AEROBRAKING THE MAGELLAN SPACECRAFT IN VENUS ORBIT

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DRAFT

ABSTRACT

A spacecraft which was not designed for atmospheric entry was successfully flown in the sensible atmosphere of Venus during the periapsis passes of more than 700 orbits, thus becoming the first spacecraft to demonstrate the use of aerobraking to significantly alter the shape of its orbit at another planet. This experimental operation utilized the force imparted by atmospheric drag near periapsis to reduce the altitude of apoapsis by nearly 8000 km using little propellant. A description of the Magellan spacecraft is briefly reviewed; its configuration and operation during aerobraking is discussed, as are its behavior in the atmosphere, concerns for possible damage, the resulting orbit, and the unique demands placed on the spacecraft controllers and JPL's Deep Space Network tracking facility (DSN), during the aerobraking operation.

THE MAGELLAN SPACECRAFT

The Magellan spacecraft built by Martin Marietta Aerospace Group, was launched in May 1989, and entered Venus orbit August 1990. Some components are of interest in this paper. These include the following: A 3.7 m diameter parabolic high-gain antenna dish is used for S-and X-band telecommunications and S-band radar mapping, and a medium antenna for S-band telecommunications. Under direction from the attitude control and articulation subsystem (AACS), electrically-driven reaction wheels provide routine attitude control. Two identical monopropellant liquid propulsion system strings each include four 445N, four 22N, and four 0.9N rocket engines mounted in modules at the end of struts extending from the spacecraft body. l-he liquid propellant system routinely employs its 0.9N engines, or “thrusters” for desaturating momentum from the reaction wheels, and performing orbit trim maneuvers. The system shares a common helium-pressurized reservoir of hydrazine which contained 132 kg at launch, and a separate helium tank for repressurization.

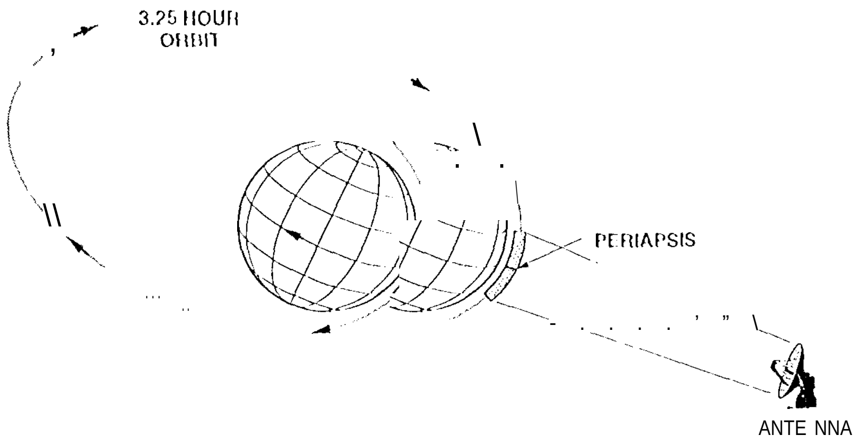
RADAR MAPPING

Magellan had conducted its radar mapping of Venus from a highly elliptical, nearly polar orbit about the planet. Nominal periapsis altitude was 170 km, apoapsis 8470 km, orbit period was 3.26 hours, and the inclination was 85°. From this orbit Magellan mapped 98% the surface of Venus, its radar experiment collecting synthetic aperture radar imaging data, altimetry, and radiometry data. The radar mapping was completed after Venus had rotated three times below Magellan’s fixed orbit. Additional experiments were conducted, including bistatic radar observations, solar coronal and solar Faraday rotation radio science, very long baseline interferometry astronomical frame ties, and atmospheric occultation radio science. Each Venus rotation period is 243 days, and is referred to as a Cycle.

GRAVITY FIELD SURVEY

Magellan spent Cycle 4 surveying the gravity field in the planet’s equatorial regions.[3] This was the last of Magellan’s originally stated primary scientific mission objectives. A gravity field survey gives important clues to understanding the nature of features visible in the radar images, since it measures mass concentrations at and below the surface. Such data is acquired by recording the doppler signature of minute spacecraft accelerations in orbit. A resolution of millimeters per second^2 (milligals), is possible with Magellan’s X-band downlink, which is based upon a highly stable X-band uplink reference frequency. The resolution obtainable at and near the surface of a planet is roughly equal to the altitude of the spacecraft, Given Magellan’s altitude of roughly 1000 km near the north pole, the smallest feature detectable in the gravity data is about 1000 km in diameter. From Magellan’s original, highly elliptical orbit, the spacecraft’s altitude was too great to measure the gravity field effectively except when it was within about 30 degrees true anomaly from periapsis, which occurred at 10”N latitude. See Figure 1.

FIG. 1 GRAVITY FIELD SURVEY FROM HIGHLY ELLIPTICAL ORBIT

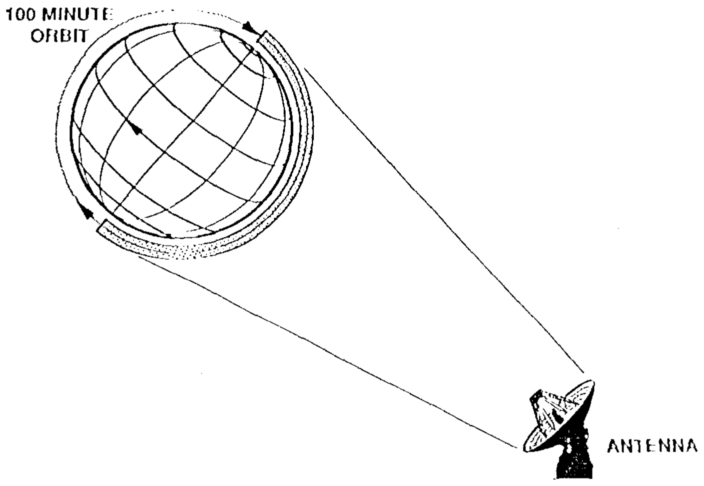


SHADED ARC REPRESENTS USEABLE GRAVITY DATA COLLECTION

OBJECTIVE FOR ATTEMPTING AEROBRAKING

The only way for Magellan to obtain meaningful gravity field data at high latitudes would be by lowering its apoapsis altitude to create a more circular orbit. It was highly desirable to measure the gravity at high latitudes because of features including Maxwell Montes in Ishtar Terra, the highest mountain on Venus, which rises 11 km above the mean terrain elevation. See Figure ?.

FIG. 2 GRAVITY FIELD SURVEY FROM NEARLY CIRCULAR ORBIT



SHADED ARC REPRESENTS USEABLE GRAVITY DATA COLLECTION

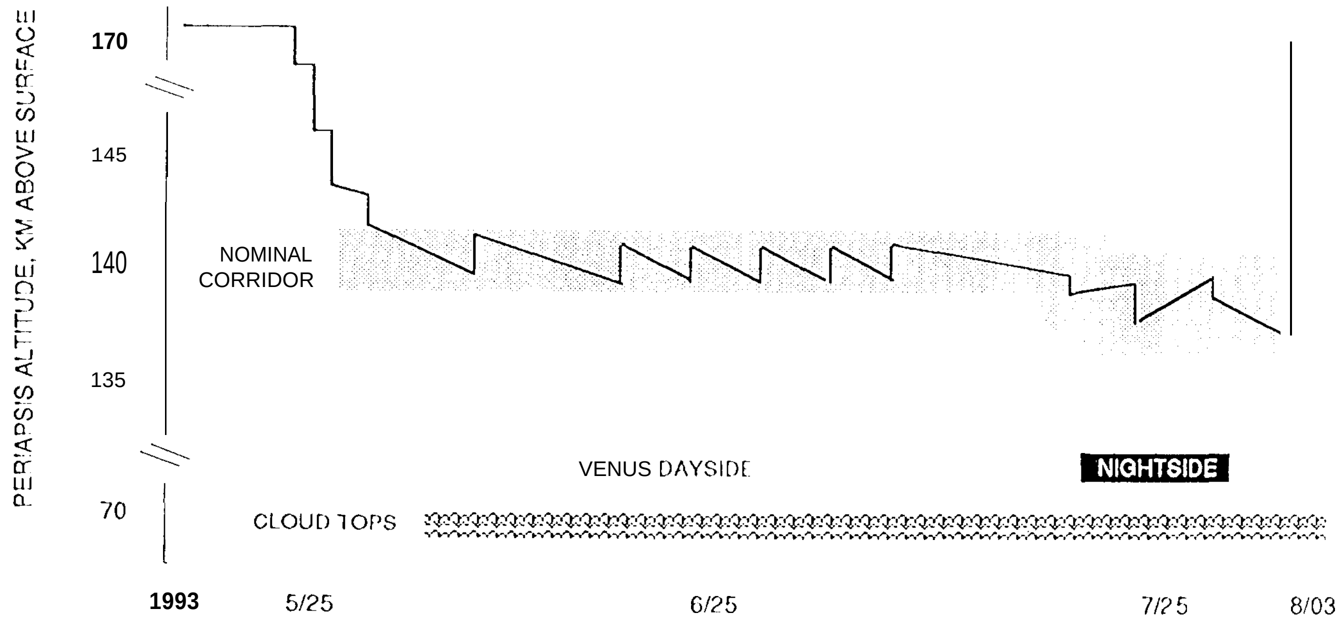
To lower apoapsis to the desired altitude via propulsive maneuvers would require an order of magnitude more propellant than Magellan carried. Aerobraking was viewed as a valid option. In addition to providing a more circular orbit, it **would demonstrate the engineering concept.** Also, measurements of the spacecraft's deceleration in the atmosphere would provide aeronomy data on Venus's upper atmosphere. Aerobraking was viewed as risky because the spacecraft was not designed for atmospheric flight. It was foreseeable that the solar panels, the HGA, and possibly other components to suffer damage from frictional heating. The experiment was deemed appropriate only because all of Magellan's primary scientific objectives had been completed, and accidental loss of the spacecraft would not be catastrophic to accomplishing the mission's intended goals.

AEROBRAKING CONFIGURATION AND OPERATION

The normal process of loading sequences of timed commands into the spacecraft's Command and Data Subsystem (CDS) for control of the spacecraft would not be appropriate for operations during the aerobraking experiment, since the orbit period would be decreasing at a rate not entirely predictable weeks or even days in advance, thus making it impossible to predict absolute times for execution of activities which must take place at certain parts of each orbit. Spacecraft engineers at Martin Marietta Aerospace Group in Denver devised a looping program to manage on-orbit activities which included a self-decrementing orbit period. The value which the looper **used to decrement its period was easily changeable by command from** Earth. In addition, the looper program could be cancelled and restarted as necessary to re-sync its activities with the latest knowledge of orbit parameters.

The propellant tank was repressurized via the separate helium tank carried for the purpose, in order to insure proper performance of the liquid propulsion system during aerobraking. With the looper software installed and operating aboard the spacecraft, on 25 May, 1993, a series of OTMs, each executed near apoapsis, reduced the periapsis altitude to permit a gradual entry into the atmosphere[4]. This was known as the "walk-in" phase. Refer to Figure 3. The nominal altitude corridor resulted from a maximum specified limit of 0.35 N/m^2 dynamic pressure acting upon the spacecraft. This limit was approached closely to prevent the experiment from proceeding too slowly. The "main phase" of aerobraking was characterized by controlling the spacecraft's altitude via periapsis-raise OTMS as the local gravity effects worked to lower the periapsis altitude. These OTMs are visible in Figure 3 as abrupt altitude increases. When Magellan's orbit crossed the terminator late in July 1993, the atmospheric density decreased at periapsis altitude in the absence of sunlight slightly more than predicted. A periapsis lower OTM brought the spacecraft lower into the atmosphere to take advantage of higher density, but the maximum specified dynamic pressure limit was reduced to 0.20 N/m^2 in anticipation of predicted density waves. On the night side, the local gravity effect worked toward increasing the periapsis altitude, and additional periapsis-lower OTMs were performed, also visible in Figure 3. On 3 August, the experiment was terminated by beginning execution of a series of periapsis-raise OTMs, after the apoapsis altitude had been successfully lowered to 540 km.

FIGURE 3. PROFILE OF AEROBRAKING OPERATIONS



ORBITAL ACTIVITY PROFILE

During aerobraking, the looper-controlled activities followed the following profile: first, a maneuver was executed to assume and then maintain the aerobraking attitude: HGA trailing opposite the velocity vector, solar arrays turned perpendicular to the velocity vector, with their back sides, that is, the sides covered with quartz

optical solar reflectors, facing the oncoming atmosphere, to present the maximum surface area to the oncoming atmospheric free molecular flow; this attitude broke off communications with Earth. The attitude control authority was changed from reaction wheels to 0.9 N thrusters for the availability of positive attitude control in the presence of atmospheric torque. Selected data from AACS and from selected thermal sensors was stored in RAM. In this configuration, the spacecraft encountered atmospheric drag approaching 9 N for periods ranging from 4 minutes **in the beginning, to 13 minutes** at the end of the 70-day experiment. Upon completion of the atmospheric drag pass, the spacecraft maneuvered to place the HGA on Earth point, delayed two minutes to allow the DSN an opportunity to phase-lock receivers and telemetry processing strings to the downlink, and then the spacecraft read out the RAM containing data on AACS and thermal performance from the completed drag pass. These data were read out three times in the beginning of the experiment, but as the orbit period decreased to minimum near the end, there was time only to read out the data once.

At apoapsis, the spacecraft performed a star calibration maneuver on odd-numbered orbits. This maneuver rotates the spacecraft so that its fixed star scanner can rotate past two selected stars, and thus update its attitude knowledge. On even-numbered orbits, the apoapsis passage was available as an opportunity to perform an OTM to raise or lower the periapsis altitude. “Canned” OTMS of six different values, three periapsis raise, and three periapsis lower, resided in the on board memory, and could be selected by use of commands stored on disk storage at JPL. If the apoapsis **pass did not require an** OTM, which was most often the case, additional **time was** available with the spacecraft’s HGA on Earth **point. This period was valuable** for obtaining Doppler data for determination of orbital parameters. Following apoapsis passage, the spacecraft would rotate to shade the bus from direct sunlight with the HGA. This orientation placed the MGA on Earth point, and communications continued until a few minutes before the series of activities began again on the next orbit, Uplinks were timed to arrive at the spacecraft every time its had finished rotating to place the HGA or MGA on Earth point. It was standard procedure to sweep the uplink frequency, catching the spacecraft’s receiver at its rest **frequency, after which it locked onto and** could track the uplink.

Controllers at JPL immediately checked the memory-read-out (MRO) data, ready to

command an OTM at the next apoapsis opportunity if limits had been exceeded in **attitude control or temperature. They never did, The highest temperature allowed for the solar arrays was 110”C, and the maximum seen was 90°. The** HGA was expected to tolerate up to 180°, but it did not have an operable temperature sensor, and its temperature had to be estimated based on measured solar array **temperatures and an estimated thermal accommodation coefficient for the** HGA. **Thruster firings were mostly confined to the periods of configuration prior to and after the atmospheric passes.**

BEHAVIOUR IN THE ATMOSPHERE

While encountering the atmosphere, the spacecraft slowly oscillated, typically about 10°, mostly in pitch, and at rates which were below the AACS’S rate limitations[5]. No instability was observed.

UPDATES FOR THE DEEP SPACE NETWORK

The DSN needs to be given predicted times to acquire Magellan’s signal when the spacecraft turns to point to Earth, and the predicted radio frequency. With Magellan’s constantly changing orbit, there were constantly changing event times. Changes in event times also means changes in radio frequencies, since the Doppler shift differs at any particular point in orbit. This was accomplished by circumventing the more lengthy process of publishing complete sets of sequence-of-events (SOE) times. Instead, a subset was provided to DSN very close to real time, as soon as new navigation solutions were incorporated in looper timing adjustment commands. These took the form of printed lists, called Ground Events Updates (GEU) which were “quick & dirty” supplements to previously published SOE data: quick in that they came from a simple software routine applied to the output of the commanding process, which was not designed to provide a complete sequence of events; “dirty” in that the software was not designed to account for transfers of uplink responsibility among overlapping stations, nor did their output benefit from a review process.

SAMPLE GEU	**COMMENT**
DSS 42 GEU	
	GEU list faxed to Australian Deep Space Station 42 Day of Year, Hours, Minutes, Seconds UTC
218232112 TXROFF	Turn uplink transmitter off
218234024 LOS, S	Expect loss of signal, S-band
218235750 ACQ **U/L, S**	Turn on uplink transmitter and begin freq. sweep
219001717 AOS, S	Expect acquisition of signal, S-band
219001802 ACQ D/L, S, 2-WAY, 40BPS	Acquire downlink, S-band, coherent with U/L, telemetry rate 40 bits per second. This list typically covered a period from beginning to end of a tracking pass, about 8 hours average.

In the latter stages of the aerobraking experiment, the controllers' reaction time for responding to a possible anomaly grew shorter due to the compression of profile activities into a shorter orbit period, and therefore the occasional accidental losses of data became more critical to avoid. Great effort was expended to identify the cause of any data outage, and to prevent recurrences. Also, as the orbit period decreased toward minimum, the time spent in the atmosphere increased, causing more drag, and faster orbit period decrease.

COMPLETION

With a final apoapsis altitude of 540 km, the orbit was adequate for the collection of high-resolution gravity field survey data at nearly all latitudes. Magellan is funded for collection of a high-resolution gravity covering perhaps 98% of planet, through the majority of Cycle 6. The high-resolution gravity field survey data will be available to assist researchers as they work to understand the puzzling nature of Earth's sister planet.

CONCLUSION

The fact that a spacecraft which was never designed for atmospheric entry successfully undertook an aerobraking operation to significantly alter its orbit at another planet implies that that future interplanetary spacecraft intentionally designed to undertake aerobraking will be able to obviate the need to carry large masses of propellant for the purpose of orbit change maneuvering.

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5. Ibid, pg 35