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The Venus Balloon Project

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On June 11 and 15, 1985, two instrumented balloons were released from the Soviet VEGA 1 and VEGA 2 spacecraft and deployed in the atmosphere of Venus. The VEGA probes flew by the planet on their way to a rendezvous with comet Halley in March 1986. Drifting with the wind at altitudes of 54 km, the balloons traveled one-third of the way around the planet during their 46-hour lifetimes. Sensors on-board the gondolas made periodic measurements of pressure, temperature, vertical wind velocity, cloud particle density, ambient light level, and frequency of lightning. The data were transmitted to Earth and received at the DSN 64-m stations and at several large antennas in the USSR. Approximately 95 percent of the telemetry data were successfully decoded at the DSN complexes and in the Soviet Union, and were provided to the international science team for analysis.

Very Long Baseline Interferometry (VLBI) data were acquired by 20 radio observatories around the world for the purpose of monitoring the Venus winds. The DSN 64-m subnet was part of a 15-station VLBI network organized by the Centre National d'Etudes Spatiales (CNES) of France. In addition, five antennas of the Soviet network participated in the experiment. VLBI data from the CNES network are currently being processed at the Jet Propulsion Laboratory.

I. Introduction

In December 1984 the Soviet Union launched two spacecraft on the VEGA mission to comet Halley. On June 11 and 15, 1985, the spacecraft flew by Venus and deployed two instrumented balloons into the planet's atmosphere. The balloons floated at an altitude of 54 km, and traveled approximately one-third of the way around the planet during their 46-hour lifetimes (Fig. 1). *In situ* measurements were transmitted directly to Earth with a primary telemetry data rate of 4 bits per second at a carrier frequency of 1667.914 MHz. Complete descriptions of the VEGA mission and the balloon experiment are given in Refs. 1 through 5.

Ground data acquisition during the balloon experiment consisted of three activities, all of which were supported by the DSN 64-m subnet:

(1) Balloon telemetry – Telemetry data acquisition and decoding, also supported by several stations in the USSR.

(2) VEGA flyby orbit determination – Acquisition and processing of one-way Doppler and Delta DOR (Delta Differential One-way Range) from the VEGA spacecraft. VEGA orbit determination was performed at JPL using the DSN data, and independently in the Soviet Union using the DSN data and two-way Doppler and range acquired by selected Soviet stations at a ground-receive frequency of approximately 6 GHz.

(3) Balloon position and velocity determination – Acquisition and processing of differential Very Long Baseline Interferometry (VLBI) measurements on each balloon and the corresponding VEGA spacecraft. VLBI data acquisition was also supported by a global network of radio observatories.

The balloon experiment is a cooperative venture of France and the Soviet Union. The French space agency Centre National d'Etudes Spatiales (CNES) was responsible for organization, implementation (as required), and operation of 15 of the 20 antennas of the worldwide network of radio observatories, which included the DSN 64-m subnet (Fig. 2). CNES also constructed some of the balloon instrumentation and established a Venus balloon science center at the Centre Spatiale de Toulouse. During the encounter periods and pre-encounter ground data system tests, CNES personnel manned the VEGA Project Operations Center at Toulouse to coordinate real-time activities between the Network Operations Control Center at JPL and the Space Research Institute in Moscow. Currently, CNES is coordinating telemetry and VLBI data exchange and analysis. Intercosmos, a branch of the USSR Academy of Sciences, has the responsibility for Soviet participation in this activity. Intercosmos made available all technical information required to conduct the ground-based portion of the experiment, and is responsible for providing to CNES all telemetry and VLBI data acquired by the five-station Soviet network.

The roles of the participating agencies are formalized by a Memorandum of Understanding between NASA and CNES, and by agreements between CNES and Intercosmos. According to these agreements, all data are to be analyzed by an international science team composed of members from France, the United States, and the Soviet Union. First results from joint analysis of the telemetry data are reported in Refs. 6 through 9.

II. Telecommunications

Radio signals were transmitted by each balloon and VEGA spacecraft bus at L-band (centered at 1667.914 MHz). Crystal oscillators were employed as on-board frequency references. The signal spectra varied in time according to a preset sequence which was re-initialized each time the L-band transmitters were turned on. At a given time, the signal took one of three forms:

(1) Pure carrier.

(2) Carrier with telemetry sidebands.

(3) Suppressed carrier and first harmonics of a 3.25-MHz square wave phase modulation (the "VLBI" tones).

Balloon telemetry data were modulated onto a subcarrier located 254.5 Hz away from the carrier, at rates of either 1 or 4 bits per second. The VLBI tones were provided mainly for the purpose of determining the position of the balloon relative to the VEGA bus, but were also used in the acquisition of Delta DOR data from the bus and an angularly nearby quasar.

The balloon transmissions occurred in bursts with durations of 330 seconds, either once or twice per hour, in order to conserve battery power. The bus transmission sequence was essentially the same as the balloon's, except that the bus transmitted continuously during the Venus encounter phase. The telemetry modulation on the bus consisted of a predetermined bit stream for testing purposes.

The balloon and bus L-band transmitters were identical. The radiated power levels were approximately 4.5 watts, and signal polarization was left circular. The peak bus antenna gain was 10 dB; the balloon omni-antenna gain varied from -3 dB to 0 dB, depending on orientation (maximum gain was achieved near the sub-Earth point, and minimum near the limb).

Implementation of the DSN 64-m subnet for reception of the balloon signals included installation of cooled FET amplifiers, L-band feeds, and upconverters to translate the 1668 MHz received signals to 2288 MHz (J. R. Withington, personal communication). The RF bandwidth of this system is 18 MHz, and the zenith noise temperature is approximately 30 K. Special equipment was also provided for downconverting the signal spectrum from IF to baseband in support of VLBI data acquisition. This hardware made it possible to record the signal spectra in the National Radio Observatory Mark II format, an international standard. Portions of this equipment were replicated by the Observatoire de Paris-Meudon in France and provided to other stations of the global network.

Prior to the encounter, the phasing of the balloon and bus transmission sequences was adjusted as required for the differential VLBI measurements. That is, for a given transmission, both spectra contained either a carrier or a pair of VLBI tones.

Balloon carrier received power as measured at the DSN 64-m subnet is shown in Fig. 3 (S. E. Borutzki, personal communication). These values are in good agreement with the estimated levels of -165 to -162 dBm.

III. Balloon Telemetry

Balloon telemetry data were provided by the DSN on computer-compatible magnetic tape in two forms: the original recorded spectra (level 0) and the demodulated and decoded data streams (level 1). Implementation details are described in Refs. 10 and 11. The science team also received estimates of the observed balloon frequency derived from telemetry processing for the purpose of obtaining preliminary estimates of zonal wind speed.

The balloon transmission sequence is illustrated in TDA document 870-20.[1] Each balloon had 46 telemetry transmissions, designated A-1 through A-46 (balloon 1) and B-1 through B-46 (balloon 2). The DSN obtained level 0 recordings for all telemetry sessions except A-45, A-46, and B-30, which were lost due to station hardware problems. DSN level 1 recordings were obtained for all recorded telemetry transmissions except A-1, B-1, B-45, and B-46. The first recordings on both balloons were not decoded by the DSN due to large signal variations resulting from erratic balloon motions. For the last two recordings from balloon 2, battery power was too low to yield the signal-to-noise ratio required for decoding. Most DSN level 1 data were produced by personnel at the Deep Space Complex near Madrid, Spain.

The Soviet network obtained level 0 recordings for the telemetry transmissions missed by the DSN. In addition, Soviet personnel produced level 1 recordings for sessions B-1 and B-30. Of the combined data set, only five telemetry transmissions have not been decoded (A-1, A/B-45, and A/B-46). The data have been analyzed by Soviet, French, and U.S. scientists, and preliminary results have been published in *Science* (Refs. 6-9).

IV. VEGA Flyby Orbit Determination

Components of the position and velocity of each balloon relative to the corresponding VEGA bus were measured using VLBI techniques. In order to obtain information on the Venus wind velocity from these differential measurements, the VEGA spacecraft orbits relative to Venus must be accurately known.

Determination of the VEGA orbits at JPL depended only on one-way data acquired at L-band by the DSN 64-m subnet as described in Ref. 12. Soviet two-way range and Doppler were not used. The DSN provided Doppler from each station and Delta DOR observations from the Goldstone-Madrid and Goldstone-Canberra baselines. Delta DOR data essentially are VLBI measurements of the spacecraft angular position relative to an angularly nearby extragalactic radio source (EGRS). Candidate L-band radio sources were selected from the DSN EGRS source catalogue, which is derived from VLBI observations at 2.3 and 8.4 GHz. Observing sessions were conducted prior to the Venus encounter to validate source strengths at 1.7 GHz.

VEGA flyby orbit estimates were based on data gathered during the maneuver-free phase from two days before Venus closest approach to thirteen days after. Within this period, there were nine successful Delta DOR acquisitions on VEGA 1, and thirteen on VEGA 2 (see Table 1 for the Delta DOR performance summary). The overall Delta DOR measurement success rate was 85 percent.

For the determination of the Venus wind velocity from differential VLBI measurements, only errors in the VEGA spacecraft position and velocity relative to Venus that are perpendicular to the Earth–Venus line (i.e., the "transverse" components) are important. The formal standard deviations of these errors for the duration of the balloon experiment are given in Fig. 4. For VEGA 1, these uncertainties are always below the balloon position and velocity accuracy goals of 15 km and 1 mps. For VEGA 2, the position errors exceed the goal about 30 hours into the experiment, but the maximum error is less than 24 km.

The VEGA 2 errors tend to be larger than those for VEGA 1 for two reasons: the orbit geometry was not as favorable as that for VEGA 1, and the VEGA 2 one-way Doppler accuracy was degraded by jumps in the frequency of the spacecraft reference oscillator.

V. Balloon Position and Velocity Determination

Balloon position and velocity estimates will be obtained from reduction of the following data:

(1) Balloon received frequency, which is a measure of velocity along the line-of-sight.

[1] Owen, E. L., *Venus Balloon Project, DSN Preparation Plan*, TDA document 870-20, JPL D-1111, Mar. 1, 1985 (JPL internal document).

(2) VLBI measurements of the angular position and velocity of each balloon relative to the corresponding bus as observed from Earth.

(3) Estimates of VEGA bus orbits relative to Venus.

(4) Estimates of balloon altitude and altitude rate based on *in situ* measurements of atmospheric pressure.

Acquisition of useful differential VLBI data was possible because the balloon and bus were simultaneously within the antenna beam at each station.

For complete determination of balloon transverse position and velocity in two dimensions from VLBI measurements, simultaneous observations from at least three stations are necessary. Maximum accuracy is achieved when the distances between stations are as large as possible (typically, several thousand kilometers). The global network yielded good observing geometry for approximately 22 hours each day.

Many of the world's most sensitive radio telescopes were part of the Venus balloon network, including eight with aperture diameters of 64 m or larger. Continuous coverage by highly sensitive antennas was required because of the low power level of the balloon transmissions. Integration times that are short compared to the signal coherence time can be used to extract signal phase from data recorded at these stations. With this information it is possible to compensate for signal phase fluctuations in order to obtain coherent detection from stations with poorer signal-to-noise characteristics.

Of the 69 transmissions from each balloon, there were only two for which DSN hardware problems caused loss of VLBI data. These were telemetry frame B-30 and the following VLBI transmission, which are expected to be recovered from VLBI recordings made at other stations of the CNES network. For balloon 1, eight transmissions are of marginal use for position and velocity determination because the bus antenna was not pointed to Earth. Two additional transmissions are probably not usable due to low signal power at the end of the balloon lifetime. For balloon 2, the bus signal was not observed for four transmissions because the spacecraft was occulted by Venus; four other transmissions are probably unusable due to low balloon signal levels. Thus, differential VLBI measurements were obtained for 120 of the balloon transmissions, out of a total of 138.

In addition to VLBI data acquisition, the DSN is supporting the processing of VLBI recordings from the CNES network. Analysis of quasar observations made by the network during the encounter period has yielded information on network clock synchronization to required levels. Time histories of balloon and bus received phase have been obtained for the majority of the DSN recordings (after a format conversion) using the hardware correlation capabilities of the Network Operations Control Center VLBI Processor.

In the next stage of processing, balloon and bus phase histories for all stations of the CNES network will be produced by the JPL/CIT VLBI Processor (Block II). These data and similar results derived from recordings made by the Soviet network will be given to the science team for further analysis.

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Table 1. VEGA Delta DOR performance

1985 Date (MM/DD)	1985 DOY	VEGA bus	DSN baseline	Status
6/08	159	1	CS	F
			CA	P
6/10	161	1	CS	F
			CA	P
6/11	162	1	CS	P
			CA	P
6/12	163	1	CS	P
			CA	F
		2	CS	P
			CA	P
6/14	165	2	CS	P
			CA	P
6/15	166	2	CS	P
			CA	P
6/16	167	2	CS	P
			CA	P
6/17	168	1	CS	P
			CA	P
		2	CS	P
			CA	P
6/18	169	1	CS	P
			CA	P
6/20	171	2	CS	P
			CA	F
6/21	172	2	CS	P
			CA	P

P = Processed
F = Failure to correlate
DOY = Day of Year
CS = California/Spain
CA = California/Australia

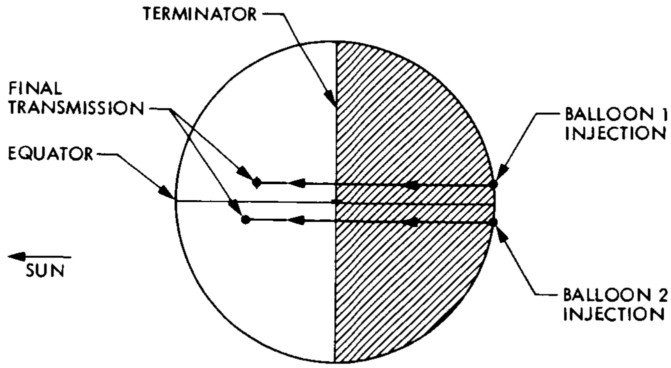

Fig. 1. Paths of balloons across Venus as viewed from Earth

LOCATION	DIAMETER (m)	LOCATION	DIAMETER (m)	LOCATION	DIAMETER (m)
1. PENTICTON, BRITISH COLUMBIA	(26)	8. ATIBAIA, BRAZIL	(14)	15. SIMEIZ, USSR	(22)
2. BIG PINE, CALIFORNIA	(40)	9. MADRID, SPAIN	(64)	16. PUSHINO, USSR	(22)
3. GOLDSTONE, CALIFORNIA	(64)	10. JODRELL BANK, ENGLAND	(26)	17. MEDVEZHI OZERA, USSR	(64)
4. FORT DAVIS, TEXAS	(26)	11. EFFELSBERG, FED. REP. GERMANY	(100)	18. ULAN-UDE, USSR	(25)
5. NORTH LIBERTY, IOWA	(18)	12. ONSALA, SWEDEN	(26)	19. USSURISK, USSR	(70)
6. WESTFORD, MASSACHUSETTS	(37)	13. HARTEBEESTHOEK, SOUTH AFRICA	(26)	20. CANBERRA, AUSTRALIA	(64)
7. ARECIBO, PUERTO RICO	(305)	14. EUPATORIA, USSR	(70)		

Fig. 2. Venus Balloon Project International Network

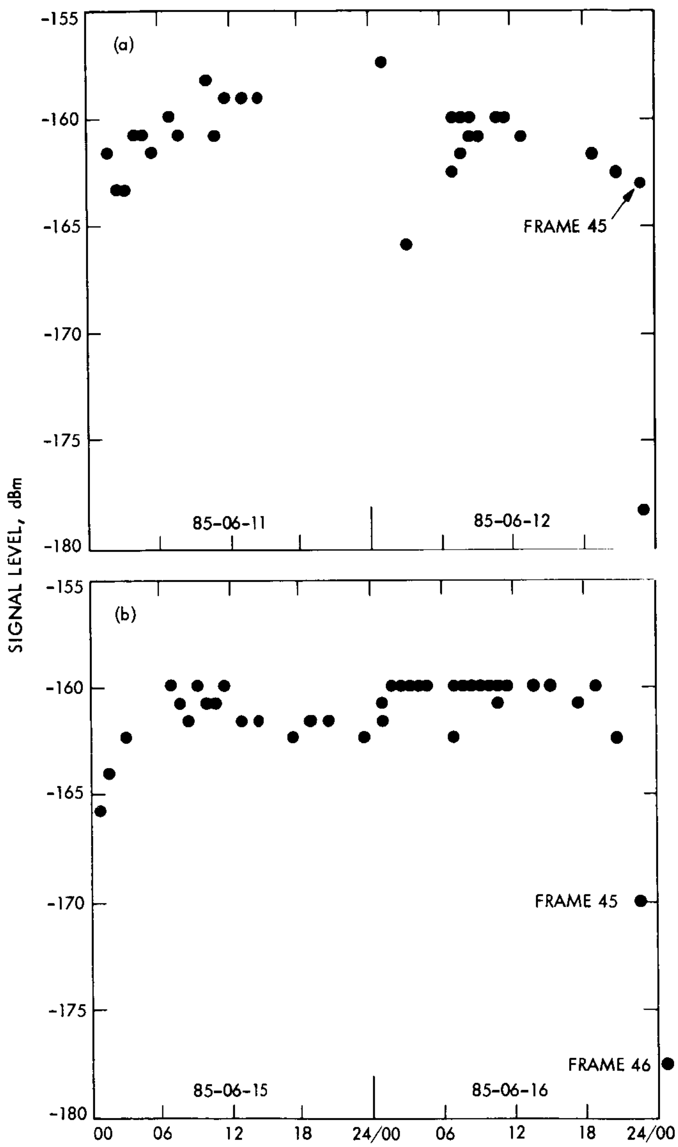

Fig. 3. Received signal level (carrier only) at DSN 64-m subnet: (a) balloon 1, (b) balloon 2

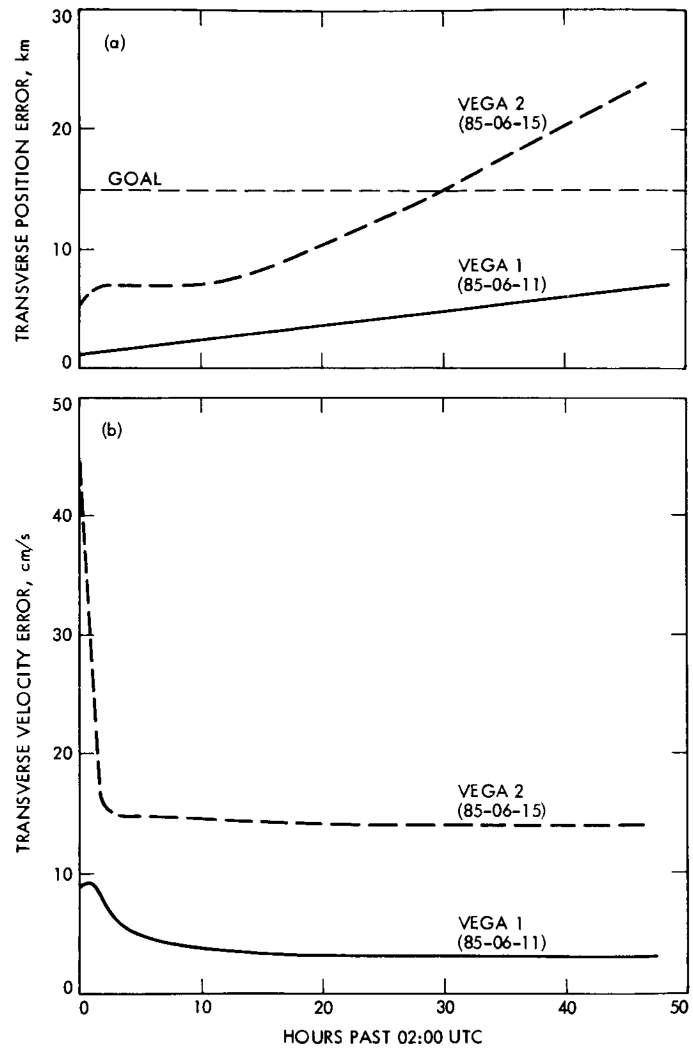

Fig. 4. Standard deviations of transverse position and velocity of VEGA bus relative to Venus: (a) position, (b) velocity