splatters, etc.
Slide 46	Still an image alone isn't very useful. Where is it? For it to make sense you have to have context . The vehicle is always asking "Where am I?", "Where am I?" every instant. It's the localization question.
Slide 47	The relative answer is, "Here you are in relation to the things around you."
Slide 48	LiDAR and the IMU measurements can answer that. Cameras contribute high resolution, LiDAR with IMU brings depth information.
Slide 49	Then there's the absolute position question "Where am I in the world?"
Slide 50	That can often be answered by the Global Navigation Satellite System (GNSS) receiver measurements.
Slide 51	But GNSS is at its best with clear sky.
Slide 52	What if you're under a bridge.
Slide 53	What then?
Slide 54	GNSS is not particularly-
Slide 55	- good here
Slide 56	Ah, that's why mobile mapping requires the integration of Global Navigation Satellite System and Inertial Measurement Unit an IMU to provide information about the position, rotation, and motion of the scanning platform.
Slide 57	That IMU is great here because it needs no outside input. It works here-
Slide 58	and here, and even here. In other words, an IMU operates pretty much anywhere. It needs no external antennas, has no visibility requirements, is immune to jamming and does not receive or emit any radiation.

Slide 59	Within itself the Inertial Measurement Unit (IMU) can measure acceleration, orientation and angular rotation rates. To do that it includes measurements from accelerometers and gyroscopes – and maybe magnetometers
Slide 60	Here's an idea about the architecture of an IMU. On a common mounting base Inertial Measurement Units (IMUs) usually have three accelerometers that are perpendicular to each other. They each measure acceleration along one axis: X, Y, Z.
Slide 61	The IMU also has three gyroscopes which are perpendicular to each other too, so the angular rate can be measured around each of the acceleration axes X, Y and Z .
Slide 62	Here they are all together. Perhaps a bit confusing.
Slide 63	Ok, each of the 3 accelerometers measure acceleration along one axis: X, Y and Z. The 3 gyroscopes are also at perpendicular to each other, so the rotations angular rate can be measured around each of the axes X, Y, and Z.
Slide 64	In practice the gyroscopes measure roll -
Slide 65	- pitch-
Slide 66	-and yaw.
Slide 67	The accelerometers have another task they measure the movement left and right
Slide 68	-left and right
Slide 69	-forward and backward-
Slide 70	-forward and backward-
Slide 71	and up and down-
Slide 72	-up and down.
Slide 73	So this is the inertial sensors assembly (ISA) of an IMU. It has a common mounting base for the triads of accelerometers and gyros, electronic circuits for temperature compensation and digitalizing the signals.
Slide 74	Here is a high-end example. This is the configuration of 3 ring laser gyros, RLGs. Each has no moving parts, no friction which really limits the drift. It is compact, light and hardy and so used in aircraft, rockets, satellites, etc. It operates on the Sagnac effect. The input laser beam is split in two, reflected by mirrors and sent around a loop, but in opposite directions. The beams are then recombined at the readout sensor. If there has been no rotation the lengths, they traveled will be exactly the same and indicated by complete constructive interference of the two beams. However, if there is rotation their path lengths vary and that causes variance in the amplitude of the phase-shifted net signal. The subsequent destructive fringe interference can be detected by photoelectric cells and the rotation rate measured
Slide 75	Here is another kind of IMU. This is the configuration of 3 fiber optic gyros, FOGs. Here is a single unit These devices are less sensitive than ring laser gyros but there are a lot of similarities in the principles of operation of fiber optic and ring laser gyros. The Sagnac effect, two beams traveling in opposite directions. The difference is instead of traveling in the resonant inert gas filled cavity of a ring laser gyro here the beams travel through a long optical fiber wound into a coil. Nevertheless, the one going against the rotation has a shorter path delay than the other beam so when the beams are brought back together the difference is apparent in the phase shift of the interference pattern. The FOG is more sensitive than the next example, the microelectromechanical system (MEMS) gyro.
Slide 76	The previous examples are often large, expensive and have substantial power requirements so their use can be limited to circumstances where these characteristics are accommodated. There is sometimes another limitation to their use. International Traffic in

Arms Regulations (ITAR) control that restricts the manufacture, sale, and distribution of defense and space-related articles and services as defined in the United States Munitions List (USML). The regulations can limit the use of some equipment outside of the US.	
Slide 77	Here are just a couple a ring laser gyro and a Fiber Optic Gyro that are ITAR controlled. There are others.
Slide 78	On the other hand, a microelectromechnical (MEMS) gyro is a mechanical device is a small combination of tiny electrical components etched in silicon. It is relatively inexpensive has low power requirements and is based on a very different principle from the others, the Coriolis effect. To illustrate the idea, imagine -
Slide 79	this mass (m) is moving in direction v→ -
Slide 80	-and simultaneously rotating. These movements together generate a perpendicular force-
Slide 81	-in the direction of the blue arrow, the Coriolis force.
Slide 82	Here's what the effect of simultaneous rotation and linear motion together looks like. This is the Coriolis effect.
Slide 83	It causes the displacement that is so useful to a MEMS gyroscope.
Slide 84	The operation is not unlike what happens to this tuning fork if it rotates while moving along. Its vibrating as you see and now moving, and rotating.
Slide 85	When these two motions happen together the Coriolis effect adds a different vibration, see the change in the direction of the vibration? It's that change in the vibration that is used to quantify the rotation itself. The underlying physical principle is that a vibrating object tends to continue vibrating in the same plane but if it rotates the Coriolis effect causes a displacing force and by measuring this force the rate of rotation can be determined.
Slide 86	So wouldn't it be great if there were masses in a MEMS gyro that acted like the tuning fork?
Slide 87	Well, actually silicon is often etched to create a pair of tuning fork masses -
Slide 88	-and just like a tuning fork these masses are stimulated by an applied oscillating electric field that makes them oscillate constantly in opposites directions. When the whole thing rotates an angular velocity is applied -
Slide 89	and the Coriolis force displaces them in opposite directions perpendicular to their vibration-
Slide 90	Again here is an illustration of the effect of the electric field making the proof masses oscillate constantly in opposites directions. However, in the presence of rotation the Coriolis force displaces them in opposite directions perpendicular to their vibration which movement results in a change in the capacitance between them, this change is sensed by the sense electrodes and the rotation quantified. So, MEMS gyroscopes do measure the displacement caused by this vibration because it is indeed directly related to the angular rate of the rotation. It is read by measuring variation in capacitance.
Slide 91	Every MEMS gyro has a proof resonant mass component. They come in several shapes disks, beams, and-
Slide 92	-etc. Here the same principles illustrated on a different shape. Here is the proof resonating mass, the driving direction and the angular rate of rotation.
Slide 93	Here is how this configuration works changing capacitance as it moves in

response to the rotation.	
Slide 94	MEMS are small, inexpensive and don't require much energy to operate so it is not surprising that these systems are now found in phones, games, autos and etc.
Slide 95	MEMS technology is also used to supply the accelerometers needed to round out the IMU.
Slide 96	Accelerometers measure inertial acceleration as described by Newton's second law a = F/m where a is acceleration, F is the physically applied force and m is the mass it to which it is applied like the mobile mapping vehicle
Slide 97	Accelerometers operate on the tendency of bodies to maintain constant translational and rotational velocity, unless disturbed by forces or torques
Slide 98	Here is a scanning electron microscope (SEM) image of an inertial MEMS accelerometer. You can see the polysilicon fingers suspended in a depressurized cavity. Just like the MEMS gyros we talked about the movement of these fingers in their proportional response to acceleration changes the capacitance of the system. Those changes are then measured by signal electronics.
Slide 99	Here are some of the similarities between this accelerometer and the MEMS gyroscope. For example, the proof resonating mass is here and its acceleration in the driving direction is registered. The difference is that the measurement is limited to acceleration and does not include angular rotation.
Slide 100	It works like this. As you see a MEMS accelerometer is a proof mass on a spring. The direction that the mass is allowed to move is known as the sensitivity axis. When there is linear acceleration along that axis it causes the proof mass to shift to one side and the amount of deflection is proportional to the acceleration.
Slide 101	Ok, that's how this thing is put together but it apparently still needs input from the GNSS receiver to provide a good fused positional solution. But why is the GNSS data needed?
Slide 102	Well, here is part of the explanation. The IMU measures the changes in position and orientation and this information is processed for localizing the mobile mapping vehicle. Said another way vectors derived from the gyros and accelerometers of the IMU are added to the last known position to calculate the next one. An IMU typically reports such data at 100–2000 Hz. (100 to 2000 times a second).
Slide 103	Here is simplified example of how an IMU works in practice. The skateboard moves along its x-axis. The on-board x-axis accelerometer detected an acceleration rate of 5 meters per second per second for just 1 second when the skateboard moved forward but it needed to slow to make a stop so during that time the accelerometer registered a -10 meters per second per second acceleration for 1/2 second and the vehicle stopped after moving 3.75 meters.
Slide 104	Ok, here is its first position after two seconds of travel now the z axis gyroscope registers a rate of 90-degrees per second for half a second as the vehicle turns 45 degrees.
Slide 105	Notice that the movements are all in the vehicle-oriented reference system. Ok, it moves along the x axis again. This time the x-axis accelerometer detected an acceleration rate of 1 meter per second per second for 10 seconds and when it slowed to make a stop the accelerometer registered a -5 meters per second per second for 2 seconds. The vehicle stopped after moving 60 meters.
Slide 106	Here we are at position 2. The total transit time from the beginning is 18.5

seconds. Now the vehicle has rotated a negative 10 degrees per second for 4.5 seconds to this orientation.	
Slide 107	Now there are accelerations in both the x-axis and the y-axis simultaneously. It is moving at 45 degrees and comes to rest at position 3.
Slide 108	This all looks great but here's the difficulty. The navigation errors, the drifts, of the IMU increased with time as the vehicle traveled this course so at each place the error has accumulated. It has gotten larger.
Slide 109	No matter the type IMUs tracks drift. Therefore, the IMU errors are compensated by the GNSS measurements. The Kalman filtering allows the integrated system to track the drifting parameters of the accelerometers and gyros of the IMU based on the statistical information from both the GNSS and the IMU. The integrated system can maintain pretty good inertial navigation accuracy even when GNSS signals are obstructed.
Slide 110	Here's an example of such IMU drift. The IMUs trajectory departed from the actual route rather substantially here and here .
Slide 111	Here is how the integration of both the IMU and the GNSS observations can make the best of both. These are the results from some mobile mapping system drives that were done at the Ohio State University's main campus in Columbus. The area with the test trajectory was mixed-urban, including some closely spaced tall buildings. Just looking at GNSS alone, here are the error estimates from the drives. See the areas of 1-2M and ½ to 1M errors estimates?
Slide 112	By integrating GNSS and IMU inputs those errors are substantially reduced.
Slide 113	Fortunately pings from the GNSS receiver can bring the IMU back to reality. So, these guys are coupled and work together to combine GNSS and IMU positions for robust positions at a high rate. Loosely-coupled and tightly coupled are common GNSS/IMU integration strategies. The most commonly used is loosely-coupled wherein the GNSS output position, and IMU incremental velocities and angular rates are combined in a separate Kalman filter.
Slide 114	There is another issue too remember in the previous example how all the positions are relative and in the vehicle system, not absolute and in the mapping system, also known as the world system. Here is an illustration of the importance of understanding how movement looks different in different reference systems.
Slide 115	In the wagon's frame of reference the ball moves backwards is stationary moves forward and is stationary again
Slide 116	However, from our mapping frame of reference the ball is stationary then moves forward continuously
Slide 117	Like the movement of the ball in the wagon the very same movement of this vehicle looks different measured in the mapping frame compared with how it looks measured in the vehicle's reference frame. So, we need to ensure that the relation between the frames are clearly quantified and known so that the final synchronized measurements from all of the various mobile mapping components are ultimately reported in the mapping reference frame. How that is done in a moment, but first let's look at the other two sensors under consideration here. LiDAR and GNSS - First LiDAR:
Slide 118	
Slide 119	**LIDAR - LI**ght **D**etection **A**nd **R**anging, a method of measuring the flight time of a beam of light to calculate range to objects at predetermined angular increments, resulting in a point cloud.

That is what LiDAR is. Here is a bit about what LiDAR is not.
Slide 120 They both use energy in the electromagnetic spectrum but fog and particulates in the atmosphere that do not inhibit RADAR do affect LIDAR.
Slide 121 LiDAR is not photography. As Tesla CEO Elon Musk famously said, "Anyone relying on lidar is doomed.“ He was referring to those trying to build the technology for autonomous driving, but the point is LiDAR does not represent what we see in the same way photography does.
Slide 122 However, the simultaneous capture of imagery and LiDAR provides the possibility of shading and classification of the point cloud. There is this fundamental difference between the two technologies photography is a passive sensor. LiDAR is an active sensor. LiDAR measures the distance between a sensor and an object with visible or near-infrared lasers. It is versatile, often mobile and has evolved into a cost-effective method of generating the very dense mass point clouds. There are several different methods of the technology used in the field.
Slide 123 There is Terrestrial LiDAR Scanning (TLS) with a stationary LiDAR sensor, usually mounted on a tripod.
Slide 124 Airborne LiDAR scanning (ALS): also called airborne laser swath mapping (ALSM), scanning with a LiDAR scanner mounted to a fixed-wing or rotor aircraft.
Slide 125 Unmanned LiDAR scanning (ULS): scanning with drones or other unmanned vehicles.
Slide 126 Mobile LiDAR scanning (Mobile Mapping): scanning from a ground-based vehicle, such as a car.
Slide 127 Mobile mapping systems use Class 1 eye-safe lasers
Slide 128 That means limited power which restricts the acquisition swaths to perhaps a few hundred meters on each side of the mobile platform and of course, the further the beams travel from the vehicle the more they spread
Slide 129 Nevertheless, the eye safe restriction is vital to allowing acquisition without any danger to people close to the sensor. Many operate in the near infrared region 905 nanometers where silicon detectors provide the best optical response, but there are systems that use a completely different frequency. They operate in the 1550nm range where a rarer material gallium arsenic is used for the detectors.
Slide 130 There are further differences in LiDAR solutions. We’ll compare a couple of them, the pulse based, also known as time-of-flight and the phase-based.
Slide 131 To understand the phase-based type it is important to know the meaning of phase in this context. It refers to the phase angles of a wavelength as you see here 0°, 90°, 180°, 270° and 360°. Now when two signals reach exactly the same phase angle at exactly the same time, they are said to *be in phase, coherent,* or *phase locked*. However, when two waves reach the same phase angle at different times, they are *out of phase* or *phase shifted,* like this.
Slide 132 If the system knows the frequency of the emitted wave, the phase shift compared to the reflected wave, and the speed of light of the atmosphere at hand the sensor can calculate the distance to the object.
Slide 133 This is very similar to the way the electronic distance measuring device, the EDM, in your total station works. Phase-based LiDAR and the modern EDMs both usually transmit multiple modulation frequencies at the same time in order to calculate unambiguous distances.
Slide 134 So phase scanners transmit a continuous wave of amplitude modulated light

and then determine ranges by measuring the difference in the phase between emitted and reflected beam. The two-way travel time is calculated by the phase-shift between the emitted and received signal and thereby gaining greater precision than the pulse-based time-of-flight method. An accurate clock is not needed here as it is in the time-flight-method. However, phase-based scanners require more energy than the time-of-flight and their range is shorter. They are often used for indoor scanning therefore time-of-flight systems are the most used in mapping systems	
Slide 135	Time-of-flight (TOF) pulse-based LiDAR emits a series of pulses that reflect and are then captured by the photosensitive element in the scanner which generates an electrical signal. That signal passes through an amplifier and on to an arithmetic circuit that uses the rising or falling edge of the pulse which combined with the speed of light delivers the distance to the measured object.
Slide 136	This is the technology typically used in Mobile Mapping.
Slide 137	The scanners on the vehicle emit a laser pulse at increments of horizontal and vertical angles.
Slide 138	They then measure the round-trip travel time from the signal emission, through the reflection from the target and the return to the sensor.
Slide 139	The moment the pulse directed by a beam-steering mechanism is emitted the scanner's clock is triggered. The signal is reflected and returns. When it is received by the photodetector the front-end electronics stop the clock, registers the time-of-acquisition and power received.
Slide 140	Therefore, the distance measurement precision is mainly a function of timing and the signal-to-noise ratio of the received laser pulse. The distance, *d*, to the reflection point can be calculated from the elapsed time Δt, and the speed of light *c* through the medium at hand by $1/2c\Delta t$. and of course an accurate clock is fundamental to this approach.
Slide 141	The distance resolution depends on the duration of the pulse and the peak power determines the maximum measurable distance. The outgoing pulse is roughly a Gaussian. Time-of-flight (TOF) are best with high peak- power pulses ~100 W and short-duration ~5 ns which requires a detection bandwidth approximately equal to the inverse of the pulse duration, or ~200 MHz.
Slide 142	The returning pulse is more complicated. It often interacts with multiple objects before returning. Most often users are most interested in the peaks for detecting the existence of an object but there is a good deal of other information in the full waveform.
Slide 143	In any case it is important to remember that when the pulse hits the obstacle it reflects some, not all, of its energy so that a small fraction of the light emitted returns to the photodetector. There are some direct (specular) reflections, but there are also spread, diffused, indirect and off-angle reflections depending on the surface. It takes a lot to maximize the signal-to-noise ratio and minimize distortion on the front-end of the scanning instrument.
Slide 144	Also, the amount of return the scanner receives depends on the distance to the target. For example, these signs were quite close to the mobile mapping vehicle yielded a substantial point cloud even at highway speed.
Slide 145	On the other hand, the points on this sign farther from the vehicle are more sparse.
Slide 146	The amount of return depends on the atmospheric conditions and the received signal will also include background light sources like streetlights, headlights or even solar

radiation.
Slide 147 LiDAR operates at wavelengths in the near-infrared, typically around 900 nm and airborne particulates larger than that wavelength inhibit the sensor.
Slide 148 Let's look at an example of a pulse-based spinning multi-beam LiDAR currently used in some Mobile Mapping vehicles such as.
Slide 149 Mandli, LiDAR USA, VISAT™, NASA's Centaur2 and Krex as well as Clearpaths Robotics robots
Slide 150 -and here.
Slide 151 This scanner uses internal MEMS accelerometers and gyros we talked about earlier and also relies on the GNSS Receiver for time-synchronization. Mounted on this Mobile Mapping vehicle the field of view is a +10.67 to -30.67 degrees for a total of 41.34 degrees. The angled mounting covers both the roadway and the other features in the environment The system collects data at a range from 1 to 80 meters.
Slide 152 When rotating at 10Hz the scanner covers 360 degrees in 32 layers. The resolution of each layer is approximately 0.16˚-
Slide 153 -so over the ~40-degrees the angular interval between the 32 layers is 1.33˚
Slide 154 You can see that in this example of the point cloud near the vehicle derived from this scanner showing the pavement, the sign and other features. Here is the imagery the point cloud alone and the photo with point cloud . Note the mentioned angular spacing between the scans.
Slide 155 As the range lengthens the point cloud becomes less dense , of course.
Slide 156 Like the other examples here is an image of a crosswalk from the Mobile Mapping vehicles onboard cameras.
Slide 157 Here is the crosswalk represented in the LiDAR point cloud.
Slide 158 Here they are together and you see the result of a slight mis-calibration in rotation and transformation between the two sensors. We'll look more closely at that issue in just a bit.
Slide 159 Handling these data can be difficult. There are some enormous files generated by Mobile Mapping.
Slide 160 Here is a chart representing the relative volume of spatial data per one square kilometer across several mapping technologies. These are the sizes produced by satellite sensors, airborne, etc. Here are the LiDAR files . Clearly, they are significantly larger than the others and the largest volume in the LiDAR work is in fact from mobile LiDAR. The difference between the red and yellow cubes on the right is the density of the points. The red is 100 point per square meter and the yellow is 300 points per square meter perhaps indicating why LiDAR data is often decimated for use, but the file size also depends on the file format.
Slide 161 Here is a chart to show how that aspect affects file size. On the top in green is ASCII, the original format for LIDAR data. Next in purple is E57 a general purpose, open standard, file format for storing point clouds and associated meta-data that is maintained by the American Society for Testing and Materials, ASTM. On the bottom in red is LAZ a lossless LIDAR Compression format. Finally, in the blue is LAS, short for LASer which is a point cloud file format that can include attributes such as intensity, RGB, etc. along with the x,y,z values.
Slide 162 LAS 1.4 is the latest specification for this standard binary format. It was originally an exchange format for laser hardware vendors and airborne applications but is now commonly used for terrestrial and mobile lidar so it makes sense that it is maintained and

published by the American Society of Photogrammetry and Remote Sensing (ASPRS). The general layout is shown in the chart. There is a public header block, there can be any number of optional Variable Length Records (VLRs), the Point Data Records and any number of optional Extended Variable Length Records (EVLRs). The public header block describes the format, the point counts and point data bounds, basically the extent of the point cloud. Interestingly it does not contain the definition of the Coordinate Reference System (CRS). The Variable Length Records (VLRs) contain variable types of data including projection information, metadata, waveform packet information and user application data. The Point Data Records provide coordinates for the points in the point cloud, flight and scan data, etc. The Extended Variable Length Records (EVLRs) were introduced in the previous version of the format LAZ 1.3. They allow a larger payload than do the VLRs and have the advantage that they can be appended to the end of an LAS file for adding projection information, for example, without having to rewrite the entire file. Now let's move on to a discussion of the foundation of the only sensor onboard the Mobile Mapping vehicle that can provide information about the absolute position of the system.
Slide 163 The Global Navigation Satellite System GNSS
Slide 164 Accurate Global Navigation Satellite System (GNSS) measurements of position, time, velocity and direction are essential to georeferencing Mobile Mapping data. Fortunately, today there are many satellites. 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.
Slide 165 There are not only more satellites today, there are more base stations – which can mean more accuracy and there are alternative methods of differential correction of GNSS.
Slide 166 One method receiving the corrections via a Real-Time Network (RTN). The base must be tracking the same constellations as the vehicle, calculate and broadcast corrections. The closer the vehicle is to the base the better. The system can generally deliver 10s of cm absolute accuracy and almost instantaneous initialization but connectivity is required to receive the correction signal over the cell phone network, LTE -
Slide 167 -and that is not always assured.
Slide 168 There are still many areas of the USA with limited, sporadic or unavailable cellular communication coverage.
Slide 169 Precise Point Positioning (PPP) is a real-time alternative to the real-time network approach. PPP does not require cell phone connectivity as the corrections are received from a geosynchronous satellite. Also, the vehicle need not be close to the base stations. However, the accuracy is less, generally a few decimeter absolute accuracy and initialization can be quite slow.
Slide 170 So while real-time kinematic GNSS can be applied to Mobile Mapping post-processed techniques are often employed to provide more collection flexibility, reliable final trajectories and checks of accuracy.
Slide 171 Post-processed differential GPS relies on stationary base stations at a known locations, to reduce most errors except atmospheric errors. Those errors vary with the length of the baseline. Therefore, the shorter the baseline the better.
Slide 172 Empirical data has shown that a baseline of 40km or less results in a type of solution known as fixed, a more accurate solution than float. Float solutions appear more frequently in the results when the baseline exceeds 40km.
Slide 173 These charts show that the accuracy of the output of a Mobile Mapping

	vehicle's data that has been checked against ground control points. It shows the distance of the base station from the vehicle 1km in light blue, 45km in red and 194 km in green.
Slide 174	Here are the absolute differences between the LiDAR data and the control points. Notice how those differences as post-processed with a 1km baseline in light blue are nearly the same as the differences with those from the 45km baseline. In other words, the LiDAR data positions from the 1km and the 45km baselines are within 1 to 2 decimeters of the control positions in both cases.
Slide 175	However, those from the 194 km baseline in green vary more substantially, generally from 2 to 5 decimeters.
Slide 176	Here are data seen in the differences between the imagery collected by the Mobile Mapping vehicle and the control positions. It again shows that the longer baseline causes degradation in the accuracy of the results, from generally 1 decimeter for the short baselines to up to 4 decimeters for the longer baselines. These data confirm that a baseline of ~40km or less provide results that are more reliably accurate.
Slide 177	Here is a very direct representation of the improvement of a short baseline over a long baseline. The yellow point at the sign center is the control point established by static GNSS observations. The short baseline point, the blue point is very close to the control point at 15 cm. The long baseline point, the purple point is 4-times further away at 60cm.
Slide 178	It is helpful that the average Continuously Operating Reference (CORS) station spacing in the conterminous United States is 70 km.
Slide 179	Consider a Mobile Mapping project on the red Highway 85 route shown here. The radii of the circles around the 2 continuously operating reference stations (CORS) are 40km. The processing after the drive can use COFC and WYLC in succession and ensure that each base will be no more than 40km from the vehicle. However, there is another consideration. Would it be worth it to extend the distance to 48km (the yellow circle) from the Mobile Mapping vehicle to cover that small portion of the work just north of Greeley? In considering that it is good to know that both COFC and WYLC track GPS and GLONASS.
Slide 180	As you see planning before a mobile mapping collection is a good practice. For example, here yesterday there were 27 GNSS satellite above a 10° mask angle at 10:30 am. However, this could be reduced substantially in an obstructed environment.
Slide 181	Such as this, it is always good to check for obstructions and satellite constellation availability -
Slide 182	-at several sites across the project area especially if the geometry varies significantly across the site.
Slide 183	For example, driving the mobile mapping vehicle down Market Street in San Francisco you go from this to this.
Slide 184	You would not want to use the same mask angle both here and here. As you know reliance on the IMU alone can be unavoidable, but it is best when that is not necessary.
Slide 185	From the beginning the GNSS antennas have been an essential feature of mobile mapping sensor configurations. They continue to be essential to success. The antennas, *radio frequency* (RF) section, filtering and intermediate frequency elements are in the front of a GNSS receiver. The antenna collects the satellite's signals and converts the incoming electromagnetic waves into electric currents sensible to the RF section of the receiver.
Slide 186	Several antenna designs are possible in GPS, but the satellite's signal has such a low power density, especially after propagating through the atmosphere, that antenna

efficiency is critical. In all cases, they must be Right Hand Circular Polarized, (RHCP), as are the GPS signals broadcast from the satellites. Polarized waves oscillate in more than one direction. The electrical field vectors of the GPS Signal have a constant magnitude, but their direction rotates so that the electrical field vector of the wave describes a helix in the direction of propagation. Said another way, circularly polarized waves are those where the angle of the electric vector rotates around an imaginary line traveling in the direction of the propagation of the wave. The rotation may be either to the right or left. The GPS signal is a Right-Hand Circularly Polarized (RHCP) wave. You can illustrate it this way. With your right hand, give the *thumbs up* signal. Now, instead of pointing your thumb up, point it in the direction that the GPS signal is propagating. Your curling fingers show you the direction of the rotation of the field.
Slide 187 It follows that antennas like this microstrip design need to accommodate right hand circular polarization. Antennas like the one illustrated -
Slide 188 -are known as patch antennas. They have a low profile, a simple construction are durable and compact. In fact, most of the receiver manufacturers offer a *microstrip* antenna. The microstrip may have a patch for each frequency so it can receive one or all of the carriers-
Slide 189 -because just looking at the GPS carriers there are three wavelengths 19 cm (L1), 24 cm (L2) and 25 cm (L5) now.
Slide 190 The next most commonly used antenna is known as a *dipole*. This is the kind of antenna that was used with the Macrometer, the first commercial GPS receiver.
Slide 191 It is still incorporated into antennas like this choke ring with the Dorne-Margolin (DM) dipole in the middle, and this one It has higher gain at low-elevation angles compared to other antennas. It has a stable phase-center and simple construction, but needs a good ground plane to mitigate multipath and increase the antenna's zenith gain- the gain of the antenna straight up.
Slide 192 A *quadrifilar* antenna is a single frequency antenna that has two orthogonal bifilar helical loops on a common axis. In mobile mapping quadrifilar antennas perform better than a microstrip on crafts that pitch and roll, like boats and airplanes. They are also used in many recreational handheld receivers. Such antennas have a good gain pattern, do not require a ground plane, but are not azimuthally symmetric.
Slide 193 A *helix* is a dual frequency antenna. It has a good gain pattern, but a high profile. It is being applied to mobile mapping on unmanned aerial vehicles (UAVs) and are also being developed for cars.
Slide 194 Antennas that are a quarter or half wavelength tend to be the most practical and efficient, so GPS antenna elements can be as small as 4 or 5 cm.
Slide 195 An antenna ought to have a bandwidth commensurate with its application. In general, the larger the bandwidth the better the performance; however, there is downside. Increased bandwidth introduces more noise and degrades the signal to noise ratio. So, a GPS microstrip antennas must have high sensitivity, high gain, to operate successfully in the necessary range about 2 to 20 MHz, which corresponds with the null-to-null bandwidth of these L1 signals -
Slide 196 and since a GPS antenna is designed to be omnidirectional the gain pattern ought to be nearly a full hemisphere but still filter out the signals from very low elevations to reduce the effects of multipath and atmospheric delays.
Slide 197 Here is the gain of a GPS antenna compared to a theoretical lossless antenna,

known as an isotropic antenna, that has perfectly equal capabilities in all directions indicated by the bounding circles. As you see the contours around the actual antenna's phase center are not as perfectly spherical.	
Slide 198	The antenna's centering is also not perfect because the phase center of the gain pattern is not consistently coincident with the antenna's actual, physical, center. The phase center is not an immovable point it actually changes slightly with the satellite's signal. For example, it is different for the L2 signal than for L1 or L5. In addition, as the azimuth, intensity, and elevation of the received signal changes, so does the difference between the phase center and the physical center. Small azimuthal effects can also be brought on by the local environment around the antenna. But most phase center variation is attributable to changes in satellite elevation. In the end, the physical center and the phase center of an antenna may be as much as a couple of centimeters from one another or as little as a few millimeters. In any case, this is another reason for the necessity of -
Slide 199	Synchronizing the Data Streams. So, we are back where we began. In Mobile Mapping we mount the sensors necessary to solve a mapping particular problem on a common platform. Each of those sensors have strengths and weaknesses. We accomplish the best results by synchronizing their data streams together. Therefore, we'll now discuss synchronizing the data from all the sensors and placing the results in the mapping frame reference system.
Slide 200	Each of these sensors has its own position, orientation and coordinate system too. It is clearly not possible to co-locate the center of the laser scanner and origins of the navigation subsystems. So, you must consider the three-dimensional offsets between them. They are called the lever arms in mobile mapping parlance. One is between the centers of the laser scanning instrument and the IMU. Another between the IMU and the cameras and one between the GNSS receiver and the IMU center. This one can be measured with a combination of tacheometry and photogrammetric bundle adjustment, but the correlation of this lever arm with other error sources like the boresight values, GNSS errors, etc. makes that approach difficult-
Slide 201	-and since it has most often been quantified during the assembly of the onboard combined GNSS/IMU system it is usually not considered in the positioning equation of MMS. Therefore, the term "lever-arm" in a mobile mapping system (MMS) is understood to mean the offset between the centers of the sensing instruments, such as the laser scanner, and the IMU.
Slide 202	The most common way of measuring the lever-arm is with a combination of tape measurements and the engineering drawings supplied for the IMU and-
Slide 203	-laser scanner, etc. -
Slide 204	This method does presume that the drawings show axes and the origins of the subassemblies correctly and the IMU and sensor are mounted to a common frame so there will not be differential motion between them during data collection because any remaining lever-arm error is a constant bias on MMS derived target positions regardless of the range.
Slide 205	The lever arm is considered in the positioning equation.
Slide 206	Ok, but how does a Mobile Mapping system and the positioning equation combine the measurements of the GNSS/IMU and the sensor to establish the position of the target .
Slide 207	First, please note that the center and three-dimensional orientation of the IMU axes makes up what is known as the body, or b-frame. It differs from the center and

orientation of the axes of the sensor which is known as the s-frame. The coordinates of the target -
Slide 208 -are first derived from the sensor's measurements, of course. So those coordinates are initially in the s-frame and symbolized by P ,position s & target indicating the target coordinates in the sensor frame
Slide 209 R rotation b-frame & s-frame stands for the rotation matrix from the body frame to the sensor frame; α,β,γ are called the boresight angles about the y, x and z axes respectively. They are used to determine the differences, the offsets, between the sensor's axes and the IMU axes mentioned earlier and then are used to correct the rotation angles from inertial system to the sensor's system.
Slide 210 As you know a b and s is the lever-arm offset between the GNSS/IMU center of the body frame to the sensor's center of the s-frame. Now we need to bring in the mapping frame.
Slide 211 After all the overall objective is to have the target coordinates in the mapping frame, the m-frame. However, these three-dimensional axes of our objective are also in a different rotation, different from the s-frame and the b-frame too, so R, rotation m and b is the rotation matrix between the mapping frame and the body frame to help with that.
Slide 212 Here are the GNSS/IMU center coordinates by P position IMU expressed in the mapping frame, the m-frame.
Slide 213 Finally by using all those terms in the calculation we arrive at the target coordinates in the mapping frame, the m frame **P** position m and target.
Slide 214 You may wonder about the significance of ¤t□ the epoch in all this. Time is quite an important factor, for example, all of these variables must be determined at the time of the pulse in order to georeference even one LiDAR return. This is somewhat complicated by the fact that the GNSS/IMU sampling of the position, attitude, and motion of the scanning platform are usually at a much slower rate than the pulse rate of the laser. In order to match the GNSS/IMU sampling rate with the sampling rate of the laser, GNSS/IMU measurements are interpolated to line up with the LiDAR measurements. Then, these positions and attitudes are combined via this equation to create a final, georeferenced point cloud.
Slide 215 So that is how you can have the position of the fire hydrant in the mapping reference system from the Mobile Mapping vehicle.
Slide 216 It looks like we have time for some questions

$$P_{target}^{m}(t) = P_{IMU}^{m}(t) + R_{b}^{m}(t)\left(a_{s}^{b} + R_{s}^{b}(\alpha, \beta, \gamma)P_{target}^{s}(t)\right)$$