AIAA-92-4521

# MAGELLAN NAVIGATION USING X-BAND DIFFERENCED DOPPLER DURING VENUS MAPPING PHASE

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## Abstract

This paper describes Magellan navigation procedures and performance during the first 1.5 years of mapping. It presents the results of studies comparing several orbit determination methods performed with and without X-band (8.4 GHz) differenced Doppler tracking data. X-band differenced Doppler has been used as a primary navigation data-type for the first time. It has been found to be a significant aid in efficiently meeting orbiter navigation requirements during the Magellan spacecraft's Venus radar-mapping phase.

## 1. Introduction

The 1989 Magellan launch to Venus was NASA/JPL's first interplanetary mission launch since Pioneer-Venus in 1978. It is the first in a new category of missions intended to build on preliminary reconnaissance and fly-by data by performing in-depth studies of solar system bodies.

The spacecraft was inserted into an elliptical, near-polar orbit around Venus on August 10, 1990. After an initial shake-down and check-out period, radar-mapping began on September 15, 1990. Synthetic aperature radar (SAR) data has been collected since that time. Over 97% of the Venusian surface has been observed at resolutions between 120 meters and 300 meters, depending on spacecraft altitude. Venus has revolved more than twice beneath Magellan's inertially fixed, 3.25 hour orbit, providing comparison images of surface features at eight month intervals.

Accurate navigation is important for successful orbital operations around Venus, as well as successful map construction. Navigational accuracy requirements are twice as stringent as those on any previous deep-space mission. As the distance between Earth and Venus varies from 41 million to 260 million kilometers, navigation must maintain day-to-day maximum relative errors of 150 meters in the radial direction and 1 kilometer in the cross-track and along-track directions.

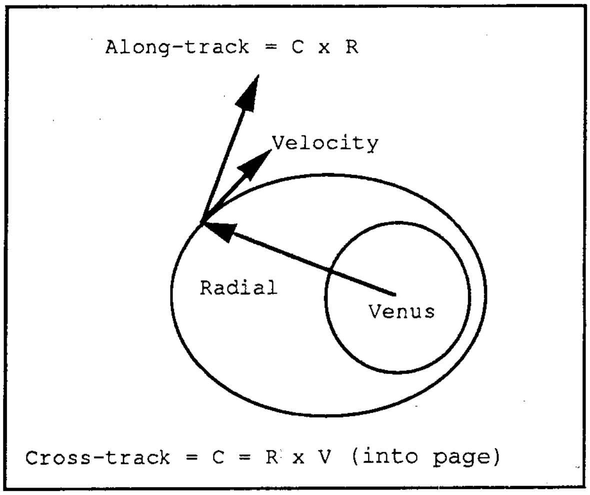


Fig. #1: Rotating spacecraft-centered coordinate directions (not to scale)

Such accuracy is needed because, unlike passive photo reconnaissance, the radar system is interacting with the surface being scanned. Radar data are acquired in strips, typically 10000 km long and 20 km wide, running north to south. These strips are assembled, during ground-processing, into larger products for detailed analysis. Accurate ephemerides are required for correct assembly of these radar mosaics. In addition, the radar system uses predicted ephemeris data to continuously adjust its operating parameters to compensate for changing view angles and topographic trends with the goal of maximizing signal return. Approximately 3000 such adjustments are made during each 35 minute mapping pass [1]. Finally, spacecraft sequences, used to trigger spacecraft hard-ware events, are based on predicted periapse-relative times. Periapse timing errors of more than 1.5 seconds can seriously degrade radar performance with significant degradation apparent from 1.0 seconds on up. Typically, Magellan timing errors accumulate between 0.1 to 0.9 seconds at the end of a 6 day (44 orbit) prediction.

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## 2. Magellan Navigation

Magellan is equipped to coherently transpond Doppler data in S-band (2.3 GHz) and X-band (8.4 GHz) frequencies only. This impacts navigation in several ways.

Two-way Doppler is sensitive to the velocity component along the line-of-sight (range-rate), but not the orbit's orientation around that line of sight. This well-known effect is most significant when Earth/Venus geometry is such that the spacecraft's orbital plane appears to be either "face-on" or "edge-on" in the plane of the sky as seen from the Earth-based tracking site. One or the other of these geometries occurs at roughly three month intervals, affecting solution accuracy for up to three weeks, or while the plane-of-sky inclination is within 15 degrees of the geometric extreme. Navigation has addressed this problem by using a differenced data type, described below.

Uncertainties in the Venusian gravity field model, particularly at Magellans' 264 km periapsis altitude, result in mismodelling of spacecraft periodic and secular accelerations. During the mission, the navigation team has used tracking data from the Pioneer-Venus orbiter and Magellan to iteratively improve a 21x21 harmonic gravity model [2]. Unfortunately, the most sensitive tracking data is not available from Magellan. During low-altitude periapse-passage, the spacecraft is physically rotated away from Earth-lock so that its fixed-position, high-gain antenna may be used as a SAR to map the Venusian surface. The Cycle-4 mission plan modifies this pattern to obtain additional gravity data at the cost of continuous ±80 degrees true anomaly radar-mapping.

Navigation procedures must keep pace with daily operations. If data are degraded due to navigational error, there can be no recovery until the next cycle, 243 days later (the period of time it takes for Venus to rotate once under Magellan's inertially fixed orbit). On the uplink side, program sequences, radar control, attitude control and periapsis time-tables are uplinked to the spacecraft twice a week so as to minimize navigation prediction errors caused by inadequately modelled dynamics and to stay current with spacecraft thermal control and science objectives.

### a. Performance Measures

For Magellan navigation, "solution" refers to the nominal weighted least-squares batch estimation process performed daily by the navigation team to determine the spacecraft position and velocity (state) at some epoch. During each 24 hour period, slightly less than 8 orbits of new tracking data are accumulated. These data are merged with the last 4 orbits from the previous day to establish a 12 orbit (39 hour) tracking data arc. This data arc is then used to estimate the spacecraft state using a methodology detailed below.

The purpose of the overlap is to minimize state discontinuities that can occur if each solution is based on an independent set of tracking measurements, while still permitting the estimation filter to respond to the latest tracking data. The overlap also permits determination of relative error by simply differencing the two trajectory solutions over a single spacecraft orbit common to both. The first trajectory is based on a previous data fit, the second on the most recent fit. From a navigation stand-point, it is this maximum relative difference between trajectory solutions (composed of 12 orbits each) that most directly affects mosaicking.

Another quantity, "absolute error", correlates more closely with actual radar performance. Absolute error is the difference between a predicted trajectory generated several days in advance (used for spacecraft programming) and the actual trajectory estimated from after-the-fact tracking data. Absolute errors cause the radar system to lose return signal since the SAR is dependent on angle and range-to-surface predictions.

Because absolute error is not immediately known, relative error is used on a daily basis to assess navigation performance. Trajectory accuracy may also be independently confirmed, on a more real-time basis, by analysis of the radar return signature during mapping and, much later, by the ability to process radar data into image mosaics on the ground.

Fig. #2 shows the cross-track, radial and along-track relative error between each overlapping, 12 orbit solution for the first 4600 Magellan orbits.

It can be seen from these plots that navigation performance has historically been affected by the orbit's inclination in the plane of the sky (the angle between Magellan's orbital plane and a line directed from the center of Venus to the tracking station). Maximum relative error is bounded by either the sine or cosine of plane-of-sky (POS) inclination multiplied by some constant. The given constants were chosen by inspection, not computationally determined.

The correlation between orbit determination (OD) error and Earth/Venus geometry exists because two-way Doppler provides only line-of-sight velocity measurements and is insensitive to velocity in the plane of the sky. Thus, position errors in the radial, along-track, and cross-track components are each proportional to the corresponding velocity component magnitudes in the plane-of-sky direction. These are sinusoidal functions of POS inclination.

The data also illustrate the difference between face-on and edge-on conditions. In-plane components, such as semi-major axis, eccentricity and argument of periapsis (closely related to radial and along-track values), show the greatest determination errors during the face-on orientation, when POS inclination is within 15 degrees of 0 or 180 degrees. At this time, in-plane velocity components are only weakly observable by two-way frequency-shift measurements since in-plane motion is occurring at right-angles to the line-of sight. Doppler-shift can be caused only by out-of-plane motion which is therefore well-determined in this orientation.

The opposite situation occurs 90 degrees later during the edge-on orientation. In this geometry, spacecraft motion occurs in the line-of-sight direction, causing out-of-plane parameters such as inclination (closely related to cross-track error) and longitude of the ascending node to be only weakly observable even as the in-plane parameters become well-determined.

Geometrically, it might be expected that radial component determination would also be slightly degraded during the edge-on orientation due to reduced radial observability at the three position extremes. This was observed early in the mission [3], but the introduction of a much improved gravity model (JPL-VGM6A) after orbit number 2800 [4] has reduced this effect below the 150 meter requirement. The radial component is most observable immediately before and after edge-on.

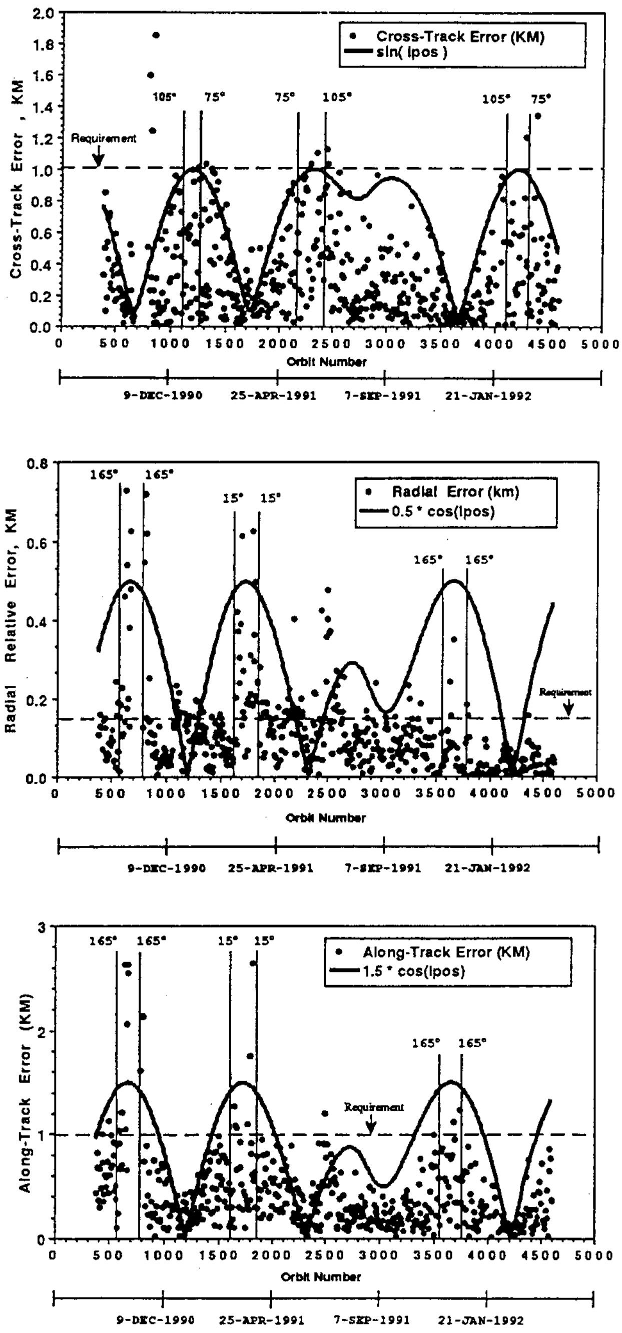



Fig. #2: Magellan relative error results since mapping began

Since POS inclination may be computed many months in advance, it is possible to predict the likely maximum error at any given time and identify periods of time when meeting flight project requirements will be difficult. However, use of an additional ground antenna effectively creates an additional line-of-sight greatly alleviating the problem, as described below.

## b. Tracking Data Types

The original Magellan mission plan [5] addressed the problems described above by supplementing two-way Doppler with Delta-Differential One-Way Doppler, an interferometric measurement of spacecraft velocity normal to the line-of-sight. This measurement was to be obtained by alternately tracking the Magellan spacecraft and an angularly nearby natural radio source (quasar) simultaneously from two of NASA's Deep Space Network (DSN) stations. An observable was formed by first differencing the spacecraft measurements made at the two stations, and then subtracting from this quantity the measured interferometric delay rate obtained by observing the natural radio source. The natural source observation essentially corrects the differenced Doppler measurement for the clock offset rate between DSN receiving stations. ΔDOD was collected successfully during Magellan cruise [6,7]. However, it became apparent that the required station clock rate calibration accuracy could be obtained from DSN site-collected measurements of Global Positioning System (GPS) satellite signals [8]. It was thus possible to greatly simplify operations by eliminating planned observations of natural radio sources. Based on studies during interplanetary cruise, it was decided that X-band differenced Doppler would be used in place of ΔDOD during mapping operations [9,10].

The theoretical basis for differenced Doppler has been understood for many years [11-14], but the method has never been used operationally for deep-space navigation. Initially, this was because station clock errors could not be determined accurately enough until the introduction of hydrogen maser time and frequency standards. A subsequent limitation was that lower-frequency S-band differenced Doppler was insufficiently accurate to be of any use because of the aliasing effects of Earth's ionosphere and interplanetary space plasma. High frequency X-band up/downlinks provide differenced Doppler measurements four times more accurate than S-band measurements [15]. Previous X-band equipped spacecraft, such as Viking 1 & 2, Voyager 1 & 2,and Pioneer 12, could have provided X-band differenced Doppler, but these missions did not have navigational accuracy requirements that warranted use of this data type.

## c. Differenced Doppler

Briefly, differenced Doppler is a type of very-long baseline interferometry in which two-way frequency-shift measurements are differenced with "three-way" frequency-shift measurements, as shown in Figure #3. The result is a quantity related to spacecraft geocentric angular velocity with respect to the baseline connecting the two receiver sites. Since the rotation rate of the Earth baseline is known, the spacecraft velocity component parallel to the baseline, thus perpendicular to the line-of-sight, may be determined. Derivations available elsewhere [3] won't be repeated here.

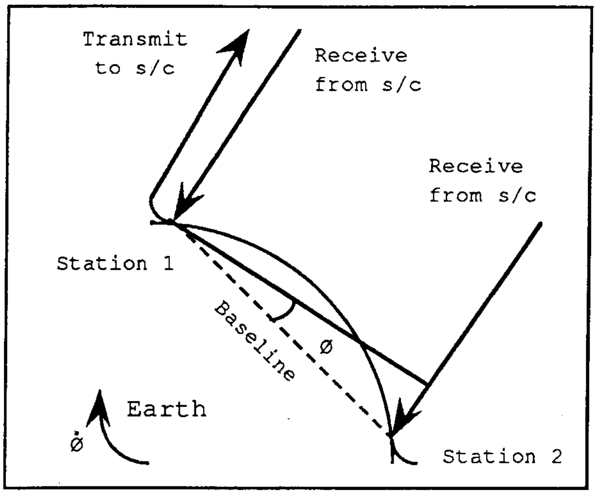



Fig.#3 : Tracking configuration

If station #1 and #2 both have a carrier lock and are simultaneously recording 2-way and 3-way measurements relative to the same transmit signal, the measurements may be differenced. Such differencing effectively cancels Doppler shift due to geocentric spacecraft motion (since the Earth rotation component along the baseline is known) and desensitizes the orbit solution process to dynamic force mismodelling by a factor equal to the ratio of the baseline to the spacecraft/Earth distance, or the approximate tangent of the parallax angle. For Magellan, this scaling ratio (or "sensitivity") of differenced Doppler is roughly 5.0E-05. For example, a mismodelled velocity of 1 mm/sec in the line-of-sight direction affects two-way Doppler residuals at this level, but a mismodelled velocity of 1 mm/sec in the cross-direction affects differenced Doppler residuals by 5.0E-05 * 1.0 mm/sec.

In addition, solar plasma delay effects due to signal interaction with charged particles, largely cancel upon station differencing. The effect of charged particles on the uplink signal is completely eliminated, since it is common to both downlinks (differenced Doppler is a one-way data-type because of this common uplink path). The two downlink ray-paths are separated in space by at most 10000 km, the length of the baseline connecting the receiving stations. Most of the power in the solar plasma fluctuations is in very low frequencies [16] so that delay rate fluctuations on the two downlink ray-paths are highly correlated and largely cancel upon differencing. Complete cancellation could be obtained through analysis of simultaneously transmitted S and X-band spacecraft downlink signals.

Once the differencing is performed, the result is a frequency shift value proportional to the spacecraft's velocity in the plane of the sky. The DSN has three baselines from which it is possible to make measurements: California-Australia, Australia-Spain and Spain-California, although the Australia-Spain baseline has a very short overlap and is not generally useable. If POS velocity measurements can be obtained from one or more of these pairs and combined with the direct range-rate measurements of 2-way Doppler, the spacecraft state will be almost completely observable when coupled with the dynamic models needed to infer position from velocity measurements.

The primary attraction of differenced Doppler is its low sensitivity to dynamic mismodelling. Any time the spacecraft is visible at two tracking stations, differenced Doppler is available, providing antennas are allocated during view-period overlaps. Clock calibrations needed for differenced Doppler are already collected on a routine basis using GPS satellite measurements.

### d. Magellan Navigation Strategy

Because of these considerations, the Magellan tracking strategy during mapping calls for two-way Doppler augmented by X-band differenced Doppler. Three-way tracking data is collected a maximum of three times each day during station overlap ("overlap" refers to the period of time when the rotating Earth platform results in the spacecraft being visible from two DSN sites simultaneously). Factors that can limit collection of this data include DSN scheduling conflicts with other spacecraft and geometries (such as spacecraft occultations) that reduce or eliminate carrier lock during station overlap. Twelve to fourteen orbits of 2-way Doppler data (300 to 1200 one-minute averaged points) and four to five passes of differenced Doppler (60 to 300 one-minute averaged points) are included in each daily solution. Tracking data are not usually available for 35 minutes either side of periapsis due to mapping activities. There is also a 15 minute gap near apoapsis when the spacecraft performs a star-scan attitude update.

To begin the solution process, a spacecraft state vector at apoapsis is found, nominally 12 orbits before the end of the most recent tracking data. Such a state may be obtained because of the 4 orbit overlap with the previous trajectory solution. Apoapsis states are used so as to minimize error due to gravity field mismodelling most consequential near periapse. A high-precision integrator then establishes a predicted trajectory by integrating the state forward to the end of the tracking data arc, according to the best dynamic model available. Predicted receiver frequencies are computed. Tracking data are examined. Predicted frequencies are subtracted from observed frequencies to form residuals. The goal of the navigation fit process is to optimize those differences since residuals of zero magnitude indicate perfect knowledge of the trajectory.

## Estimation Models

There are about 4000 program input variables required to execute the procedure described above, although most (such as station locations) remain fixed. On a daily basis, the navigation team changes fewer than 10% of these to update the dynamic model and, typically, examines trade-offs between less than five adjustable parameters in search of an optimal residual fit which provides the best state estimate.

Spacecraft dynamical models include a 21 x 21 Venus harmonic gravity field model, Venus rotational and polar motion effects, tidal accelerations and point mass gravity perturbations caused by the Sun and planets. A nominal single-layer, static-exponential atmosphere model accounts for drag effects. At periapse, Magellan encounters an atmospheric density ranging from 3.0E-16 g/cc on the day-side to 1.0E-17 g/cc on the night-side.

During the Magellan cruise to Venus, reflectivity coefficients of spacecraft components were computed for a solar radiation pressure model based on a flat-plate/parabolic antenna definition of the spacecraft. A 0.5 second error in periapse times can accumulate if navigation models of solar panel orientation are offset 45 degrees from the actual orientation over a 14 day prediction.

Momentum wheel desaturation events occur every other orbit near apoapsis. These small 4 minute thruster firings are initiated to remove angular momentum and keep wheel spin-rates within specification. The unbalanced firings can impart a $\Delta V$ of 1 to 3 mm/s. The navigation team models spacecraft orientation about its center of mass throughout most of each orbit to correctly account for solar pressure and thruster firing directions.

A timing and polar motion model includes the effect of tidal deformation on the Earth's moment of inertia and is updated every week. DSN clock offsets are determined to nanonsecond levels daily, using the GPS reference, and provided to the navigation team three times a week. The navigation team has been able to remove biases in the differenced Doppler tracking data by using daily clock offset values obtained from a linear least-squares fit of 20 days worth of clock-offset reports, instead of the individual reported values.

Other models describe radio signal propagation effects, such as signal interaction with charged particles in the Earth's atmosphere. Relativistic bending of the signal path due to the gravity field of the Sun is also computed.

## Procedures

Once models are established for a given arc of tracking data, several heuristic methods may be used to fit the data and improve state knowledge. Standard practice is to estimate the 6 component state and base-density. Estimating base-density has the effect of absorbing some gravity field mismodelling, thus reducing the aliasing of such error into the state estimate.

The basic procedure is this: a nominal weighting matrix is established for the data types available. For 2-way Doppler (hereafter referred to as F2) X-band up/downlink, 1.0 mm/sec (0.0565 Hz) is used for weighting purposes to allow for dynamic mismodelling. For X-band differenced Doppler (hereafter F2MF3), 0.1 mm/sec (0.0028 Hz) is used as the nominal weight.

A reference trajectory is integrated forward from epoch to the end of the data arc as described earlier. The tracking data is examined and two sets of residuals are formed. Pass-through residuals reflect the integration of the initial state in the presence of the dynamical models described above, indicating how well the previous trajectory solution fits the new tracking data. Post-fit residuals, refer to the new trajectory estimated by a least squares single batch algorithm.

Post-fit F2 residual RMS is computed along with the pre-fit F2MF3 residual RMS. These RMS values are used to establish a nominal RMS weighting matrix. The estimation process is repeated to develop a new state correction vector and new post-fit residuals.

The RMS is used for weighting, instead of sigma, to compensate for any bias away from a residual mean of zero. The F2 RMS is taken from the post-fit case (where it is a minimum due to the strength of the data type and the fact it has been fit) and the F2MF3 RMS from the pre-fit (where it is a maximum) so as to begin with a situation in which 2-way Doppler information dominates the solution. A deweight process is performed. This involves multiplying the nominal F2 RMS by some real value greater than one, decreasing the weight of F2 and effectively increasing the weight of F2MF3 data.

This balancing is necessary because of the lower sensitivity of F2MF3 described above; F2 measures velocity directly while F2MF3 velocity data are scaled by the sensitivity ratio. In addition, there are usually between 3 and 10 F2 measurements available for each F2MF3 point. Deweighting allows F2MF3 information to be gradually brought in as the solution is backed away from an F2 dominated fit. Normally, between 4 and 15 different deweight factors are examined before one is identified as giving the best fit.

All Magellan navigation analysis is performed on a dedicated local network composed of two 28.5 MIPS Sun/Sparc stations, a Sun 3/260 and three Sun 3/60's running Unix, with 4 gigabytes of on-line hard-disk storage.

## Determining the Best Fit

The goal of the fit process is to find a parameter set (thus state) that results in a post-fit F2MF3 residual RMS value less than the pre-fit F2MF3 RMS without increasing the post-fit F2 residual RMS more than 3 to 5 times the initial post-fit F2 RMS value. Such a situation indicates F2 and F2MF3 data are both being fit so that line-of-sight and plane-of-sky data are incorporated.

Relative error may be used to select a single solution from among several that have good data fits. Orbital elements are often plotted for each proposed trajectory and compared with preceding solutions. This quickly indicates which elements are less well-determined.

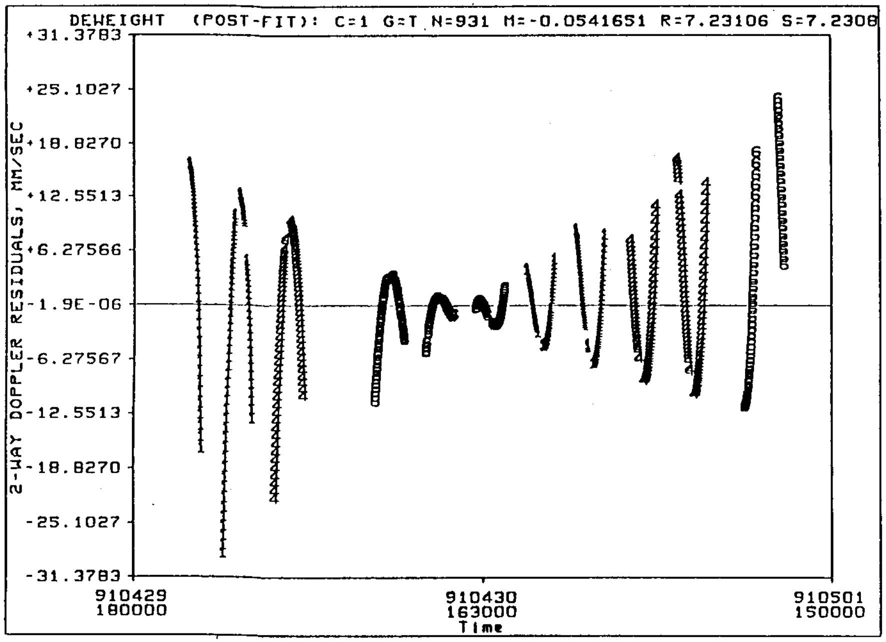
## Other Approaches

Due to gaps in the available tracking data or a pathological geometry, the data arc may be lengthened beyond 12 orbits to 14 or, rarely, 16 orbits to include more data and improve the estimate.

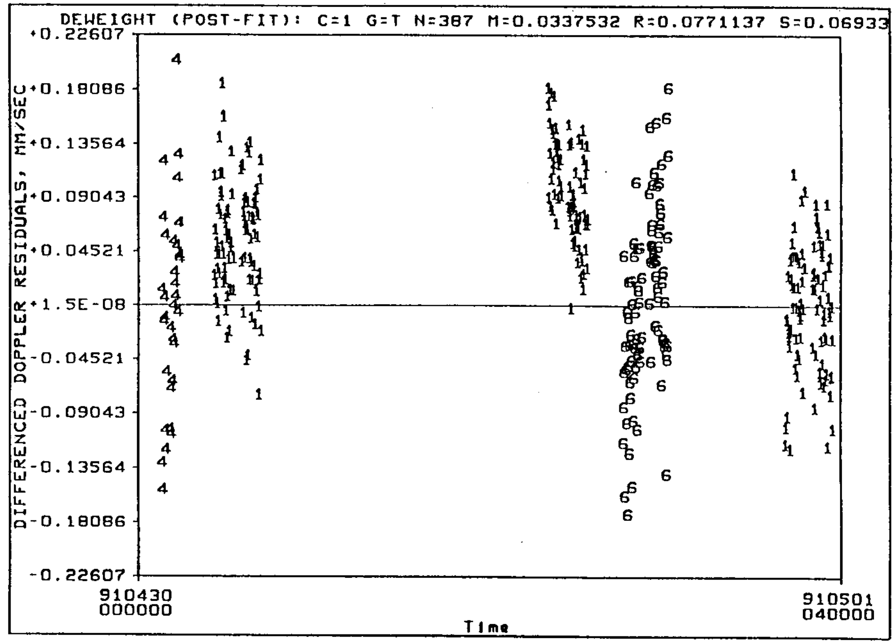
Although the initial state is obtained from the previous fit trajectory, the algorithm is only lightly constrained and free to develop corrections according to the latest tracking data. Thus, each daily solution is independent of previous solutions within a wide boundary. A-priori sigmas of 10000 km and 1 km/s constrain position and velocity state components.

Another solution method was developed one year into the mapping phase. It involves estimating a local 5x5 harmonic gravity field in addition to the state and atmospheric base-density. The goal is to minimize errors caused by known deficiencies in the global field, recognizing the 8 month (1 cycle) minimum time required to develop each new global

Figure #4: X-Band Two-Way Doppler and Differenced Doppler Residuals




(a)

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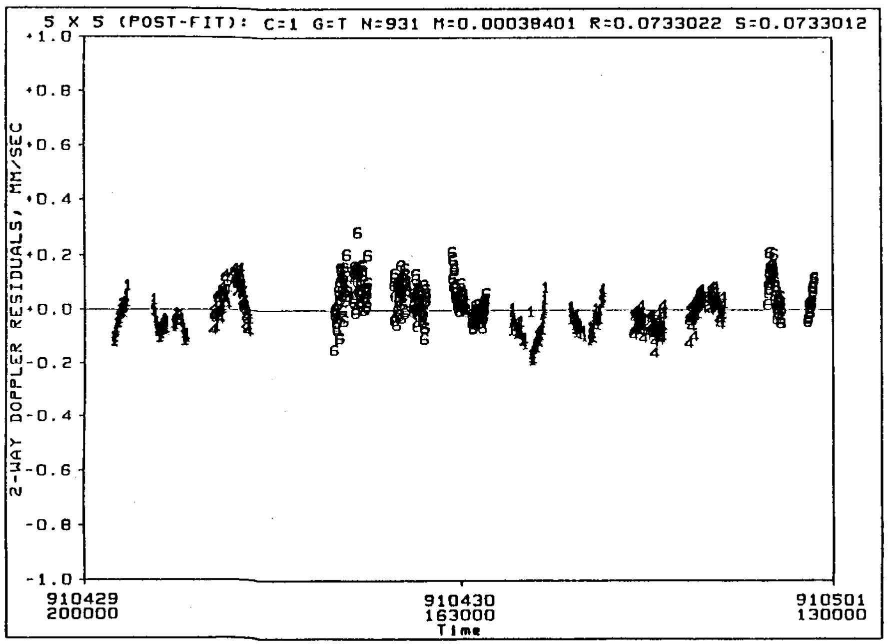


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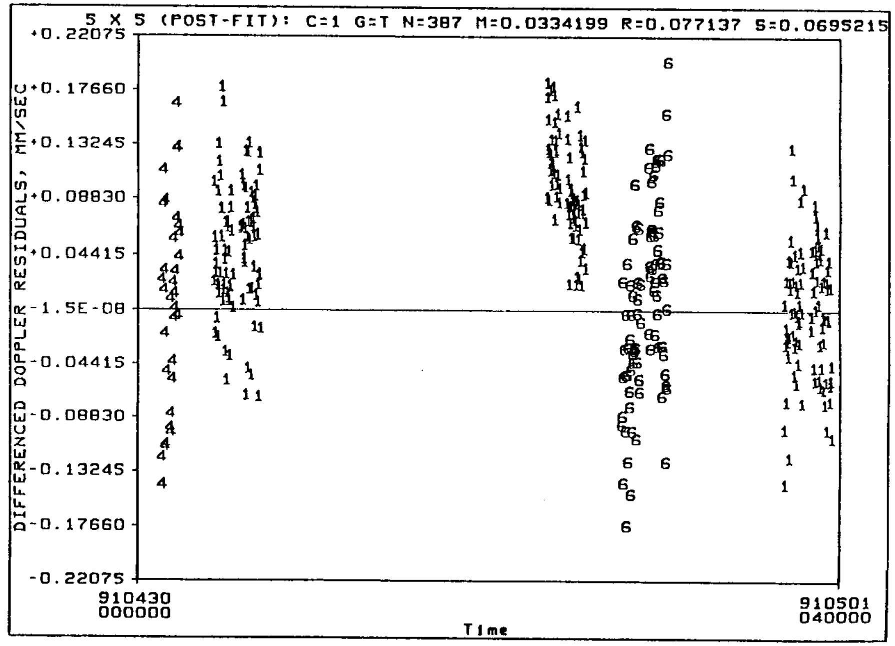



(d)

model. The local field is used only when estimating the state, not for subsequent trajectory predictions.

The initial difficulty with this method was obtaining a realistic 5x5 a-priori covariance matrix. The formal covariance obtained from the global field estimate is optimistic because of uncalibrated error sources known and unknown. To address this, trial covariance matrices, some multiple of the original, were established. Parallel fits were performed using the standard estimate list (state plus base-density) until a covariance was found which did not appear to over or under-constrain the 5x5 solution. While traversing regions of the planet that have a rapidly changing gravity field structure (such as Beta Regio), this method permits accurate solutions to be made without constraining the state.

Four post-fit residual plots are shown in Figure #4 illustrating results produced by two basic fit methods. Values across the top display the number of 1-minute averaged points, the mean, RMS, and sigma results. Plots (a) and (b) depict a standard state plus base-density deweight fit. Note the distinctive "bow-tie" F2 residual pattern produced by the least-squares fit. Large gaps reflect the lack of tracking data during mapping. Small 15 minute apoapsis star calibration gaps may also be seen. Plots (c) and (d) are from an F2 & F2MF3 RMS 5x5 gravity estimate (39 solve-for parameters). F2 residuals are less than 1 mm/sec, indicating the correction vector has absorbed most of the dynamic mismodelling and distributed it among the estimated parameters, leaving only a small dynamic signature remaining in near noise-level residuals. F2MF3 RMS and sigma statistics for the two methods are insignificantly different. This illustrates the characteristic F2MF3 insensitivity to dynamic mismodelling mentioned earlier.

## 3. X-Band Differenced Doppler Contribution Study

A study was undertaken to quantify the contribution of X-band differenced Doppler to Magellan navigation performance. Five days of tracking data spanning three unique geometries were fit. Five different solution methods were used on each independent 5-day arc, for each geometry. This represents a total of 75 cases. Solution methods were:

a) F2MF3 & F2 deweight (standard "best" fit)
b) F2-only RMS weighted, 5x5 field estimate
c) F2 & F2Mf3 RMS weighted, 5x5 field estimate
d) F2 & F2MF3 RMS weighted
e) F2-only RMS weighted

Appropriate estimation models were established for each day of the three intervals. The most recent gravity model was used. It incorporates two cycles of Magellan F2 X-band data and is designated JPL-MGN04. An initial state for the first day was obtained from the historical Magellan ephemeris. A trajectory was determined using one fit method, then used to generate initial conditions for the next day, and so on, for all five days. The process was repeated using the next solution method. Thus, each five-day thread represents an independent assessment of what would have been obtained during five days of daily operations if a given method had actually been used to process the tracking data.

### a. Relative Error Results

Results are presented in nine graphs (Figure #5) showing the radial, cross-track, and along-track errors for each method during the three geometries. There are three comparisons between the five independent solution methods that permit direct isolation of the contribution of X-band differenced Doppler:

(1) F2-only RMS fits versus F2 & F2MF3 RMS fits reveal the effect of simply including RMS weighted F2MF3.

(2) F2 & F2MF3 RMS fits versus deweight fits reveal the effect of deweight balancing F2MF3.

(3) F2-only RMS 5x5 fits versus F2 & F2MF3 RMS 5x5 fits reveal the effect of incorporating F2MF3 in a state, base-density and local gravity estimate.

For the three unique geometries, there are thus a total of nine independent comparisons to be made.

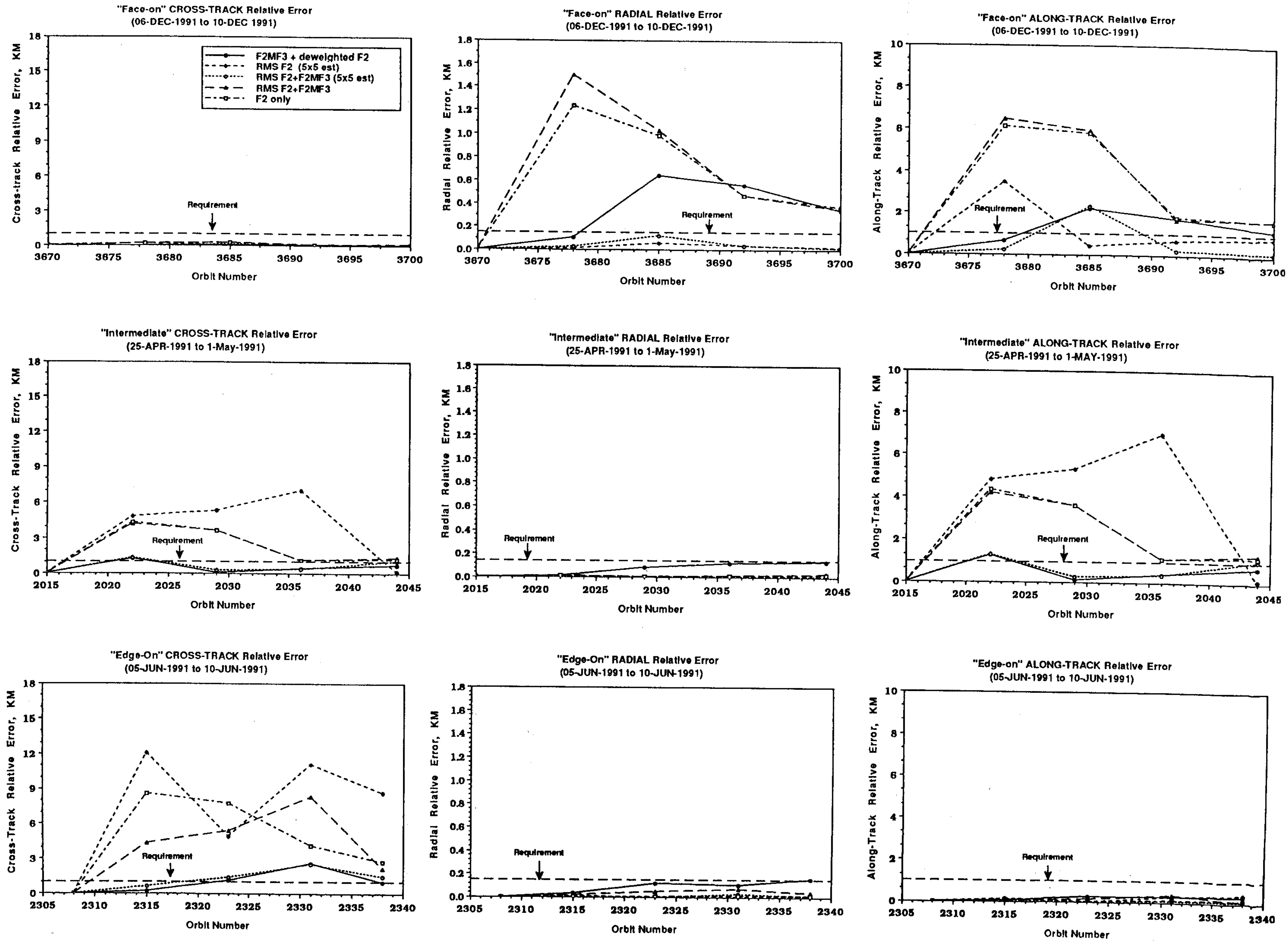
#### Face-On (174.4° to 176.5°)

Magellan has not passed through an exact face-on, so the face-on analysis was made as close to the extreme as possible. This interval also had a geocentric declination near 9 degrees. Previous Magellan experience has shown Doppler degradation due to low declination is not manifest until declinations of ±3 degrees occur.

In this geometry, in-plane parameters are weakly observable. The poorest overall results were obtained here. This is reflected in radial and along-track relative error results that consistently exceeded requirements. Best results were obtained from the two 5x5 gravity field estimation methods, both of which exceeded requirements (by 2 - 5 km) on only one day. The corresponding type (3) comparison shows the variant including F2MF3 giving slightly better over-all results. Poorest face-on results were obtained from F2 & F2MF3 RMS weighted fits, which had error magnitudes between 2 and 6 km throughout the interval. Deweight relative errors lay between these two extremes. Although deweight case error magnitudes exceeded 2 km along-track and 600 m radial for at least 3 days, a type (2) comparison again shows X-band differenced Doppler making a major contribution, reducing relative error by a factor of three as it is incorporated into the fit.

F2 & F2MF3 RMS weighted relative error magnitudes were worse than the F2-only RMS case (type (1) comparison) because the nominal RMS weighting scheme used reflects pre-fit F2MF3 and post-fit F2 residual RMS. This effectively desensitizes the fit to some plane-of-sky information until deweighting is implemented. This slightly degrades the F2 & F2MF3 RMS solutions (relative to an F2-only RMS fit) in a geometry in which only plane-of-sky information is available. Thus, this comparison indirectly reveals a positive contribution made by X-band differenced Doppler.

## Figure #5: X-Band F2MF3 contribution relative error results



## Intermediate Results (45° to 49°)

In this geometry, in-plane and out-of-plane information content is of equal, intermediate quality. While graph scales are different, it may be seen that cross-track and along-track intermediate relative error profiles are nearly identical across the interval.

Best results were obtained from the deweight method, the poorest from the F2-only RMS 5x5 case. A type (1) comparison shows insignificant change relative to the F2-only method when RMS weighted F2MF3 is introduced. The 5 km error contrast between the two 5x5 methods illustrates the contribution of X-band differenced Doppler, as does the 2.5 km error contrast between the deweight case (best) and the F2 & F2MF3 RMS case.

## Edge-on Results (88° to 92°)

In this geometry, out-of-plane parameters are weakly observable. The deweight method provided best overall cross-track results. The F2 & F2MF3 RMS 5x5 fits were only slightly worse than the deweight case. By contrast, the F2-only RMS 5x5 fit was the worst case overall, with relative errors on the order of 10 km throughout the interval. Also note the contrast between standard F2-only RMS fits and the deweight case. The F2-only RMS errors are on the order of 6 to 8 km. All three comparison tests show X-band differenced Doppler making a major contribution during edge-on.

## Conclusion

Supplementing two-way Doppler with X-band differenced Doppler substantially improves Magellan orbit determination during all three unique geometries, reducing relative error by factors of 300-400% over F2-only procedures. Of the nine independent comparisons made, eight show X-band differenced Doppler substantially improving trajectory solutions. One of three tests during the intermediate geometry gave a neutral result. The greatest contribution occurs during edge-on, when the presence of this data-type is critical to maintaining state knowledge. In cases where navigation requirements still cannot be met by nominal methods, the use of X-band differenced Doppler permits useful solutions to be obtained by either lengthening the data arc, or by establishing a relatively loose a-priori covariance, thereby permitting the constrained estimator to remain responsive to the latest tracking data. This is most likely to occur during a face-on geometry.

Magellan is the first deep-space mission to incorporate X-band differenced Doppler as a primary navigation data type. In its first 20 months, Magellan has produced a high resolution radar map of more than 97% of the surface of Venus, an Earth-size planet. Substantially improved harmonic gravity fields have been developed as the mission progressed, reducing navigation uncertainties. Techniques such as the linear least-squares fit of GPS clock calibration data and local gravity field estimation have been found to improve solutions. Meeting stringent navigation requirements has been routinely dependent on collection of X-band differenced Doppler, used in conjunction with two-way Doppler. X-band differenced Doppler provides velocity data perpendicular to the line-of-sight especially important during face-on and edge-on orbit plane orientations. X-band differenced Doppler may be collected during station overlaps, if accurate time and frequency standards are available. Differenced Doppler has been incorporated into all of the more than 500 navigation solutions delivered so far during the orbit phase.

## Acknowledgements

The authors want to acknowledge D.B. Engelhardt and G.R. Kronschnabl, navigation team members on leave-of-absence, and R.J. Haw, former navigation team member, whose work directly contributed to the results discussed herein.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract to the National Aeronautics and Space Administration. The Magellan project is managed for the National Aeronautics and Space Administration by the Jet Propulsion Laboratory, California Institute of Technology.

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