Scintillation Effects On Space Shuttle GPS Data

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BIOGRAPHIES

John L. Goodman is employed by United Space Alliance at the NASA Johnson Space Center. He is currently assigned to the Mission Operations Directorate Rendezvous Guidance and Procedures Office, where his duties entail Mission Control Center support and creation of new Space Shuttle cockpit displays. Mr. Goodman graduated from the University of Arizona in 1986 with a B. S. in Aerospace Engineering. His experience includes Space Shuttle flight software verification, and integration of Global Positioning System (GPS) and Embedded GPS Inertial Navigation System (GPS/INS or EGI) units for the Space Shuttle and Crew Return Vehicle.

Leonard Kramer has interests in numerical methods and modeling and has experience in industrial applications of the microwave properties of emulsions. He is a member of the technical staff for United Space Alliance in Houston, Texas. He has participated in research concerning the earth rotation and earth atmosphere angular momentum, and modeling of a high-energy ion population in the Venus ionosphere. He received a B.S. degree in Mathematics in 1981 from Towson State University; a B.S. degree in Mechanical Engineering from the University of Maryland in 1985; and an M.S. in 1991 and a Ph.D. in 1993 in Space Physics from Rice University.

ABSTRACT

Irregularities in ionospheric electron density result in variation in amplitude and phase of Global Positioning System (GPS) signals, or scintillation. GPS receivers tracking scintillated signals may lose carrier phase or frequency lock in the case of phase scintillation. Amplitude scintillation can cause "enhancement" or "fading" of GPS signals and result in loss of lock. Scintillation can occur over the equatorial and polar regions and is a function of location, time of day, season, and solar and geomagnetic activity. Mid latitude regions are affected only very rarely, resulting from highly disturbed auroral events. In the spring of 1998, due to increasing concerns about scintillation of GPS signals during the upcoming solar maximum, the Space Shuttle Program began to assess the impact of scintillation on Collins Miniaturized Airborne GPS Receiver (MAGR) units that are to replace Tactical Air Control and Navigation (TACAN) units on the Space Shuttle orbiters. The Shuttle Program must determine if scintillation effects pose a threat to safety of flight and mission success or require procedural and flight rule changes. Flight controllers in Mission Control must understand scintillation effects on GPS to properly diagnose "off nominal" GPS receiver performance. GPS data from recent Space Shuttle missions indicate that the signals tracked by the Shuttle MAGR manifest scintillation. Scintillation is observed as anomalous noise in velocity measurements lasting for up to 20 minutes on Shuttle orbit passes and are not accounted for in the error budget of the MAGR accuracy parameters. These events are typically coincident with latitude and local time occurrence of previously identified equatorial spread F within about 20 degrees of the magnetic equator. The geographic and seasonal history of these events from ground-based observations and a simple theoretical model, which have potential for predicting events for operational purposes, are reviewed.

INTRODUCTION

Development of an operational GPS unit to replace TACAN was begun in 1994. The Shuttle Program desired an off the shelf, in-production military unit to take advantage of the existing production line, logistics base and proven firmware. The Collins MAGR, a 5 channel unit developed in the early 1990s, was selected for the Shuttle. The Shuttle program is an authorized user of GPS.

The Shuttle Program directed that GPS be integrated "in parallel" with the existing "baseline" navigation on the orbiters [1]. This architecture treats the GPS receiver as a complete navigation system. MAGR/S state vectors are not filtered by the Shuttle flight software, but pass through a series of Quality Assurance (QA) checks and a selection algorithm before being incorporated into navigation. The MAGR/S units receive position, velocity, and attitude aiding from the Shuttle flight software during all flight phases.

The MAGR blends pseudo range and delta range (range rate) observables along with aiding data in a state solution using a Kalman filter that employs process noise tuned to a high level. The high process noise protects the receiver state somewhat against unmodeled walk offs, simplifies the firmware design, and makes it somewhat generic in applications. The MAGR filter and navigation algorithms were designed so that the unit could be integrated into a wide variety of platforms without having to substantially modify the Kalman filter for each application. Filter tuning assumes a worst case inertial measurement unit and receiver clock. The downside to that approach is that the receiver is not optimized for space navigation. As a result, MAGR/S velocity error, and the resulting semi-major axis error, are not acceptable for orbit maneuver planning and rendezvous. MAGR/S performance is more than adequate to support emergency deorbit and landing.

A single MAGR/S unit (the "single string" configuration) is being flown on each orbiter for several years during a test and certification program. The MAGR/S flown during the test phase has two antennas, on the top and bottom of the crew compartment. Input from the antennas are passed through pre-amplifiers and a signal combiner before reaching the MAGR/S.

Once the MAGR/S units and Shuttle support software for GPS are certified, the three TACAN units on each orbiter will be removed and two MAGR/S receivers will be added, for a total of three MAGR/Ss per orbiter.

Antennas for the two additional MAGRs are on the top (Figure 1) and bottom (Figure 2) of the nose in places formerly occupied by TACAN antennas. The first "three string GPS flight" (no TACAN) is expected to occur no earlier than 2003.
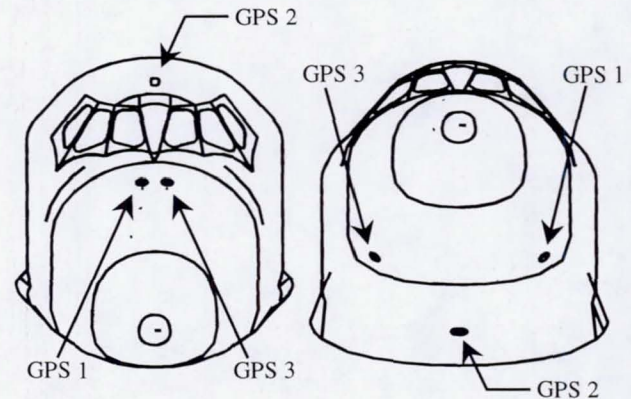
Figure 1: Upper GPS Antenna Locations   **Figure 2: Lower GPS Antenna Locations**

The first flight of the MAGR/S (single string) was on STS-79 in September of 1996. MAGR/S data was available in "real time" to Mission Control personnel during ascent and entry. More flights followed (STS-81, 82, 84, 85, 89, 91, 95, 88, 96, 103, 99, 101, 106 and 92) as each orbiter in the fleet was equipped with a single MAGR/S receiver. STS-91, June 1998, was the first flight during which GPS data was available "in real time" to Mission Control personnel during the orbital phase of flight.

In January of 1998, the Flight Director Office at the NASA/JSC held a series of meetings to review the Shuttle GPS project and identify potential safety concerns. One issue identified was the impact of ionospheric scintillation on GPS. United Space Alliance personnel began an extensive literature search on the subject and discussed the issue with ionospheric experts within the GPS community.

On the evening of November 3, 1998, during the flight of STS-95, NASA Mission Control Ascent/Entry Guidance and Procedures Officer Glenn Pogue noted two periods of "noisy" GPS velocity. The phenomenon was observed on two consecutive orbits, as the Shuttle Discovery was off the west coast of South America, during the early evening hours. The noisy velocity was in the range of 5 to 7 feet/second for about 5 minutes. Based on the scintillation study conducted the previous spring, ionospheric scintillation was identified as the most probable cause. Subsequent analysis, discussed in this paper, supports that conclusion.
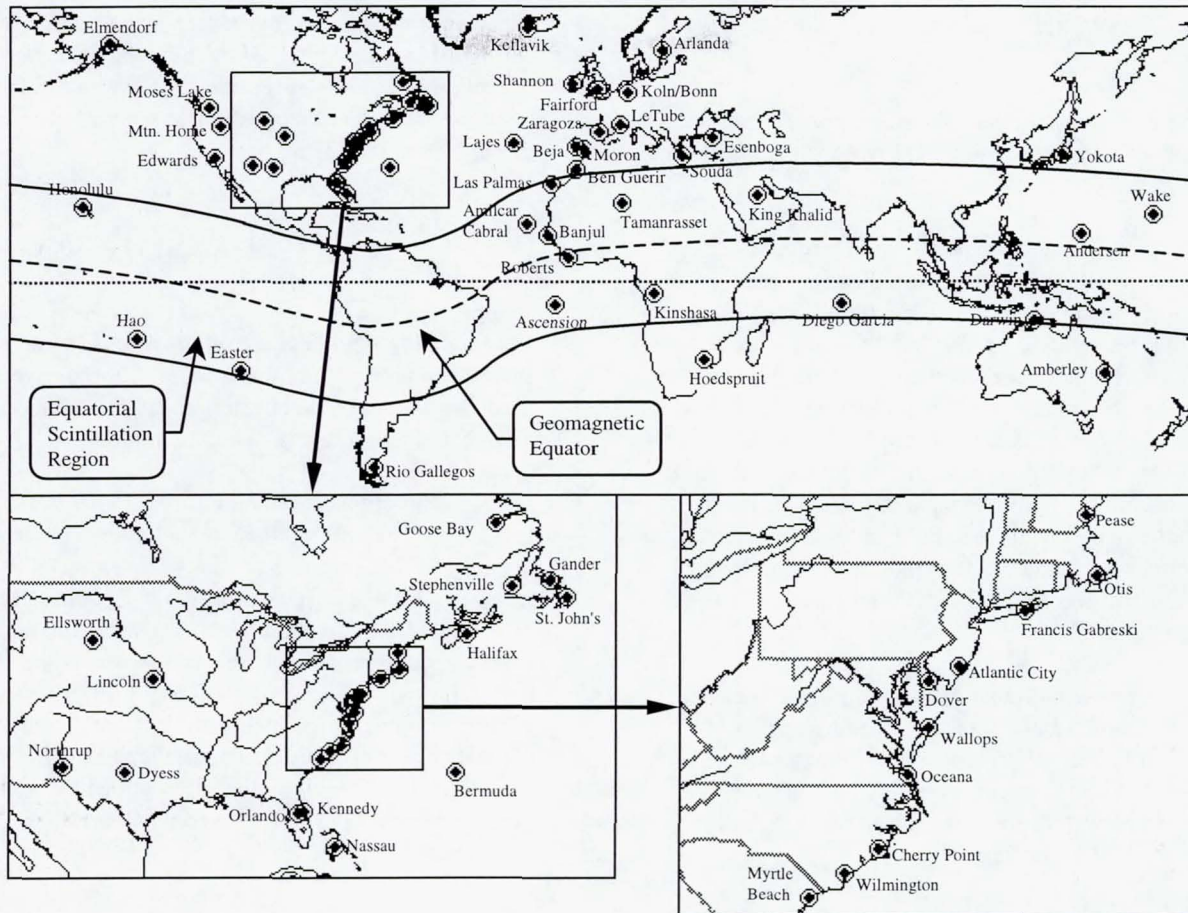
Space Shuttle Program Approved Landing Sites

**Figure 3: Magnetic Equator, Equatorial Scintillation Region
(Appleton Anomaly) And Shuttle Program Landing Sites**

REVIEW OF SCINTILLATION MECHANISM

Scintillation is thought to result from variability in the ionospheric index of refraction associated with depleted ionospheric density occurring at low to mid latitudes (Figure 3) and in Polar Regions. Although the GPS dual frequency correction is very precise, especially in a low dynamic regime, the detail of how the radiation interacts with ionospheric irregularities is more complex.

The literature discusses modes of interference attributed to an inhomogeneous ionosphere. When an inhomogeneity is placed between the radiation source and receiver, wave front paths are distorted and overlap, resulting in interference effects and areas of highly attenuated signal. Titheridge [2] and the work by Yeh and Liu [3] are thorough treatments of the physics of this radio wave scintillation.

The geophysical causes of the ionospheric irregularities are described in many sources and have been the subject of research for many years. The book by Kelly [4] is a good starting point for readers interested in this aspect of the phenomenon.

The primary contributions to index of refraction are in the altitude regions approximately between 150 to 400 kilometers. This happens also to be the operating altitude of the Shuttle. For the class of radiation represented by the GPS signal in the ionosphere, there is almost no energy loss resulting from absorption. The permittivity, which is the material property determining index of refraction, is accurately determined according to a dispersion relationship:

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$$(1) \qquad \varepsilon(\bar{x},t) = \left(1 - \left(\frac{\omega_P(\bar{x},t)}{\omega}\right)^2\right)\varepsilon_0$$

where ε_0 is the free space dielectric constant, ω is the frequency of the radiation, and $\omega_P(\bar{x}, t)$ is the plasma frequency.

Plasma frequency is a normal mode frequency associated with displacement of electrons relative to the heavy positive charge carriers in the plasma. Plasma frequency is proportional to the square root of free electron number density and is therefore a function of time and position in the ionosphere. Equation 1 proceeds from an application of Maxwell's equations to a plasma requiring that electron thermal motions are negligible compared to displacements from the radiation electric field and that magnetic field perturbations to the electron motions are negligible. These conditions prevail at GPS frequencies in the ionosphere.

As the wave front transits the medium, the net effect is an interference pattern accumulated by reason of a phase shift over all possible paths between the transmitter and receiver. For any path between the transmitter and receiver, the phase of the radiation may be computed according to:

$$(2) \qquad \delta\phi_S = \frac{\omega}{c\sqrt{\varepsilon_0}}\int\sqrt{\varepsilon(\bar{x},t)}ds$$

where s is an arbitrary path and c is the speed of light. The electric field for the received signal is accumulated over all possible paths:

$$E(x,t) = E_0\sum_s e^{i(\delta\phi_S - \omega t)}$$

$$(3) \qquad = E_0 e^{-i\omega t}\sum_s e^{i\delta\phi_S}$$

$$= E_0 e^{-i\omega t}\Phi(\bar{x},t)$$

where $E_0 e^{-i\omega t}$ is the electric field at the transmitter and i is the complex value $(-1)^{1/2}$. The parameter $\Phi(\bar{x},t)$ is a complex valued phase envelope that modulates the received signal resulting from interference.

We see from equation (3) that the receiver may experience regions where $\Phi(\bar{x},t)$ is zero, effectively extinguishing the signal. If the time variations in $\varepsilon(\bar{x},t)$ of equation (2) are slow compared to variations resulting from the motion of the spacecraft, then through equation (3) we have:

$$(4) \qquad \frac{dE(x,t)}{dt} = E_0 e^{-i\omega t}\left(-i\omega\Phi(\bar{x},t) + \vec{\nabla}\Phi(\bar{x},t)\cdot\vec{V}\right)$$

The changing field in equation (4) results from the forward motion, $\vec{V}$, of the spacecraft through the gradients in a variable interference phase envelope. This can effectively alias a signal modulation.

Velocity directly scales the perturbing effect in equation (4). The relative importance of such interference is apparent by looking at the order of magnitudes of the terms in parenthesis in equation (4). Specifically, ω is of order 10^{10} radian per second and this is the normal frequency accepted by the receiver. Any signal aliased by the forward motion with velocity $\vec{V}$ of order 10^4 meters per second permits an order of magnitude estimate of the relative change in the phase envelope. This causes a velocity perturbation of order 1 meter/sec (seen in Figure 4), which is in turn caused by the ionospheric variability:

$$(5) \qquad \frac{\vec{\nabla}\Phi(\bar{x},t)}{\Phi(\bar{x},t)} \approx 10^2 m^{-1}$$

Equation (5) is our estimate of the relative scale of variability in the phase envelope. The scale of gradients in equation (5) are necessary in order for the velocity term to make any effective contribution to the signal seen by the receiver.

We speculate that this gradient is associated with the GPS signal path intercepting very high plasma gradients associated with smaller scale irregularities within plasma voids or bubbles previously identified in low latitude regions. These kind of irregularities are also present in polar regions and we may be seeing some evidence of scintillation in that region as well. High gradients are not unexpected since the geomagnetic field inhibits cross field transport and the boundary between bubble (vacuum) and plasma should be no wider than an electron gyro-radius.

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For an orbiting vehicle, velocity is about 10 times greater than terrestrial applications, and the risks associated with ionospheric variability are proportional to that increased velocity. On entry and landing of the Shuttle, the effect is mitigated since velocities have dropped to more conventional values.

Geographic distributions of ionospheric inhomogeneities are due to several processes occurring in the upper atmosphere. Processes occurring at low latitude are believed to be most important for Space Shuttle operations. At equatorial latitudes, scintillation results from the interaction of the GPS radiation with ionospheric depletions associated with the Appleton Anomaly. The theoretical mechanism for creation of these depletions has been studied for many years and is believed to be related to the appearance of a plasma instability that interacts with the geomagnetic field, giving rise to meridionally oriented wedge shaped bubbles or voids. The depletion mechanism is enhanced when sunset occurs simultaneously at the regions where conjugate points of the dipole magnetic field intersect the collision dominated altitude bands in the ionosphere. It is complemented by seasonal variability in the motions of the neutral atmosphere at ionosphere heights and geographic variability in the declination of the magnetic field [5]. This is the cause of certain seasonal variability in occurrence. More recently, Knight and Finn [6,7] in a series of papers describe models that incorporate scintillation physics with statistical behavior of geographic and seasonal occurrence. These models may permit operational prediction.

It is important to emphasize that the Appleton Anomaly is entirely distinct from the South Atlantic Anomaly. The well known region of weak magnetic field in the South Atlantic permits high energy plasma of solar and magnetospheric origin to reach low altitudes and creates a radiation hazard to flight crews in that region. We have no theoretical or observational basis to expect any effect on the electromagnetic signals from the GPS satellites as a result of the South Atlantic Anomaly. Conversely, the plasma in the regions confined to the Appleton Anomaly is shielded from the magnetosphere and does not represent any known biological hazard.

It is clear then that any theory explaining the phenomenon we are reporting in this paper must take into account the nearness of the Shuttle to inhomogeneous ionospheric structures. It should also account for the high velocity of the spacecraft and geomorphology of the ionospheric processes. The velocity scaling effect that we believe to

be operative in the phase noise reported here is not the usual manifestation of scintillation reported for ground observations. It is, never the less, clearly related to the regions associated with scintillation.

ANALYSIS OF FLIGHT DATA

Velocity noise has been noted in comparisons of the MAGR velocity with the onboard navigation state and the post flight Best Estimate of Trajectory (BET) (Figure 4). So far, velocity noise has been identified on Space Shuttle missions 106 (September 2000), 101 (May 2000), 99 (February 2000), 96 (May-June 1999), 88 (December 1998), 95 (October–November 1998) and 91 (June 1998).

The noise lasts anywhere from 5 minutes up to 20 minutes. The noise has been observed to peak as high as 11 feet/second, but most of the time is below 5 feet/second. This is outside the MAGR/S 3 sigma (three times the root mean squared) velocity specification of 0.3 feet/second, and is greater than the acceptable noise in the existing Shuttle navigation system. MAGR/S position comparison analysis did not exhibit noise.

During some noisy velocity events, the velocity vector from the MAGR/S failed a QA check. In some cases, the comparison of the current velocity with the previous MAGR/S velocity (propagated to the current time) exceeded a threshold. Another quality assurance check that was occasionally failed involved a compare between the current navigation velocity vector in the Shuttle computers and the current MAGR/S velocity. Those MAGR/S state vectors whose velocity failed one or more of the quality assurance checks would not have been considered for use in updating the Shuttle navigation state.

Examination of pseudorange and delta range residuals obtained via the MAGR/S Instrumentation Port indicate that the MAGR/S Kalman filter is processing noisy delta range residuals from all four satellites tracked for measurements (Figure 5). Carrier frequency lock is maintained, and there is no degradation in signal strength. One instance of loss of lock occurred (channel 2), due to the satellite being off the gain pattern of the antennas. The MAGR/S FOM remained low (Figure 6), except for one period of non-optimum satellite geometry.
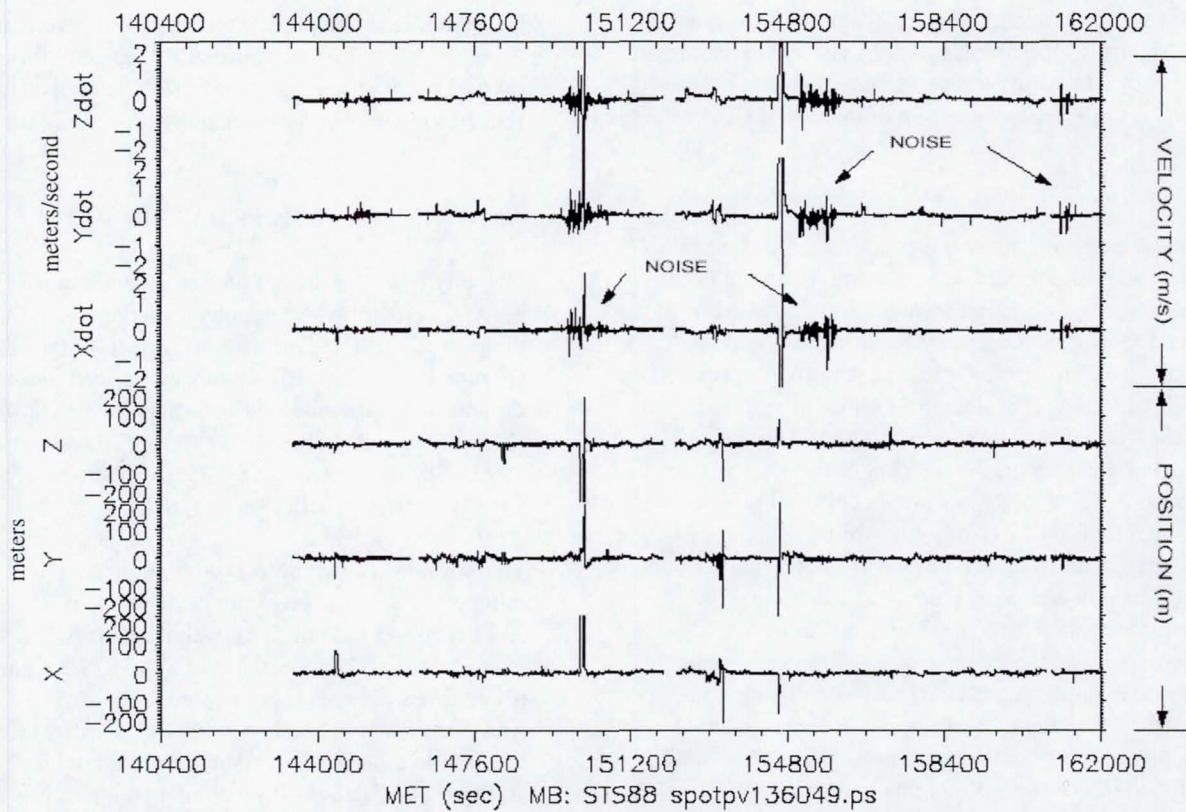
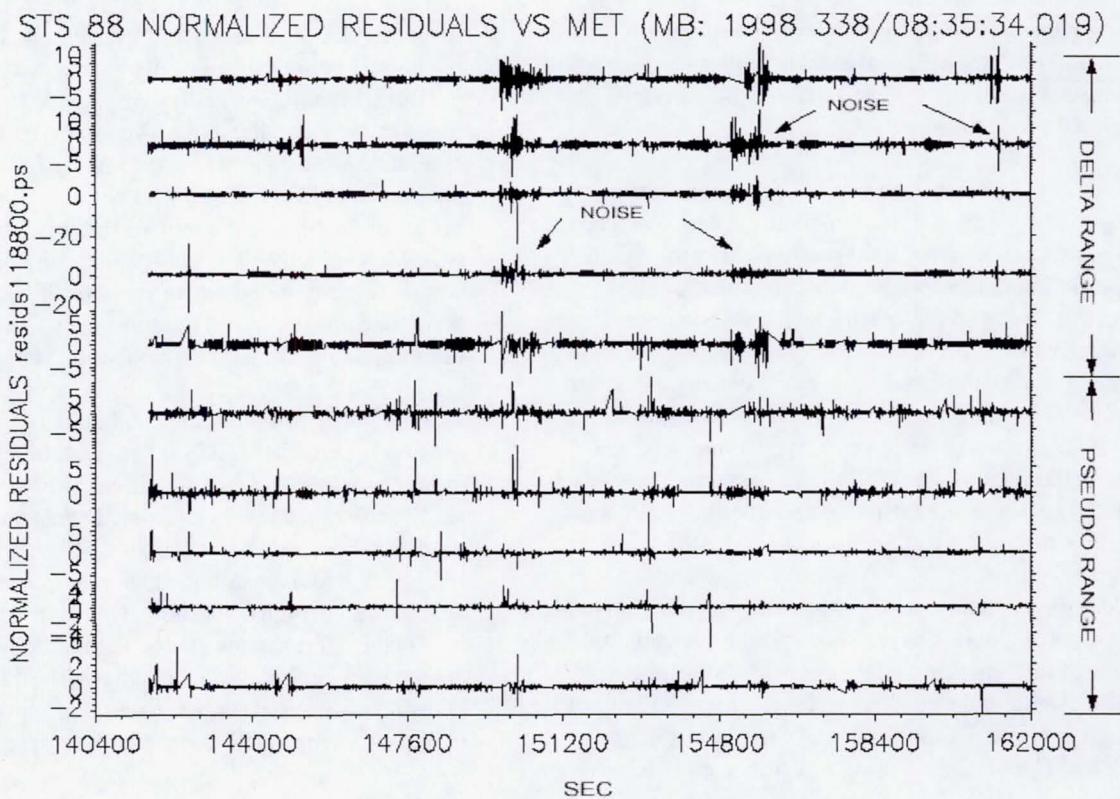**Figure 4: Inertial Position And Velocity Errors During Three STS-88 Noisy Velocity Periods.**

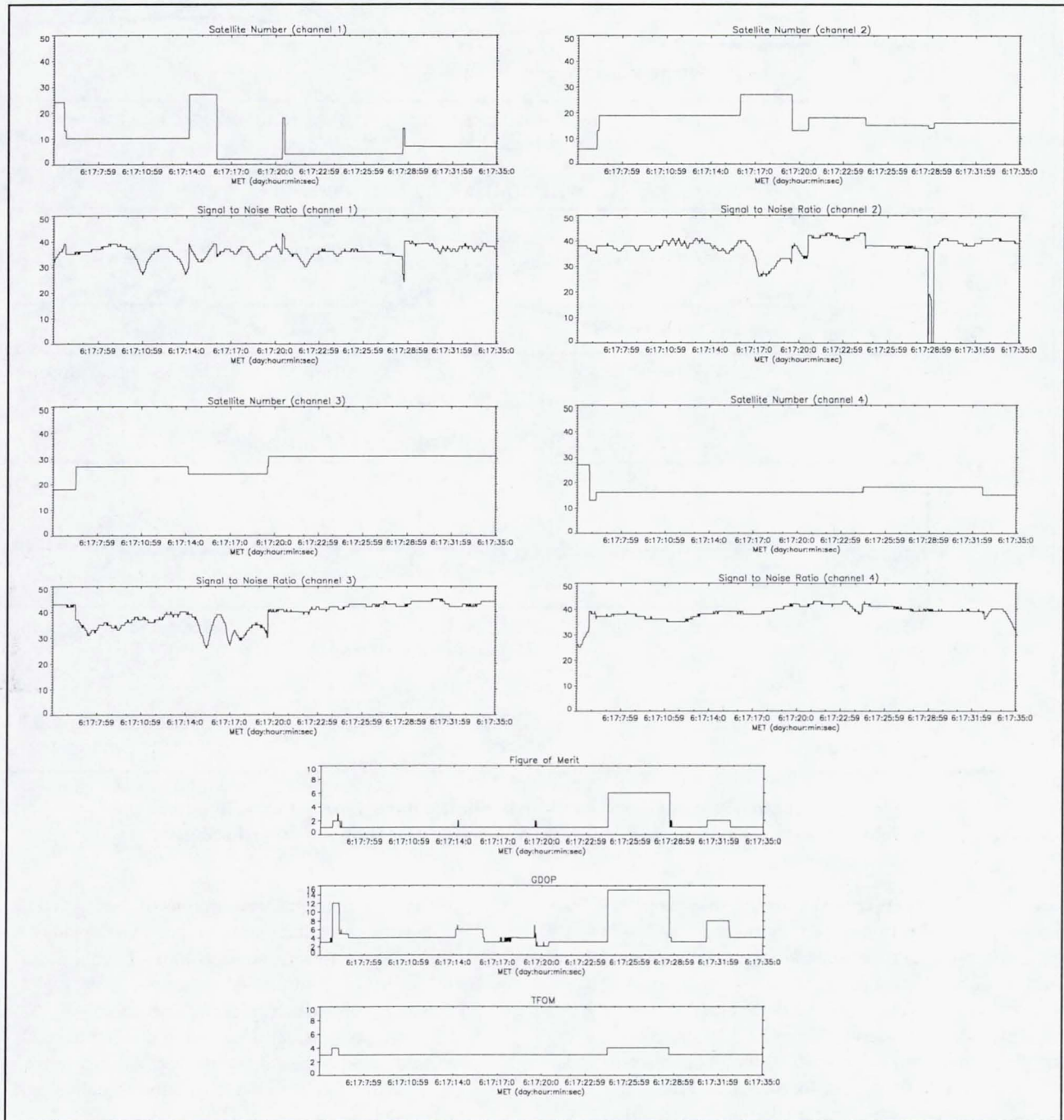**Figure 5: Normalized Measurement Residuals Per Hardware Channel, STS-88.**
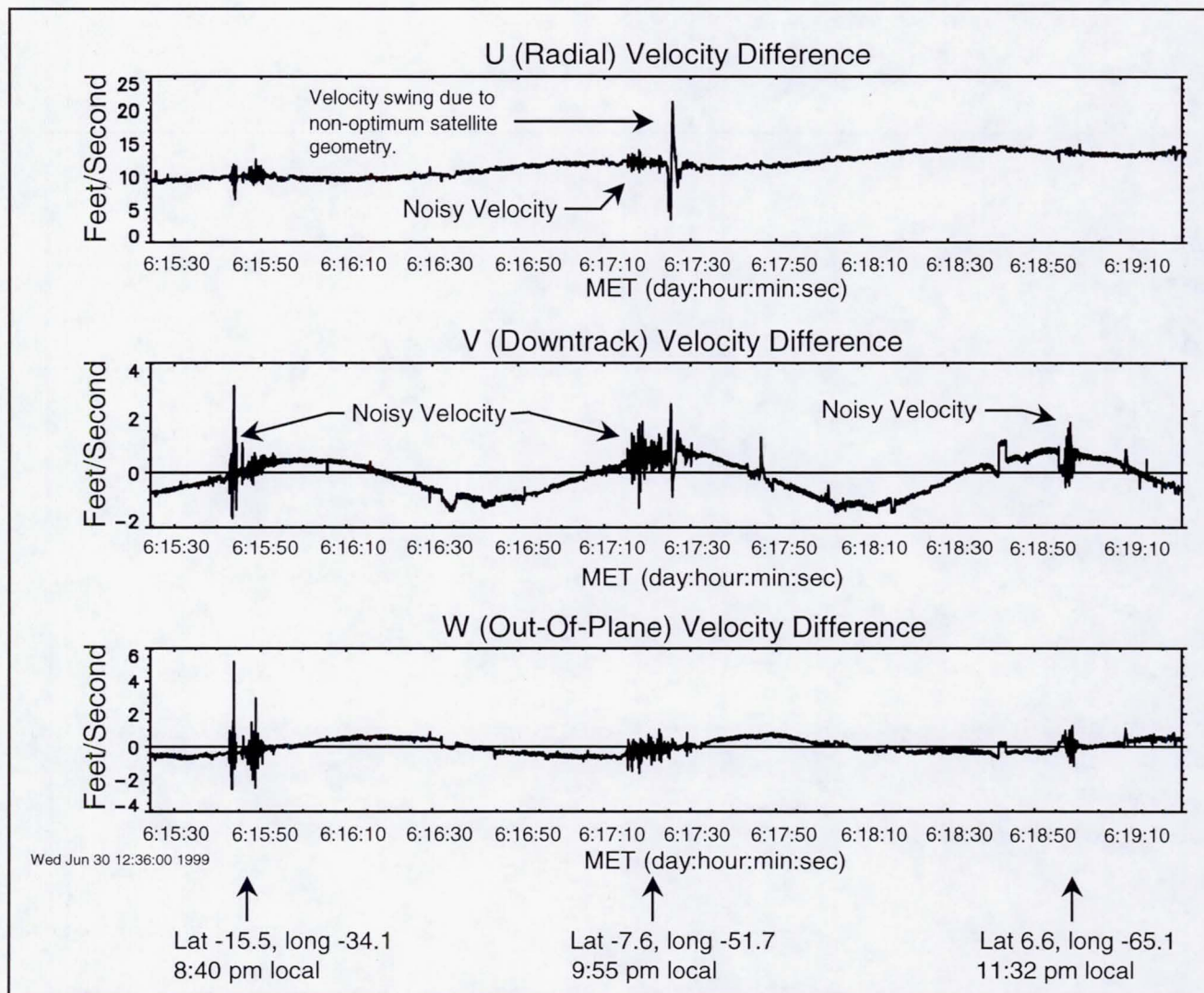
Figure 6: Channel Data For An STS-88 Velocity Noise Period

Figure 7: Comparison of GPS velocity with Shuttle navigation velocity, illustrating velocity noise periods on three consecutive orbits. Bias is due to error in Shuttle navigation state.

Noisy velocity events tended to occur on two or three consecutive orbits (Figure 7). "Pairs" and "triplets" of velocity noise events are separated by time periods (17 to 21.5 hours on some flights). After several events occurred during STS-88, it was determined that pairs and triplets were spaced by about 21.5 hours. This enabled future events during the flight to be reliably predicted. Predictions were forwarded to Mission Control personnel, who verified that noisy velocity periods occurred within 2 or 3 minutes of the predicted times.

Early in the investigation, attitude maneuvers and translational burns for orbit maintenance/rendezvous were ruled out as the cause of the velocity noise. Since occurrences of ionospheric scintillation are most

likely over the equatorial regions of the Earth and between sunset and midnight, plots were made illustrating position and local time. Location and local time of the noisy velocity periods are consistent with descriptions of equatorial ionospheric scintillation found in the literature. It should be noted that there are also velocity noise periods that fall outside the equatorial regions and evening hours.

Most STS-99 (February 2000) (Figure 8) events occurred over the Pacific Ocean, off the coasts of Central and South America. During STS-88 (December 1998) (Figures 9 and 10) and STS-95 (October-November 1998) (Figures 11 and 12), most velocity noise periods were over or near South
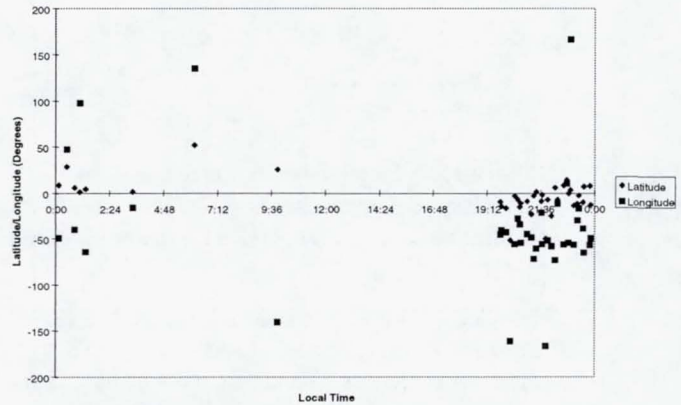
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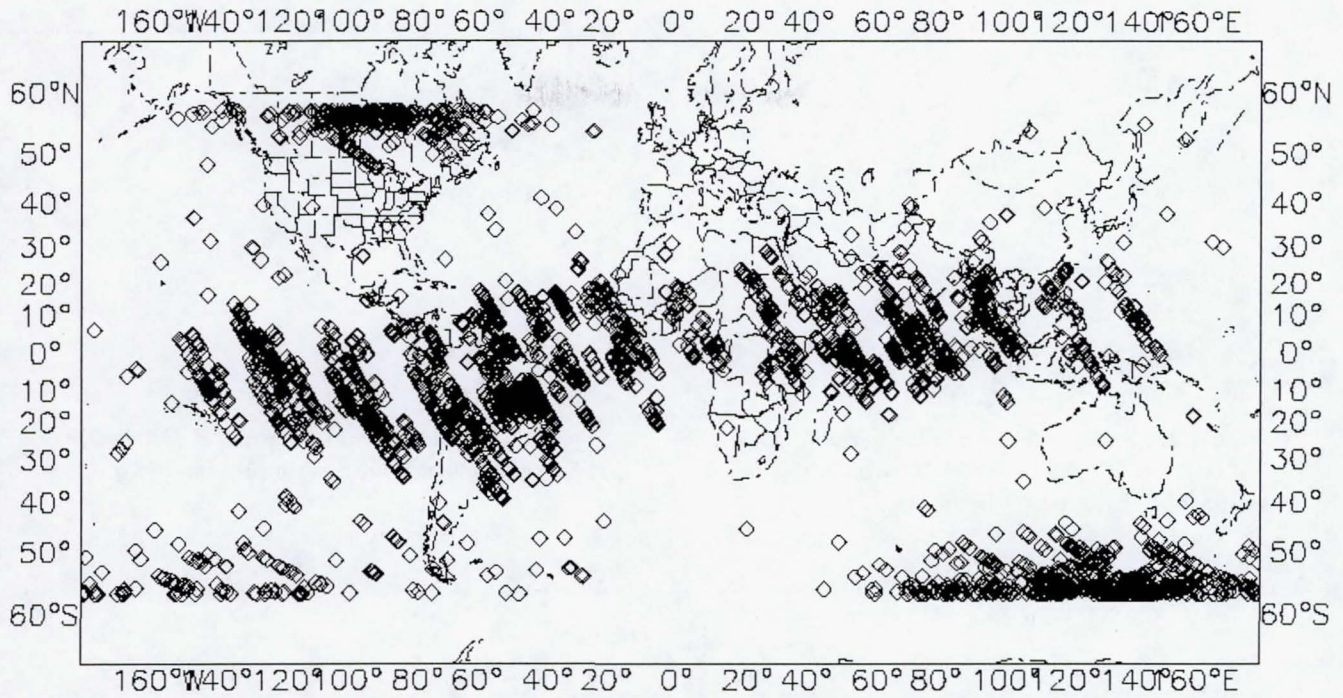
Figure 8: STS-99, GPS normalized delta range residuals > 2 sigma and FOM = 1. Events < 2 seconds after satellite switches excluded. Orbital altitude approximately 126 NM, 57 degree inclination. Mission flown from 2/11/00 to 2/22/00.
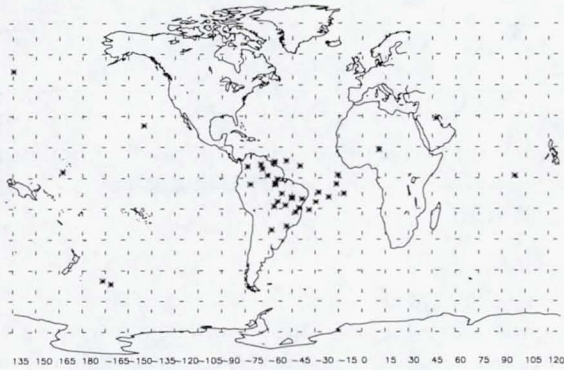
Figure 9: STS-88 velocity noise midpoints. Mission flown from 12/4/98 to 12/15/98. Orbital altitude ~ 210 NM, 51.6 degree inclination.

Figure 10: Geographic and temporal distribution of STS-88 velocity noise period midpoints.
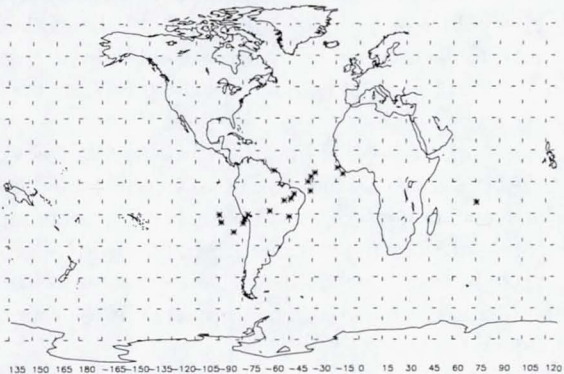
Figure 11: STS-95 velocity noise midpoints. Mission flown from 10/29/98 to 11/7/98. Orbital altitude ~ 310 NM., 28.45 degree inclination.

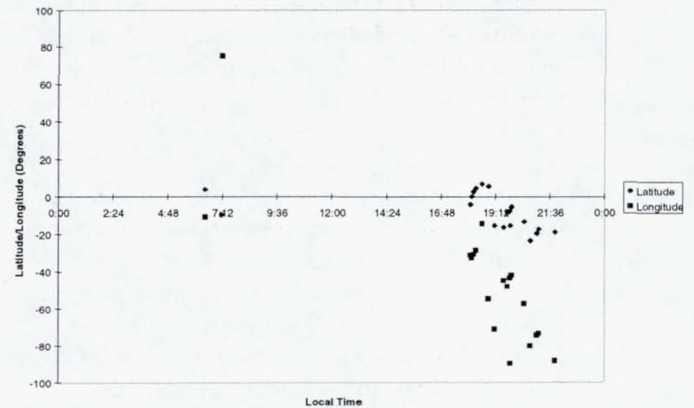Figure 12: Geographic and temporal distribution of STS-95 velocity noise period midpoints.

Figure 13: STS-96 velocity noise midpoints. Mission flown from 5/27/99 to 6/6/99. Orbital altitude ~ 205 NM,, 51.6 degree inclination.

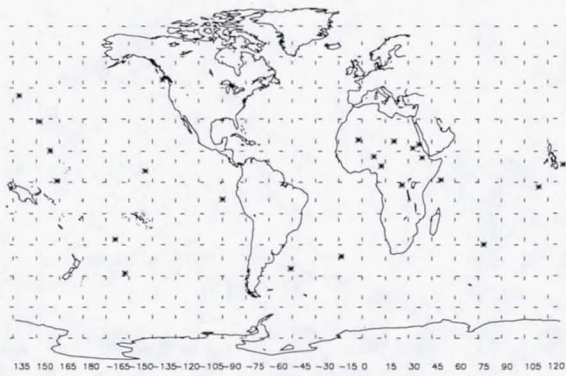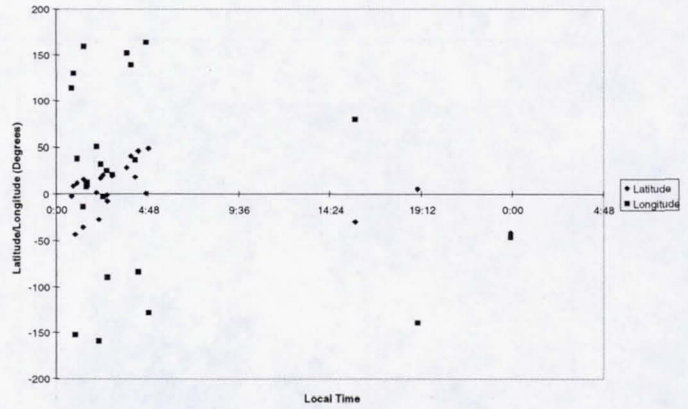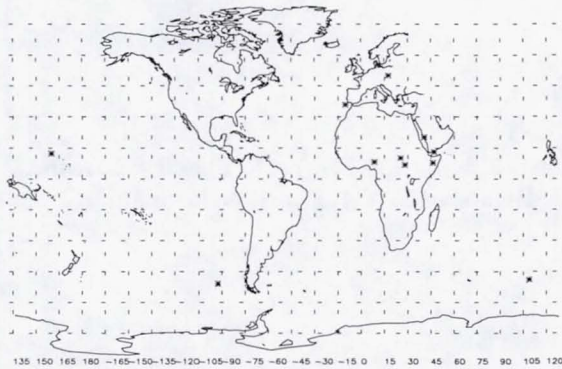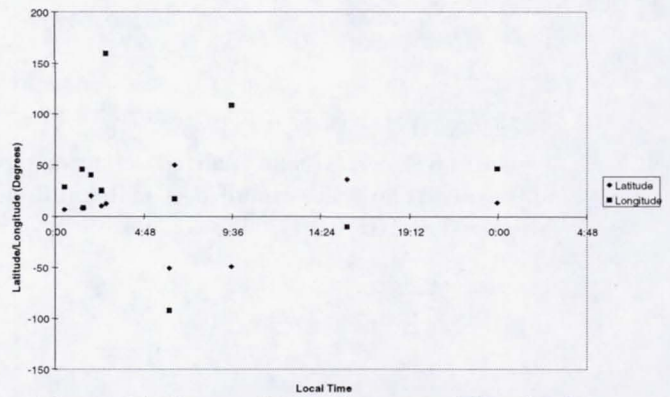
Figure 14: Geographic and temporal distribution of STS-96 velocity noise period midpoints.

Figure 15: STS-91 velocity noise midpoints. MAGR/S was operating from 6/2/98 to 6/8/98. Orbital altitude ~ 200 NM., 51.6 degree inclination.

Figure 16: Geographic and temporal distribution of STS-91 velocity noise period midpoints.

America between sunset and midnight. For STS-96 (May-June 1999) (Figures 13 and 14) and STS-91 (June 1998) (Figures 15 and 16), most of the events occurred over Africa between midnight and 5 a.m. (local time).

Winter missions exhibit more velocity noise than summer missions, although the statistical support for any causal relationship to season is not present. No velocity noise periods have been identified during vehicle entry.

The absence of any apparent fading of the signals through the scintillation structures indicates that the MAGR/S is sensitive enough to detect this noise but that the physical variations are too small to effect any significant variation in the phase envelope of equation (3), which would result in fading. Further, this suggests that the scintillation structures

themselves are not associated with any extinction of the transmitted signal. This implies that the phase envelope results from only a minor perturbation of the wave front consistent with the idea that the spacecraft is close to the ionospheric anomalies. It is likely, based on our theoretical arguments, then, that the high velocity of the spacecraft is amplifying the received scintillation. We would encourage more work utilizing the methods similar to those described in Knight and Finn [6,7] and in Yeh and Liu [3] to help understand this phenomenon.

Other work to improve filtering using the dynamics of the orbit and inertial measurements to remove the noise is also encouraged. The MAGR/S is not optimum in this regard. Recent work on the Mission Control ground filter by United Space Alliance shows that the velocity perturbations are completely eliminated by appropriate Kalman filtering.

For the on-orbit phase of flight, some MAGR/S state vectors during velocity noise events "fail" QA checks in the Shuttle computers. The noise seen thus far does not pose a problem for use of MAGR/S state vectors for emergency deorbit. MAGR/S vectors are not accurate enough to be used for on-orbit maneuver planning and rendezvous. The GPS ground filter developed by United Space Alliance will remove any velocity noise effects.

SCINTILLATION INDUCED SIGNAL FADING

The scintillation manifestation most frequently discussed in the literature is signal fading that leads to loss of lock or acquisition failures. No signal fading has been observed on Space Shuttle missions that could be attributed to ionospheric scintillation.

Testing of a stationary, unaided MAGR under equatorial scintillation conditions with signal fading has been conducted using the Air Force Research Lab (AFRL) Antenna Wave Front Simulator (AWFS) [8]. Published results indicated that signal fading due to scintillation results in frequent loss of lock, code phase tracking without carrier frequency tracking, and higher FOM values.

Published data from the AFWS tests are very similar to MAGR/S performance during the "plasma" region of entry. The plasma region refers to that period during entry when atmospheric drag ionizes the gas surrounding the spacecraft and blocks radio communication. Plasma effects begin to degrade Shuttle lower antenna tracking of GPS satellites as high as 320,000 feet. Upper antenna tracking begins to degrade about the time of the first roll maneuver (typically around 285,000 feet). In spite of the plasma, the MAGR/S still tracks 1 to 4 satellites during the plasma region. Frequent loss of lock occurs, along with loss of carrier frequency lock (code lock is maintained).

Upper antenna plasma effects begin to subside by around 217,000 feet, and continuous code and carrier frequency tracking on four satellites resumes by 200,000 feet. Lower antenna tracking can be degraded by plasma until around 185,000 feet.

It is anticipated that any fading during entry resulting from ionospheric scintillation would have the same impact on the MAGR/S as the effect of plasma described above. The effects are postulated to be loss of lock/reacquisition, incomplete data collection, and

code tracking without carrier frequency tracking. Scintillation can cause extended periods of less than four satellite tracking, failed ephemeris collection and suboptimal satellite geometry due to failed navigation satellite changes, and difficulty in collecting GPS satellite ephemeredes. Continuous less than four satellite tracking, failed satellite acquisitions and failed ephemeris downloads can result in an increasingly inaccurate MAGR/S state vector. Signal fading induced by ionospheric scintillation has not been observed during entry.

The overall effect of severe fading due to scintillation would be "loss of service," since the state from a receiver could fail one or more of the QA checks and not be a candidate for selection to update the Shuttle navigation state. With three receivers on the Shuttle that have different antenna bore sights, it is likely that all three MAGR/S units will not be tracking the same satellites. Scintillation effects will vary between the three receivers. The best defense is simply to have the receivers powered on as long as possible before entry to allow the receivers to collect as many ephemerides as possible. The orbiter does not have to have continuous GPS tracking throughout entry to obtain GPS vectors for navigation.

Nominal Space Shuttle landings occur in the continental United States, well away from the magnetic equator. Signals from one or two tracked satellites may pass through equatorial scintillation plumes. However, due to the entry ground track, it is likely that not all visible GPS satellite signals would be scintillated.

Landing sites in the equatorial scintillation region are for emergency purposes only. For these landing sites from sunset to midnight, the orbiter may fly under scintillation plumes ("overhead scintillation"). This could result in scintillation of all visible satellite signals. Due to orbiter ground track and plume geometry/kinematics, the orbiter would probably not experience a "scintillated sky" all the way from entry interface to landing if performing emergency landings or Trans Atlantic Landings.

IMPACT OF SCINTILLATION INDUCED VELOCITY NOISE ON SPACE SHUTTLE USE OF GPS

During the flights in question, GPS was not used operationally by the Shuttle navigation system, as it is not certified. The observed velocity noise posed no threat to orbital or entry operations.

Observed velocity noise is lower than the guidance constraints for entry. These constraints define maximum position and velocity errors which the Shuttle guidance and flight control system can "fly out" and still land safely.

As a result of the theoretical velocity dependence on the scintillation induced noise, noisy state events are expected to be less severe on entry than on orbit. The degree of mitigation is as much as an order of magnitude because the Shuttle is slower on entry by that amount.

On orbit, MAGR/S states (both with and without scintillation induced velocity noise) are not accurate enough for use in maneuver planning by Mission Control. A Mission Control based GPS ground filter is currently being developed by United Space Alliance to support the International Space Station (ISS) and the Space Shuttle [1]. This filter will process ISS GPS (an unauthorized user) and Shuttle MAGR/S state vectors to provide vectors that are accurate enough for orbit maneuver planning and rendezvous. The ground filter will be designed to incorporate the gravity field, solar and lunar perturbations, atmospheric drag and inertial measurements to eliminate the effects of scintillation induced velocity noise.

While the possibility of scintillation impacts on MAGR/S performance exist, available data and theory suggests that it is not a threat to mission success or safety. Furthermore, ionospheric scintillation cannot currently be accurately forecast or nowcast to permit operational decisions to be made by RF users (satellite communications and GPS).

SCINTILLATION IMPACTS ON OTHER SPACE–BORNE USERS OF GPS

Two emerging uses of GPS for space applications consist of GPS attitude determination [9] and formation flying of satellites [10]. Both attitude determination and some relative GPS systems use carrier phase tracking, which is more vulnerable to scintillation than the carrier frequency tracking employed by the MAGR. Scintillation can easily disrupt carrier phase tracking, and make it difficult for receivers tracking carrier phase to resolve integer ambiguities.

Whether or not scintillation would impact a GPS receiver is a function of the receiver's tracking loop design and Kalman filter tuning.

SUMMARY

Flight tests of a Collins 5 channel Miniaturized Airborne GPS Receiver (MAGR/S) on the Space Shuttle have revealed scintillation effects in the velocity data. Noisy velocity of up to 11 feet/second occurs for periods from 5 to 20 minutes. Spatial and temporal characterization of most of the events matches that in the literature for equatorial ionospheric scintillation. Analysis of flight data indicates that the MAGR Kalman filter is processing noisy delta range measurements and that appropriate filter tuning could mitigate the effects of scintillation. The absence of significant levels of signal fading is due to the proximity of the Shuttle to the regions of variable ionospheric density that are scintillating the GPS signals. Velocity dependence of phase scintillation indicates that any scintillation induced velocity noise that occurs during entry would be lower than that seen on orbit. Ionospheric scintillation is not believed to be a constraint to certifying GPS as a TACAN replacement for the Shuttle program. The Shuttle Program will continue to monitor MAGR/S flight data, developments in scintillation physics, and user experience in the GPS arena. Spacecraft using GPS units that employ carrier phase tracking (attitude determination, formation flying) may be especially vulnerable to ionospheric scintillation. Shuttle GPS data indicates that an orbiting platform can be used to quantify the spatial and temporal characteristics of ionospheric scintillation on a global scale. More work needs to be done to characterize scintillation physics, GPS receiver performance, and develop an ionospheric scintillation "forecast/nowcast" capability.

REFERENCES

[1] Goodman, John L., "Space Shuttle Navigation In The GPS Era," *Proceedings of the National Technical Meeting 2001*, Institute Of Navigation, Long Beach, CA, January 22-24, 2001.

[2] Titheridge, J.E., "The Diffraction of Satellite Signals By Isolated Ionospheric Irregularities," *Journal of Atmospheric And Terrestrial Physics*, 1971, 33, pages 47-69.

[3] K.C. Yeh and C Liu , Radio Wave Scintillation in the Ionosphere, *1982 Proc. IEEE*, 70(4,) pages 324-259.

[4] Kelley, M. C., The Earth's Ionosphere: Plasma Physics and Electrodynamics, Academic Press, San Diego, 1989.

[5] Aarons, J., "The Longitudinal Morphology of Equatorial F-Layer Irregularities Relevant to Their Occurrence," *Space Science Reviews*, 1993.

[6] Knight, Mark F., and Anthony Finn, "A Comparison of Predicted and Measured GPS Performance in an Ionospheric Scintillation Environment", Australian Defense Science and Technology Organization (DSTO), *Proceedings of ION GPS-99*, September 14-17, 1999, Nashville, Tennessee, pages 1437-1450.

[7] Knight, Mark F., and Anthony Finn, "The Effects of Ionospheric Scintillations on GPS", Australian Defense Science and Technology Organization (DSTO), *Proceedings of ION GPS-98*, September 15-18, 1998, Nashville, Tennessee, pages 673-685.

[8] Jacobs, Denise, et. al., "Test Bed For Evaluation Of GPS Receivers' Performance In Ionospheric Scintillation – A Progress Report," *Proceedings of the 1998 National Technical Meeting of the Institute Of Navigation*, January 21-23, 1998, Long Beach, CA.

[9] Lightsey, E. Glenn, Greg C. Blackburn and James E. Simpson, "Going Up: A GPS Receiver Adapts To Space," *GPS World*, Volume 11, Number 9, September 2000, pages 30 - 34.

[10] Bauer, F. H., et al, "Enabling Spacecraft Formation Flying Through Spaceborne GPS and Enhanced Autonomy Technologies," *Proceedings of the ION GPS-99 Conference*, Nashville, TN, September 14-17, 1999.

Scintillation Effects On Space Shuttle GPS Data
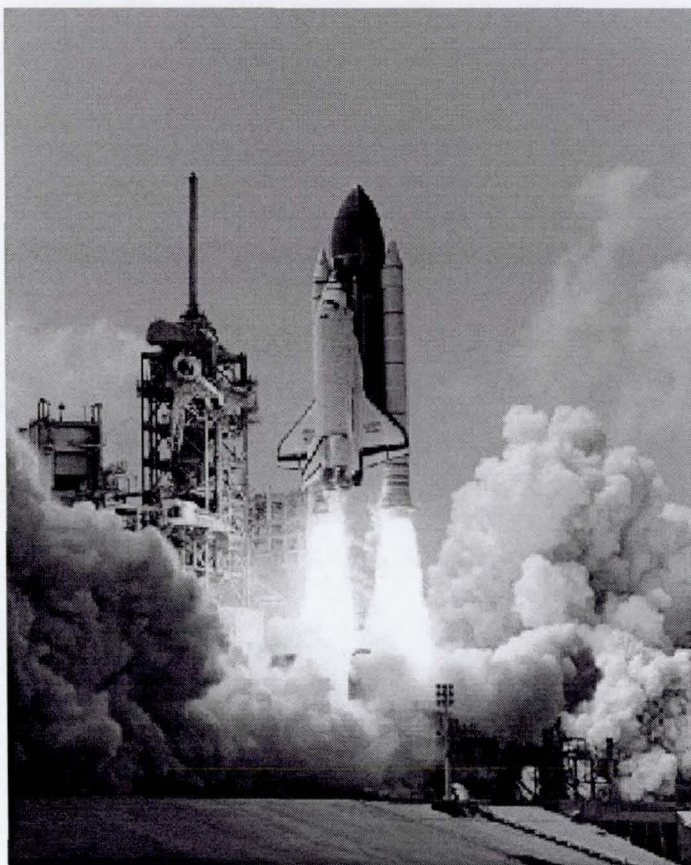
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Agenda

- Space Shuttle Program GPS Effort

- Overview Of Ionospheric Scintillation

- Noisy GPS Velocity Observed During Shuttle Missions

- Impact Of Scintillation On Shuttle Program Use Of GPS

- Conclusions

Space Shuttle Program Is Certifying GPS To Replace TACAN

- A keyed, 5 channel Collins Miniaturized Airborne GPS Receiver (MAGR) is onboard Endeavour, Discovery and Atlantis for data collection. Columbia will first fly a MAGR on STS-107.

- MAGR flights began with STS-79 in September, 1996.

- Once the MAGR is certified for TACAN replacement, 3 MAGRs will replace 3 TACANs on each orbiter. First flight without TACAN expected no earlier than 2003.

Scintillation Is Caused By Electron Density Irregularities

- Volumes of density irregularities sometimes called "plasma bubbles" or "scintillation structures." These appear in the polar regions associated with the aurora, and in equatorial regions at night.

- Rapid variation in amplitude and phase of GPS signals (twinkle, twinkle little star).

- The geophysical causes are reasonably well understood and involve factors related to solar wind interaction with the Earth's magnetosphere and ionosphere. However, the temporal and spatial variability of scintillation structures is highly variable and not well understood.

- GPS satellite motion, drift of scintillation structure and motion of GPS receiver determine level of scintillation seen by receiver.

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Most Severe Scintillation Occurs In The Equatorial Region

Space Shuttle Program Approved Landing Sites

Equatorial
Scintillation
Region →

Geomagnetic
Equator

(Map of Space Shuttle Program Approved Landing Sites with labeled sites including Elmendorf, Moses Lake, Ellsworth, Mountain Home, Edwards, Northrup, Lincoln, Dyess, Honolulu, Hao, Goose Bay, Keflavic, Shannon, Fairford, Arlanda, Koln/Bonn, Istres, Zaragoza, Lajes, Beja, Moron, Esenboga, Las Palmas, Ben Guerir, Gouda, Amilcar Cabral, Banjul, Tamanrasset, King Khalid, Yokota, Wake, Andersen, Belalis, Ascension, Kinshasa, Diego Garcia, Darwin, Hoedspruit, Amberley, Stephenville, Gander, St. John's, Pease, Grenier, Otis, Halifax, Rio Gallegos, Atlantic City, Dover, Wallops, Oceana, Myrtle Beach, Cherry Point, Willmington, Bermuda, Kennedy, Nassau)

• Equatorial scintillation (Appleton Anomaly) occurs between sunset and the early morning hours.

• Polar scintillation occurs over the polar cap and the night side of the aurora oval. On rare occasions, auroral oval expansion, causes scintillation in the mid latitude region.
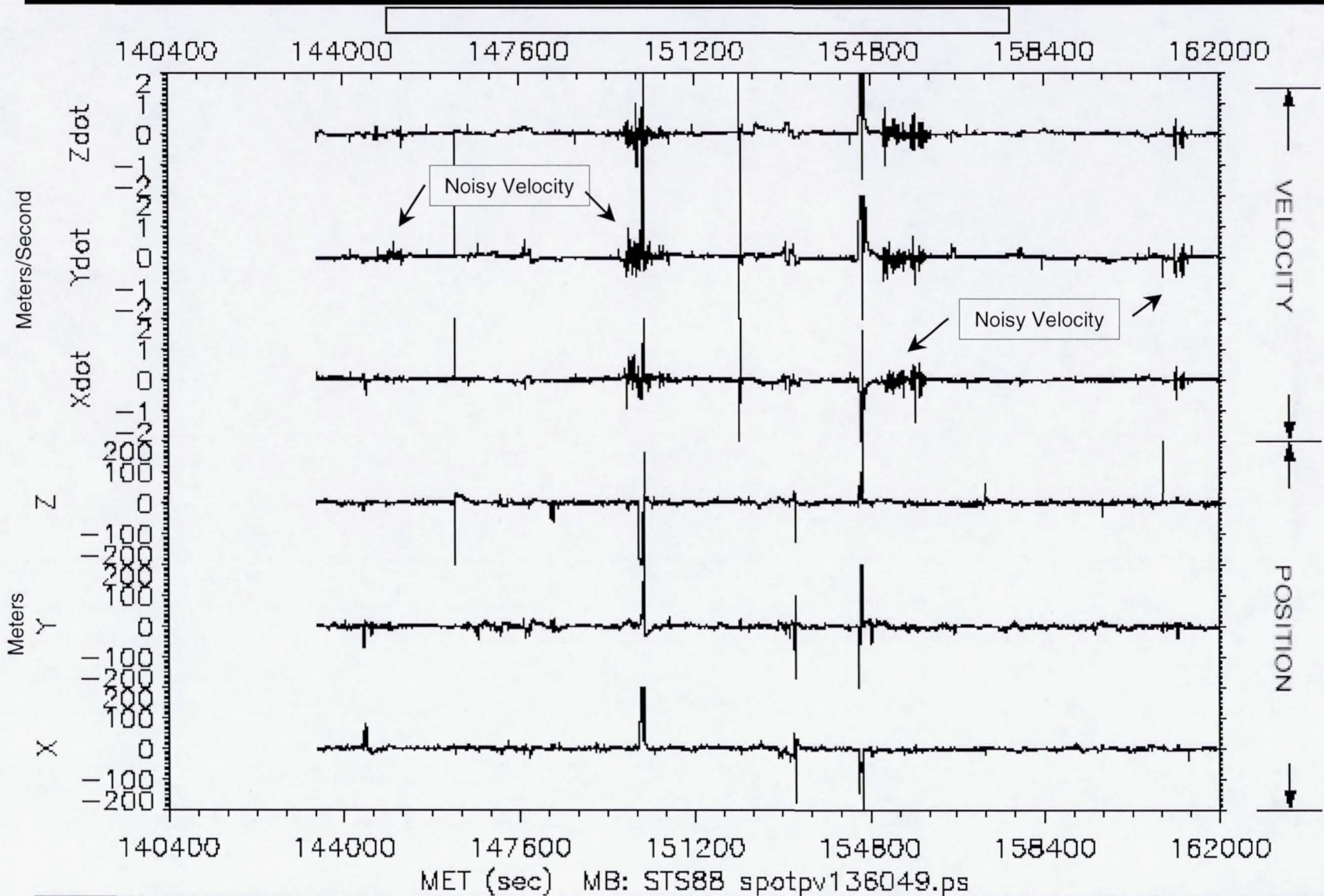
Noise Observed In MAGR Velocity

- MAGR velocity noise, up to 11 feet/second, lasting from 5 to 20 minutes. Observed on all Shuttle flights examined (92, 106, 101, 99, 96, 88, 95 and 91).

- Signal strength (C/No) does not appear to be impacted significantly.

- Analysis indicates that MAGR Kalman filter is processing noisy delta range measurements.

- GPS solution in these regions is outside of the GPS 3 sigma (3 times RMS) specification of 0.3 ft/sec.

- Location and local time of noisy periods is consistent with equatorial and polar ionospheric scintillation.

- Attitude and orbital adjustment maneuvers have been ruled out.

STS-99 Noisy Delta Range Events
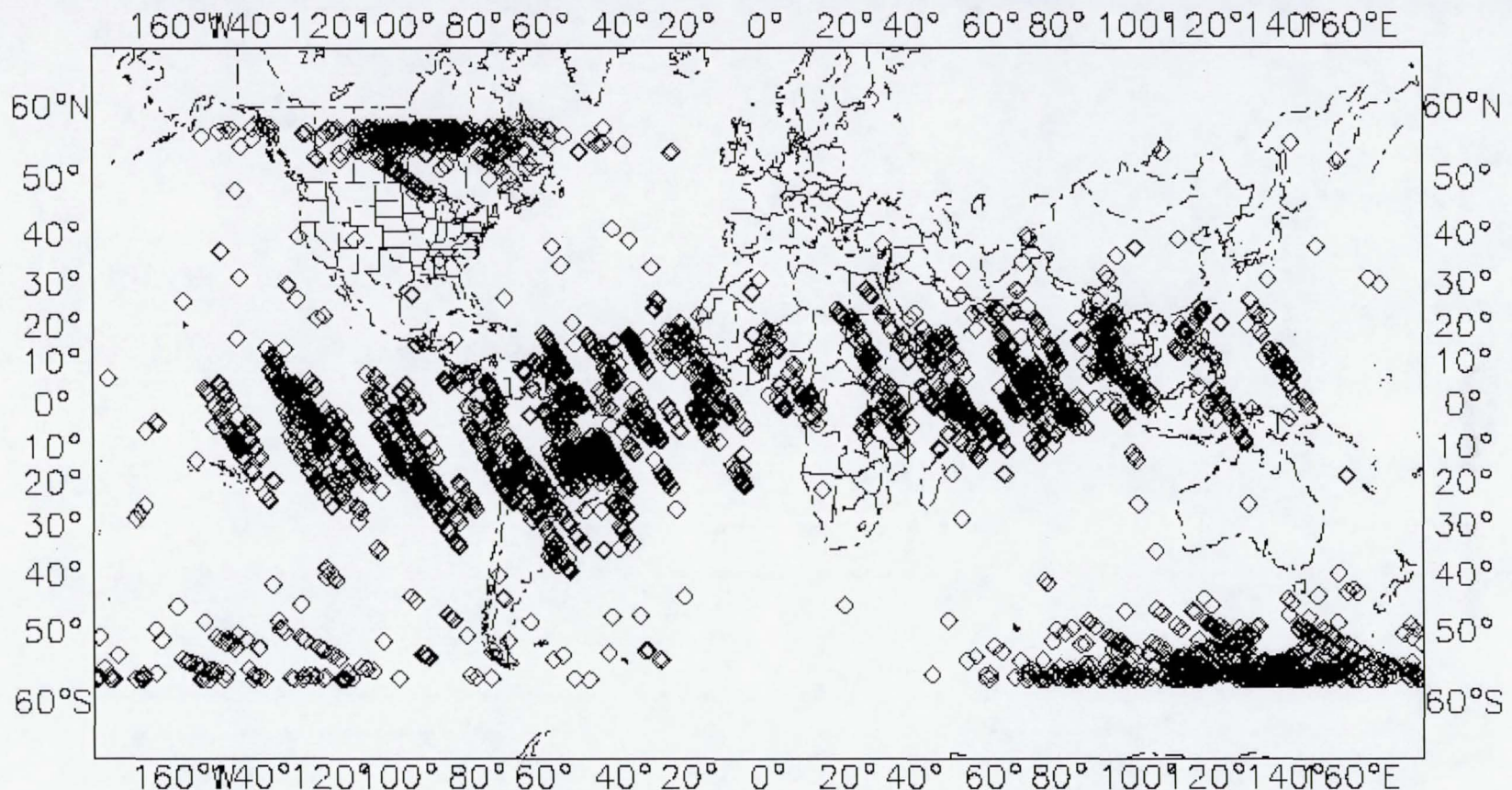
- GPS normalized delta range residuals > 2 sigma and FOM = 1.
- Events < 2 seconds after satellite switches excluded.
- Orbital altitude approximately 126 NM, 57 degree inclination.
- Mission flown from 2/11/00 to 2/22/00.

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STS-88 Position And Velocity Errors

MET (sec)   MB: STS88 spotpv136049.ps

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STS-88 Measurement Residuals Per Channel

STS 88 NORMALIZED RESIDUALS VS MET (MB: 1998 338/08:35:34.019)

Noisy delta range

Noisy delta range

DELTA RANGE

PSEUDO RANGE

NORMALIZED RESIDUALS resids118800.ps

SEC

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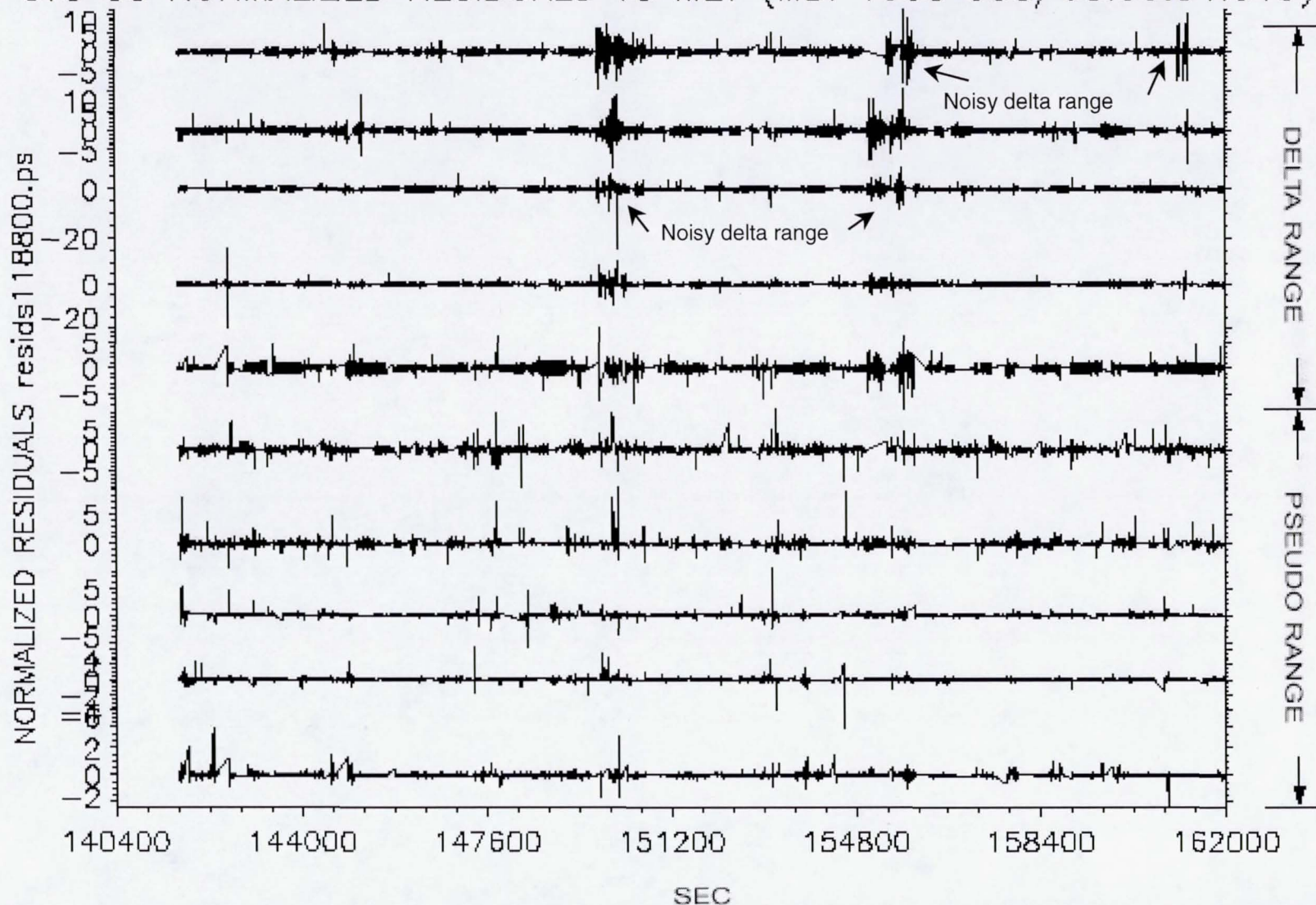
Equatorial Characteristics Of Noisy Velocity Incidents

- Equatorial distribution of noisy velocity incidents coincide with published data and theory for scintillation associated with the Appleton Anomaly (references in paper).

- Most periods for winter flights were over or near South America. Most periods for summer flights were over Africa.

- Velocity noise and lack of C/No impact (fading) suggests phase scintillation. Amplitude scintillation has not been identified in Shuttle MAGR data.

- Orbiter is probably too close to scintillation structures for amplitude scintillation to occur.

- Delta range measurements for all satellites tracked appear to be noisy, suggesting that the Shuttle is flying through volumes of ionospheric density irregularities. High orbital velocity of the Shuttle may amplify the effect relative to Earth based observations.

No Scintillation Induced Signal Fading Has Been Identified

- Signal fading is the ionospheric scintillation effect that is most commonly reported in the literature.

- Air Force Research Lab (AFRL) Antenna Wave Front Simulator (AWFS) MAGR scintillation test data has been examined.

  - Unaided, stationary MAGR exhibited loss of lock and state 3 tracking due to scintillation induced fading.

  - MAGR tracking performance during AFRL tests are very similar to MAGR performance during the reentry plasma region.

- No signal fading has been observed in Shuttle data that is attributable to ionospheric scintillation.

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Velocity Noise Is Not A Threat To Shuttle GPS Certification

- Theory predicts (covered in the paper) that scintillation induced velocity noise decreases in magnitude with decreasing vehicle velocity.

- Velocity Quality Assurance checks "edit" some MAGR velocity vectors during noise periods.

- Velocity noise well within acceptable limits for TACAN replacement. Velocity noise on-orbit does not constrain use of MAGR states for emergency deorbit.

- Impact of scintillation induced fading (not seen by the Shuttle MAGR thus far) on Trans-Atlantic Aborts to North Africa and equatorial emergency landings needs to be assessed, but may be very difficult to quantify.

- Equatorial scintillation is not believed pose a threat to CONUS landing sites.

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Conclusions

- Kalman filter and residual edit test modifications that rigorously incorporate orbital dynamics appear to eliminate the manifestation of velocity noise induced by scintillation.

- Ability to observe the Appleton Anomaly and auroral oval scintillation is an important scientific product. Shuttle MAGR data can be used to further characterize the seasonal and geographic incidence of scintillation on a global scale.

- Velocity noise will have to be examined for impact on any future orbit GPS applications requiring better accuracy than TACAN replacement or that process carrier phase measurements (rendezvous/formation flying, attitude determination).

- Current ability to forecast/nowcast scintillation impacts is not good enough to support impact assessment or real time decision making by GPS users.

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