MR. DOYLE: Thank you Dan. Back in the days when I was in the field parties I was on the triangulation party, we thought we were a whole lot better because we were two dimensional, level guys were only one dimensional. I think you get an appreciation now for the difficulty of this process of defining a vertical data, something we oftentimes take very casually, but it's a very difficult process for us to design and maintain and, obviously, one that is absolutely critical to our national infrastructure. I now would like to introduce Dr. Richard Snay. He just recently retired from the National Geodetic Survey and he was one of the great leaders in helping us develop and manage our continuously operating reference station network. Richard.

DR. RICHARD SNAY: John, how come we all got old but you stayed young? There's a story about a math professor; he was commiserating one of his academic colleagues and he'd say, the first time I taught calculus, nobody understood it. The second time, still nobody understood it. The third time, yes, I understood it. I would like to tell that story to remind myself that this is very much a learning experience for me as it is for you. Let us start with the concept of an earth-centered earth-fixed reference frame. By earth fixed, we mean that it is rotating with the earth so the axes stay with the earth. So, the Z-axis we choose as earth's pole of rotation, and the X-axis is in the equator is the Prime Meridian, and the Y-axis is just a perpendicular direction to those two. So, there you have a right hand system. And your scale is a meter (stick); however, your measuring system can best work in meters. Now, X, Y, Z is fine, you can get all your positions in that, but we introduce an ellipsoid so that we can work in something that's more familiar with us. Once we have done this, there are complications because of the Earth's dynamics. For instance, the pole of rotation does not pierce the earth surface at the same point it moves over days, weeks, and months -- it's constantly moving. If you can slide through the next few slides. This is sort of shows the duality – go ahead – between the X, Y Z system and latitude and longitude height system. And I'm not going to give you a lesson in geodesy, but I want to see this and until you get to the cartoon.

Ellipsoid. Okay, so we have two systems, X, Y, Z and latitude longitude height, and this cartoon shows why we don't normally do it X, Y and Z. X, Y, Z is convenient for us to do all the computations, but we use latitude and longitude and height because they have physical meaning to us. For example, when I was a boy scout, they told me that latitude was the elevation angle to the north star, Polaris, longitude was time, and height was how far a ball would fall, if I dropped it, before it hit the ocean.

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So I'm going to talk about three earth centered earth fixed reference frames. And the first one is the North American datum of 1983, which is the legal reference system in the United States, and in this country the National Geodetic Survey is responsible, in Canada, it's the Geodetic Survey Division. Mike Craymer, our colleague from the Geodetic Survey Division, is here today. It was first realized in 1986, it was revised when we did HARN surveys, high accuracy reference network surveys, and revised again when we did our introduction to the CORS program. Originally, it was essentially a horizontal reference system, but it has evolved to 3 dimensional reference system thanks to GPS. But I lie, it is not a 3dimensional reference system, it is a 4 dimensional reference system. More about that later.

Next slide.

We found out that the center of the reference system was two meters off from the center of the Earth because when we defined NAD 83, the best space measurements we had were the transit Doppler and that's how good they were, so we found out later that we were off by this two meters, or so. In 1990, we worked with Canada and we redefined it so that NAD 83 would become mathematically equivalent to what was then ITRF, the international terrestrial reference frame of 1996. The idea is that if you know the coordinates and one reference system, you can compute the exact coordinates in the other reference system, it’s not an approximation, it’s an exact equation, it’s a definition of NAD 83 now. And vice-versa, if you know the NAD 83 coordinates you can compute the 96 coordinates. Also in this definition, we were careful to state that we wanted it to be the frame to be moving with the North American plate because the North American plate is moving with respect to other places and we want to be that our reference frame stayed with the North American plate.

This is sort of the history of where we have gone in NAD 27. Back then, we really didn't have a concept of absolute accuracy. We talked in terms of relative accuracy in terms of how well it was that we through the distance for direction between two points as a function of how far apart those points were. When we introduced NAD 83 in 1986, the original one, we did have a concept because we had the Doppler. And that gave us an accuracy, in an absolute sense, of about a meter. And we – but still, we refer to the relative accuracy between the points because the relative accuracy was much better than a meter. Then, we introduced the HARN, high accuracy reference network; these were passive reference stations that were positioned by GPS. We did it state by state, and we found is that we could get much better relative positions and much better absolute positions. And then, our early 90's area, we introduced CORS, the concept between absolute and relative position blurred. So we just talked in terms of how accurate they were, the coordinates were. Horizontally we thought they were on the order of two centimeters, and then the vertical, ellipsoid height that is, they were four centimeters, give or take. This is the HARN network. You can see some states are more ambitious than others, and we introduced a datum for each state.

The next slide is the Continuously Operating Reference Stations. This was a – covered the whole United States plus stations in New Mexico, Canada, Afghanistan, Iraq, Ethiopia – these are GPS receivers that work 24 hours a day, 7 days a week, and GPS data is made available to you. We work with over 200 agencies to make this data available to you.

Okay. Now, let me go through a little naming convention here at NGS, our jargon, to so-to-speak. We wanted to differentiate between the different realizations of NAD 83 so we put a name inside a bracket and call that name a datum tag. So the original NAD 83 we call NAD 83(1986) and again this was based mostly on triangulation data, trilateration data and Doppler data. Yes, we did have some GPS data, but only a handful of measurements, and there was some VLBI in there also. But these are the three major observing systems. Then, with the HARN, we identified the year that the observations were made and this is not always true but, for the most case, it was. So we go to state, and Tennessee was the first state and we did that survey in 1987. So that datum, or that realization, of NAD 83 in Tennessee was called NAD 83(1987) and we went through all the states. Now when the CORS came along, we

introduced what is called, NAD 83(CORS96). The 96 refers to that this datum was the one that was defined in terms of ITRF 96. This is when we made the mathematical connection between ITRF and NAD 83 that exists still today. Then, a few years ago, three years ago, we wanted to get all the statewide datums, if you will, as one and we wanted to make them consistent with the CORS. So we did an adjustment and called that NAD 83(NSRS2007).

Next slide.

The first HARN surveys were completed between 1987 and 1997. Next: But what we found out is GPS equipment at that time was not as good as we thought, or was not as good as you think it is today. Also we didn't have satellite orbits just solved the obits along with the satellite positions. But then the IGS orbits came along, and so we could solve the positions, hence we went through each datum again and got a new realization of NAD 83 in each state. That occurred between 1997 and 2005. This was part of the height modernization project. Okay. And then, we adjusted all of these statewide networks again with other GPS surveys and we completed and those were completed in 2007.

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Okay so this adjustment removed the discrepancies on the order of three to six centimeters, and also made it consistent with the CORS network. This is the reference framework we call NSRS 2007.

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Now, this is the international jargon. Instead of talking about datums we calling it a geometric reference system and this is just a rule for assigning position forms to points on the earth, a theoretical construct. Then, a reference frame is an actual realization where you actually assign quadrants to specific points. So the difference between a system, which is a theoretical thing, while a reference frame is an actual thing. So in terms of NAD 83, the term NAD 83 itself is a reference system, when you put the datum tag on there, then it becomes a reference frame. So just to say that this is NAD 83 is not precise enough, you have to say what realization of NAD 83. The term realization here is important because that's how the system becomes a frame, by actually assigning quadrants to points.

Now, the next reference system I want to talk about is WGS 84 and by far, I think this is the most popular reference system in the world, simply because GPS positioning is done with respect to WGS 84. The Department of Defense is the responsible agency. Originally, John Bossler and his colleagues did an excellent job he worked DoD so that NAD 83 and WGS 84 could be the best possible. But in the early 90's, the Department of Defense redefined WGS 84 so it became consistent because ITRF, as opposed to NGS, because they realized that they wanted to be geocentric because most of their military applications needed for them to be geocentric around the world. This is a map. The circles on this map show where the tracking stations for the WGS 84 are, and there is about a dozen of them. What they do is they determine what the ITRF coordinates are for those points and then solve for the orbits and positions of the satellites from those ground points, so the orbits, even though you are talking about WGS 84, are

almost the same as ITRF. WGS 84 has, itself, gone through several versions or realizations, the original one is called WGS 84 (Transit), this was the one that was this was based on NAD 83 because this was based on the Doppler system; this was before GPS. Then, when they went to the new GPS system for defining WGS 84, they would put in parenthesis, the name of the GPS week that was introduced. So we have gone through three of them so far. If you call transit, there's four of them and people in the Department of Defense told me they were going to introduce a fifth one in 2011 to be consistent with ITRF 2008. So again WGS 84 is a reference system, when you put the parenthesis or the datum tag, whatever you want to call it, inside that becomes a reference frame. So it is not precise enough to say that my coordinates are in WGS 84, you have to say they're in WGS 84 (G1150), or whatever, because they have changed over time.

Okay, we talked about the international reference system. This is developed by the academic community. There is an agency called International Earth Rotation and Reference Frame Service (IERS), which is sanctioned by the IAG , the International Association of Geodesy, that is responsible for defining this. And, then the definition so that they become the international standards for origins orientation scale. And, the way they realize it is by positions of law, several hundred points around the world.

Over the years, they introduced several reference frames. ITRS is a system, just a definition. So they take certain measurement types and they define a reference frame, that is, they assign quadrants to points, and ITRF 88. And at first, they were doing it every year, but recently, they have slacked off, and now, they are only doing it every few years. The current one is ITRF 2005, but within a month, or so, we expect they will adopt ITRF 2008. The meaning of 2008 means they will use observations up through the end of 2008, so even though it will not be adopted 2010 they will call it ITRF 2008. You see here the type of measurements that are involved, GPS, VLBI, Satellite Laser Ranging and DORIS and I'm not going through that, because I got more slides than Dan does. The neat thing about it is the combination of several solutions and besides each one of these techniques is an institute or consortium of people that do that solution so the GPS people do one solution and so forth and so on. But even in a GPS, there are 8 different analysis centers around the world that independently do the solution and then merge at the highest level; that goes to the IGS, and the IGS submits that combined solution to the IERS, and then the IERS combine with the satellite rating, and so forth. So it is very rigorous. These are the stations that were used for defining ITRF-96. Since then, there are several more stations that have been added, especially in the southern hemisphere.

Okay. Now, they had to tackle the problem of what do you do about plate tectonics. Each continent, or so, is on a stable, more or less stable, plate and they are all moving at the rate of several centimeters a year and which plate do you say is the reference plate? The way they address that is instead of picking one plate, they said let's make it so that over the whole surface of the earth, the average horizontal motion is zero, no average horizontal motion. So, what that mean is now, that each plates as they move, so here you see the motion in the north American plate and sort of a counter clockwise rotation and actually the rotation pole is down there near Ecuador. And I don't think you can read the numbers, but down near Florida it's on the order of one centimeter a year, and up along the Canadian border its two centimeters as year, and if you go further up than there it's even more. Also, over in Hawaii, which is right here, the motion is

about seven centimeters a year, and you can see the Pacific Plate moving differently, and then there is the Caribbean Plate down in the lower right hand corner, and so forth.

So now, we have all these reference systems and all these reference frames, but mathematical linked by something called Helmert similarity transformation. Similarity simply means that you are preserving the shape. A Swiss Mathematician determined, several centuries ago, that if you have motion along the surface of a sphere it can be defined by three rotations. So what you have is three translations, three rotations, and one differential scale.

If you sort of step through the next slides there, what this shows is the effects of the first translation, go ahead, keep going on, and this looks like the affect on ellipsoid heights. So by moving, shifting the origin, you actually change the ellipsoid height.

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This shows the motion or the relationship by rotating it between the NAD 83, in green, and the ITRF, in blue, how the X-coordinate changes.

The next slide.

Okay, so this is the 7 parameter transformation that Canada and we adopted in 1988 or so, and you see the 7 parameters. And if you look at the top 3 translations, that's where you get the 2.2-meters, or so, between the different origins. The way we come up with this is we had about 12 VLBI stations in the United States, and at the time this was the most precise definition of coordinates in the United States and in Canada, and we had ITRF coordinates and we had NAD coordinates and we just solved for the best parameters that defined them, but if you look at the rotation, it's not just a single parameter, it is a linear equation as function of time, t is time in that, which means that the rotations are not constant but they are rotating with the surface of the earth. And those parameters, Canada and I, us, adopted them so them agree with the latest geophysical model for motion. So those three parameters of the time thing are the plate motion of the North America plate according to ITRF. So instead of seven parameters, we really have ten parameters, and if you think that the others should also be a function of times, then, you have fourteen parameters, two times seven.

OKAY, this is just a little bit of mathematics showing that if you know that you know the transformation from ITRF 96 to NAD 83 you can also get the transformation from the other datum to between other datums, simply by summation of them, simply adding the coefficients one by one. And then, if you want to know transformation from B to A, you can get the one from A to B just by changing the sign. Okay. Now, we have some software we call horizontal time position which has all of these equations coded into them and they have the 14 parameters to go through from all the different values of ITRF, all the different values from WGS 84, and NAD 83. What we would like to do is encourage the software companies to encode these equations in their software and low-and-behold, one software company does, and has done so. So, hopefully this will be picked up by other software companies.

Okay, now, let's talk about replacing NAD 83. What we want is a geocentric reference system. And I see two options; there may be more, and we can talk about that this afternoon and tomorrow. Option one is to just go with ITRF 2,000, or whatever, whichever one is current when we decide to go there. The other one is to pick a reference frame that agrees with ITRF 2000XX at some instance of time. But then, it slowly moves with the North American plate so that the coordinates remains constant and stable in the North American plate. Let's look at those two options. The first option, the advantage is that there would be one reference frame, in the whole world, wouldn't that be great. Put all the software transforming companies out of business, but for the rest of us, it would be great. So that, like I said before, WGS 84 is equivalent to ITRF 2000 currently, and will be made equivalent to ITRF 2008 when ITRF 2008 comes along. So first thing, we would all be WGS 84 or ITRF, whatever your favorite system is, NAD would evolve to that. The disadvantage though, would be that the points inside of North America would be moving. And in eastern and central North America, the motion would be on the order of one to two centimeters a year. However, in the areas near the plate boundaries like California, or western Oregon, Western Washington, Alaska, or Canada, the motion would be more than two centimeters a year. So that is option one. Option two is to pick it so that the North American plate moves with the reference frame. So that advantage is that points in the eastern part of the North America would have no significant horizontal motion. The disadvantage of that is that we need a different reference frame for each plate, one for the North American plate, Canada, Mexico, so forth. But in Hawaii, we would need a model for the Pacific Plate. For Puerto Rico and the Virgin Islands we would need a model for the Caribbean Plate. For Guam we would need a model for the Philippine Plate. Also, if you're near a plate boundary, they don't move with the plate, the interaction between the plates causes deformation within them. So that a single model would not work. So this is a picture of plate tectonics on the major plates, the boundaries between the plates bottom are red where they have spreading between plates, the blue is where we have convergence between plates, and the yellow, like in California, is where the two plates are moving parallel to one another. So in North America, most of it is on the North America plate except California, and they can fall off any time. Hawaii is on the Pacific Plate, Puerto Rico is on the Caribbean plate, and Guam is on the Philippine Plate.

Okay, so what if we go with a plate fix model like NAD 83 is? Recently, Chris Pearson and some other people, have come up with what the motion is in the western United States relative to stable North America, and the interval here is four millimeters per year. So everything in white is less than four millimeters per year. This is fixed in North America. So everything to the east of that blue is supposedly less than four millimeters per year. So as you go further west across the boundary of Washington and California, you go up to a maximum of about five centimeters a year. So in this, even if we pick a fixed North American plate, what are the people on the West Coast would have to deal with here? So what is the choice, ITRF or fix North America? Either or. Either or. Well, what if we looked at an analogy with time, we have essentially two different time systems; we have universal coordinate time with global applications, and we have local time within a single time zone, and we have grown accustomed to that. We know how to transform from one to the other because we've made it for the most part so they can just add or subtract a few integral number of hours and you go from one to the other. So we have learned to live with that. Can we do the same thing in a geospatial world? Can we live with two reference frames, one for global, or interplate motion, of interplate applications, and one for intraplate

applications. So you would have really two sets of coordinates for every point depending on which you are talking about, the international application like the military has or the FAA has when they are flying planes from the United States to Europe. So you have two. In the conversion between the two would be simply three parameters, transformation would be a rotation rate, three rotation rates.

Okay, this is the last slide before I get the hook.

So this is a concern with horizontal motion. Now, my colleagues and I, or my former colleagues – I don't know how to say it, I retired a week ago – of doing reprocessing all the CORS and one of the benefits of that is to come up with a map of vertical velocity. This is a primary view of that, but the most comprehensive map we have to date of what the vertical velocity is. And the idea of this map is that now we have ideas of what the vertical velocity is, we don't – we can stop being concerned about that, and not think of the vertical edge or stable or just talk about the motion in Houston, Galvaston, or Southern Louisiana. We can actually quantify that now, and let me stop there.

MR. DOYLE: As I mentioned earlier, a lot of food for thought. Speaking of food, good time to obviously to break for lunch, a couple of things before we do that. Again, I would like to take this opportunity to remind everyone about the minute session signup sheet outside. Do us a favor please, if you sign up for a minute session, write your name very legibly, so we can read it and pronounce it I hope. Lunch is going to be served in the Science Center. We would ask that our NOS colleagues allow all our visitors to go ahead first and then we can follow on. And I would also like to invite all of you, if you see somebody around who represents one of our sponsors to give them a little thanks and just to reiterate, the sponsors are the Coastal and Geodetic Survey, The Heritage Society, the National Society of Professional Surveyors, the Potomac Chapter of the American Society for Photogrammetry and Remote Sensing, ESRI, TOPCON, and especially the American Association of the Geodetic Survey; and of you see any AAGS members, give them a special big pat on the back. So, we will break for lunch until 1:30. I invite you all to take time to talk to Richard, to talk to Dru, to talk to Dan, and others from NGS who were involved in this process and get some more information we will come back at 1:30 and start with our panel sessions. Thank you.