Galileo Array Study Team Report

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The Galileo Array Study Team was formed in April 1990 in response to concerns about the adequacy of support plans for the very important arrival of Galileo at Jupiter in December 1995. The team is composed of personnel with varying responsibilities in the Deep Space Network (DSN) and Galileo Project. The concerns that led to the team's creation were various, but of principal importance were the high-wind events at Goldstone, which caused DSN antennas to be stowed during the February 1990 Venus flyby, and the failure of the Madrid 70-m antenna bearing late in 1989, which resulted in over a month of unscheduled downtime for investigation and repair. The team's stated objective is "to devise and recommend a plan which can assure effective network support of the Galileo arrival day events." The team was given freedom to explore both the requirements and any reasonable response to those requirements. In general, the team concluded that the already-established plans are in fact the best plans to pursue, based on the knowledge available today. This conclusion could be revised after Galileo's high-gain antenna is unfurled in early 1991. This article summarizes the process of the study and the rationale that led to the team's conclusion.

I. Galileo at Jupiter

Figure 1 shows the sequence of mission events when Galileo arrives at Jupiter on December 7, 1995. As specified in the Galileo mission plan and driven by the mission values associated with each of its specific targets, the desired aggregate project plus Deep Space Network (DSN) confidence in successful data acquisition is 99 percent for the probe data, 98 percent for the Io passage, and 95 percent for other acquired science data. In a risk-management sense, the DSN data-capture step has been allocated about half of the allowed hazard, meaning that this step must be accomplished at a 99-percent confidence level for Io.

Except for the Io encounter, overall support for these events is considered to be adequately handled by the DSN's three-antenna arrays, consisting of one 70-m and two high-efficiency 34-m antennas. In particular, the probe data are considered to be adequately secure since there is dual coverage by Goldstone and Canberra and the data are also being recorded for later playback. Because of the probe entry's dual coverage, the Io passage falls into a transition period between Madrid and Goldstone. This transition is accompanied by an interval of low telecommunications margins.

The Io encounter science data are second only to the probe data in importance. Data are returned at a rate of 134.4 kbps, which is the only rate at which the full complement of data from the solid-state imaging (SSI) camera, the near infrared map spectrometer (NIMS), and the plasma wave subsystem (PWS) can be simultaneously acquired. This total data set is the key to understanding this part of the Jovian system. Galileo's arrival day is its only opportunity to study Io closely because of the high radiation it will experience this close to Jupiter. The total amount of data returned during the Io encounter will require several times the space available on the tape recorder and, therefore, must be returned in real time.

Galileo follows its arrival day activity with about six months of long, looping orbit about Jupiter before beginning a sequence of nearly monthly targeted encounters with the Jovian satellites. A brief review of the requirements and DSN-support capabilities for the tour confirms that no additional substantive challenges should arise during Galileo's encounters with the Jovian satellites. Figure 2 shows the Galileo spacecraft-to-Earth range from arrival through the tour interval, using one candidate tour sequence. Other scales indicate the relative link performance that is dependent upon that range and the support capability of various DSN antenna configurations. The notation 70/34/34 indicates a capability provided by the basic three-antenna array, while 70/34/34(SC) indicates the same array with a new ultralow-noise amplifier installed in one of the 34-m antennas. It is clear from this figure that the arrival day and Io encounter represent the most challenging period for the mission. Consideration of the tour will not levy additional drivers on the DSN configuration.

II. Data-Capture Confidence

There are two items that must be considered when assessing confidence in data capture. One is the telecommunications link confidence, which depends upon the planned DSN receiving configuration. The other is the functional availability of the elements of that planned configuration. The element availabilities are extractable from observed statistics of network operation. Link confidence levels are developed from the link design control table process, assuming that the DSN configuration is equal to that planned. Variables of weather, background noise, and equipment performance parameters are all included in this process, as is the noise from Jupiter itself. The predicted signal strength at a specified confidence level is calculated as the mean signal strength less a specified multiple of the 1-sigma statistical uncertainty in the variable parameters.

Two key elements of the link design may be subject to revision early next year. These are the performance of the Galileo high-gain antenna (HGA), which will only be unfurled after the first Earth flyby, and the new experimental convolutional code [1,2], which will become fully testable after the HGA is in use. In the unlikely event that the new coding scheme fails to work, or that the single special encoder on the spacecraft is disabled, the anticipated 1.3-dB benefit would be lost. After testing, the uncertainty in HGA performance should be lessened, but its actual value could be better or worse than the design value. The study has assumed nominal performance for both.

On the lower half of Fig. 1 is a plot of the predicted Galileo signal level relative to a 95-percent confidence threshold for 134 kbps. This confidence level is in a link-design sense and does not yet include element reliabilities. For a short period during the Io passage, the link confidence level is below this nominal 95 percent. The average during the Io passage is well above this, but below the 99-percent target level. Some augmentation of the DSN configuration beyond the 70/34/34 array is needed to meet that target. That need grows when element reliabilities are included.

The DSN keeps records of the support given to each of its customers by each of its facility elements, including the times when it is inoperative due to failures of a critical component. Analyses of that data are published periodically.[1] For 1989, total outage of the telemetry support function was 2.07 percent of scheduled support time. About half of that occurred in subsystems that cannot be made redundant, such as the antenna or its microwave elements. The remainder occurred in subsystems that would be paralleled in reliability for critical support periods such as the Io encounter. Embedded within those outage statistics are the times when antennas must be stowed due to excess wind. These were separately identified for Goldstone,[2] the windiest of the three sites, as being less than 0.2 percent of total time. Of that, only a tenth (0.02 percent of total time) is common between two antennas at the site. Thus, excess wind does not appear to be a significant source of common-mode failures for the multiantenna array at Goldstone.

Long-duration outages such as the one from the failure of the Madrid 70-m antenna elevation bearing in late 1989 are not fully characterized by the operational statistics.[3] The sample set is very small, with only one two-month outage occurring in the almost 20-year life of that antenna. Another similar but shorter outage was caused by the failure of the hydrostatic azimuth bearing of the Goldstone 64-m antenna shortly after the 1981 Voyager Saturn encounter. This was followed by extensive rebuilding of the concrete pedestal of that antenna, which corrected the problems leading to the bearing failure. This second outage to make repairs was not a surprise, but it can be likened to scheduled elective surgery taken at a convenient slack period for mission needs. Across the Network, the numbers suggest that long-term random outages could add perhaps 0.5 percent to the risk that any given antenna is unavailable when needed. Subjectively, based on past experience, it could be argued that this is quite an overestimation of the actual risk for critical events.

One other imponderable is the exposure to hazards that might remove an entire complex from service for a substantial period of time. This topic was addressed in a study last year, which concluded that such exposure should be less than 1 percent at any time for any site.[4] This consideration may become more significant in the future if the Space Exploration Initiative blossoms and the DSN must prepare to support piloted missions in deep space.

III. DSN Configuration Options

A wide range of options was examined for plausible changes to the DSN configuration to meet the Galileo–Jupiter arrival day needs. These options included DSN internal elements and non-DSN receiving elements. Since the largest risk for element reliability is the possibility of an outage in the 70-m antennas, the seemingly obvious solution is to provide backup in kind—with a "spare" 70-m antenna at both Goldstone and Madrid, which would also be useful in supporting a variety of other missions when not assigned to Galileo arrival duty. But such a solution is expensive, and its justification would rest substantially on the needs of those other missions. A related solution is a single 70-m antenna with an ultralow-noise amplifier at a new site located two to five hours in longitude east of Goldstone. This again is expensive but, depending upon location, could have significant added value to other missions. A full consideration of these factors and a ranking of these options are outside the scope of the work reported here.

Other internal options were considered that might work together to provide an adequate solution. The addition of an ultralow-noise amplifier to the 34-m beam-waveguide (BWG) antenna would add almost 2 dB to the sensitivity of that antenna alone, but only 0.5 dB to the 70/34/34 array [3]. The addition of another 34-m BWG antenna using the current low-noise amplifiers (LNAs) adds about 1.1 dB to the array. Neither addition is enough to establish a fallback for a potential outage of the 70-m antenna, although they do raise the confidence level for the full array at the Madrid–Goldstone transition to well above 95 percent. The old 34-m antennas, which are due to be replaced before 1995, could be retained at some expense by providing new electronic assemblies for the replacement antennas while leaving the old antenna systems intact. But such a step would add surprisingly little to the array performance, only about 0.5 dB, again not enough to satisfy the needs. The addition of the ultralow-noise amplifier to the 70-m antenna adds sensitivity to the array, but increases the portion of the overall signal capture capability that is at risk to a single failure. It does not satisfy Galileo's needs.

A minimally satisfactory solution can be developed by first making the assumption that common hazards to the three current DSN complexes will not cause all the antennas to be unavailable at the same time. This assumption has strong implications for the design of the facility and

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[1] D. W. Ginavan, "DSN Workload by Project, 1989 Only," Bendix Field Engineering CMO Report (internal document), Jet Propulsion Laboratory, Pasadena, California, May 31, 1990.

[2] L. Butcher to D. J. Mudgway, personal communication, Jet Propulsion Laboratory, Pasadena, California, June 5, 1990.

[3] D. W. Ginavan, op. cit.

[4] J. W. Layland and R. Stevens, "DSN Site Loss Impacts" (internal document), Jet Propulsion Laboratory, Pasadena, California, May 17, 1989.

the equipment configuration within each complex, including the power system, communication and control paths, and exposure to wind or other hazards. If this assumption is valid, then adding both an ultralow-noise amplifier to the planned 34-m BWG antennas and an additional 34-m BWG-type antenna with an ultralow-noise amplifier would appear to meet the stated 99-percent confidence needed for the Galileo–Io passage, given the current understanding of link parameters. The critical feature is that the partial array without the 70-m antenna be able to capture data under most conditions, since the risk of being without the 70-m antenna is itself on the order of 1–2 percent. If this subarray provides 75-percent confidence of data capture, this part of the data outage risk is reduced to below 0.5 percent. For a unique event such as arrival day, short-term operational use of the Goldstone Advanced Systems Research and Development antenna might be considered—although this still leaves the Madrid half of the Io passage exposed.

IV. Non-DSN Elements

Galileo's arrival at Jupiter has many characteristics in common with Voyager's far outer planet encounters that make seeking assistance outside the DSN appropriate. These encounters are unique events that make demands upon support capabilities that will not be repeated for many years. Galileo's needs are far more challenging than those of most contemporary missions. Internally adding to the DSN to fully meet those needs would give the Network more facilities to maintain than is necessary for the needs of most other missions. Thus, it is appropriate to look outside the DSN for present or planned facilities of other agencies that can assist in satisfying Galileo arrival day needs. A list of potentially useful facilities was taken from research done for the Voyager Interagency Array Study [4]. Table 1 shows an updated chart of these facilities, including both large space agency apertures and radio observatories. Figure 3 is a world map showing features and locations of various space agency antennas.

Most of the facilities identified in Fig. 3 either cannot "see" Galileo at the time of the Io passage or are too small to be useful. The most interesting candidates are those that could potentially provide stand-alone support to Galileo. Both the National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) near Socorro, New Mexico, and the planned NRAO Green Bank Telescope (GBT) are in this category. The VLA will be able to see about 80 percent of the Io encounter period, while the GBT could conceivably see the entire passage. Other antennas that might be useful in an array include the Algonquin Observatory 46-m, the NRAO Green Bank 43-m, and the Owens Valley 40-m. However, adding any one of these non-DSN elements would require significant expense, and none of these last three is individually strong enough to fill in for a missing 70-m antenna. Thus, further consideration of these second-tier candidates would only occur if an insoluble problem arises with the VLA and GBT.

Having a non-DSN support site capable of stand-alone operation has some additional desirable features for engineering its configuration. One does not need, for example, the complexity of arraying that requires both the signal combiner and the co-observing DSN site to be properly operating. That means data transfer to the DSN might be in real time only and not require backup recording or, if both are needed, then each is simplified. The actual system configuration will be strongly driven by required functional availability. Finally, the signal-processing equipment that would be deployed at any stand-alone site could become the nucleus of a transportable backup unit, which has been considered for recovery from major site outages.[5]

Although the details of the work will differ, incorporating either the VLA or the GBT into the Network configuration for Galileo's arrival at Jupiter represents a substantial investment of NASA money and effort. The GBT, as currently designed, will be the equivalent of a 100-m, clear-aperture, fully steerable antenna and will be located in the hills of West Virginia. It is now in the early stages of design and construction, with completion planned for early 1995. For the GBT project to meet both its schedule and performance goals will be a worthy challenge for all involved.

The VLA, which was outfitted for X-band (8.4-GHz) receiving and Voyager signal capture by NASA, served admirably during the encounter with Neptune [5]. Nevertheless, some obstacles remain for providing similar support to Galileo. Much of the DSN signal-processing equipment that was used for the Neptune encounter has been deployed elsewhere in the Network and would have to be replaced. In addition, Jupiter hot-body noise will affect not only the overall Galileo link performance at the Io encounter but also the ability of the VLA to coherently combine the Galileo signal. This will likely require the use of one of the larger VLA configurations. And, finally, the data rate and coding scheme of Galileo are such that the effects of the VLA's 1.6-msec signal gap[6] [6,7] must be lessened before

[5] Ibid.

[6] S. Dolinar, "VLA Gap Effects Pertinent at Galileo's Data Rates," JPL Interoffice Memorandum 331-88.2-044 (internal document), Jet Propulsion Laboratory, Pasadena, California, July 14, 1988.

the arrival at Jupiter can be supported. These issues will be the subject of further study.

At first glance, fiber optics appears to be the most likely technology, both for eliminating the VLA signal gap and for enabling a wider bandwidth signal path to increase the sensitivity of the VLA as a scientific instrument. The NRAO has considered this as part of their long-range plan for enhancing the VLA. If present technology can meet these needs, it appears that a go-ahead could be given in early 1991 for the first step of installing the fiber-optic signal path and that closing the signal gap could be accomplished in 1994 or 1995 in time for Galileo's arrival at Jupiter. The signal-processing changes needed for a sensitivity boost could then be accomplished by NRAO as their resources allowed.

V. Conclusions

In order to achieve the desired 99-percent confidence level in capturing Galileo-Io passage data, some form of backup to the 70-m antennas at Goldstone and Madrid is essential. The simplest and most reasonable answer appears to be use of the NRAO VLA or GBT. This assumes that open technical or schedule issues pertinent to the implementation of either of these sites will be solved. Further, given the relative expected performance levels of these sites versus the DSN during the hand-over from Madrid to Goldstone, it seems appropriate that the NRAO site become the primary data source during that interval. Alternative answers involving additions to DSN sites, while deserving of further consideration based on other missions' needs, are nonetheless expensive to implement and don't appear to be supportable based on Galileo needs alone.

Open issues to be considered include the technical risk of eliminating the VLA's 1.6-msec signal gap, the schedule risk that would accompany a dependence upon the GBT, and the schedule and funding risk that would accompany selection of a more expensive DSN internal solution. Also of concern is the uncertainty of Galileo's high-gain antenna performance and the new experimental coding scheme, both of which will be tested in 1991. Given that the outcome of these tests remains within reasonable range of present predictions, these general conclusions will not change.

The study team has recommended to DSN management that a joint JPL–NRAO study be formally initiated into the technical details of a potential Galileo support configuration. This would be consistent with prior tentative plans to enlist the VLA in support of Galileo's arrival at Jupiter. It is also timely and allows the team to carefully plan for and establish the needed capability by 1995. That recommendation was accepted and a joint JPL–NRAO study is now under way.

References

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[6] S. J. Dolinar, "VLA Telemetry Performance with Concatenated Coding for Voyager at Neptune," *TDA Progress Report 42-95*, vol. July–September 1988, Jet Propulsion Laboratory, Pasadena, California, pp. 112–133, November 15, 1988.

[7] L. J. Deutsch, "An Update on the Use of the VLA for Telemetry Reception," *TDA Progress Report 42-72*, vol. October–December 1982, Jet Propulsion Laboratory, Pasadena, California, pp. 51–60, February 15, 1983.

Table 1. Catalog of antenna facilities with X-band surfaces

Institution	Location	East longitude	Latitude	Aperture, m	Area, m^2	8-GHz performance		Percentage equivalent, 64-m	Remarks
						Efficiency	System temperature		
70-m DSS	DSN			70	3,848	68	25	163	Three longitudes
Nuffield R.A.L.	Jodrell Bank, UK	358	+53	76	4,536	20	50	56[a]	Far-north upgrade by 1992
Nuffield R.A.L.	Cambridge, UK	000	+52	32	804	70(?)	N/A	38[a]	On line 1990
Franco–German	Spain	359	+38	30	707	60	—	26[a]	mm-wave radio astronomy instrument
MPIR	Effelsberg, FRG	006	+50	100	7,854	45	90	220[a]	Far north
Instituto di R/A	Bologna; 2nd element Sicily	012	+43	32(2ea)	1,609	60	?	60[a]	mm-wave radio astronomy array
IKI, USSR	Yevpatoriya CC-1	033	+45	70	3,848	50	N/A	120[a]	
IKI, USSR	Ussurijsk CC-2	134	+44	70	3,848	50	N/A	120[a]	
Tokyo Astrophysics Observatory	Nobeyama, Japan	138	+35	45	1,590	60	N/A	59[a]	Radio astronomy instrument
ISAS	Usuda, Japan	138	+35	64	3,217	60	N/A	120[a]	Good at 2 GHz
CSIRO	Parkes, NSW	148	-33	64	3,217	40	25	80	Configuration for Voyager at Uranus/ Neptune
Owens Valley Radio Observatory	Big Pine, CA	242	+37	40	1,257	50	150	39[a]	
NRAO-VLA	Socorro, NM	253	+34	25(27ea)	13,253	60	35	300	New for Voyager at Neptune
NRAO-GB	Green Bank, WV	281	+38	43	1,452	50	40	45[a]	
NRAO-GBT	Green Bank, WV	281	+38	100	7,854	65(?)	—	320[a]	In planning
Algonquin Park	Algonquin Park, Ont., Canada	282	+45	46	1,661	50	N/A	52[a]	
Haystack	Haystack, MA	289	+42	37	1,075	40	100	27[a]	Lose 1 dB to dome
Arecibo	Arecibo, PR	294	+18	305	73,062	40	N/A	1817[a]	Useful only ±20 hour angle and declination = −2 to +39

[a] Assumes provision of 25-K LNA.

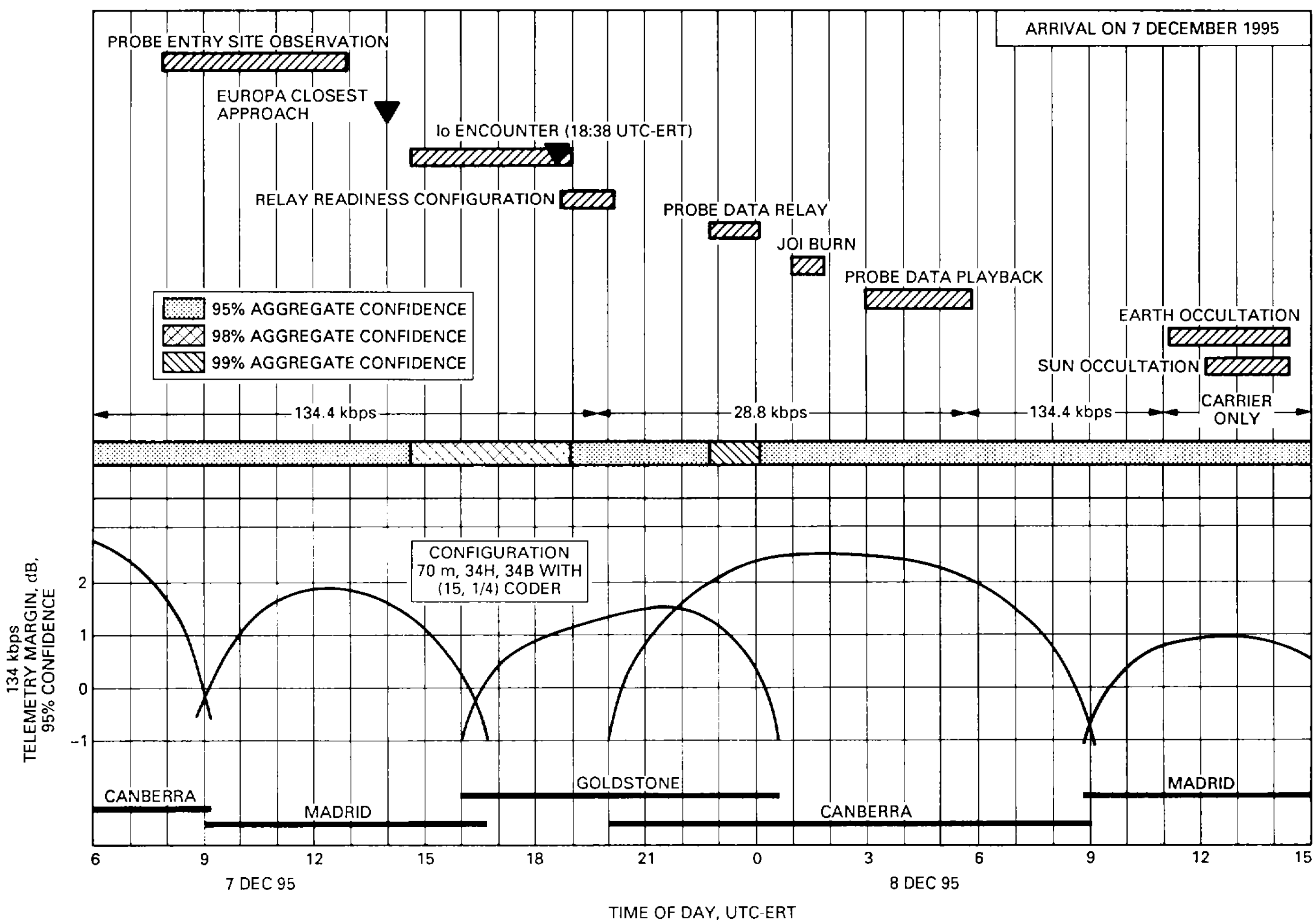


Fig. 1. Galileo arrival day major events profile.

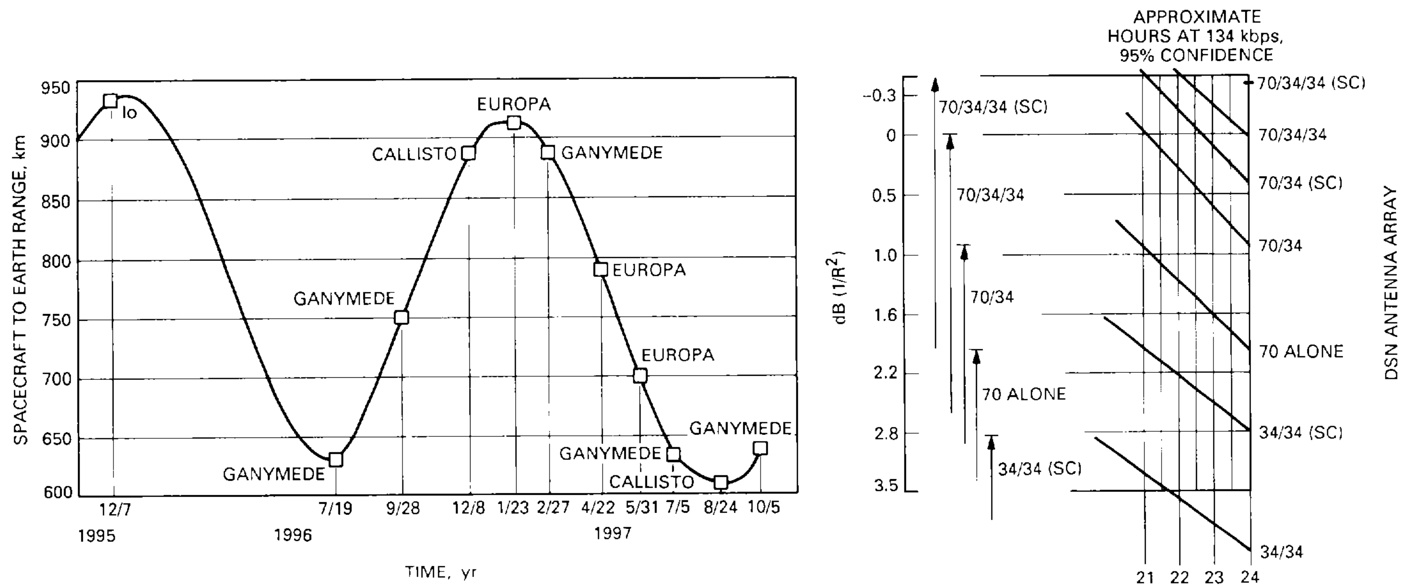
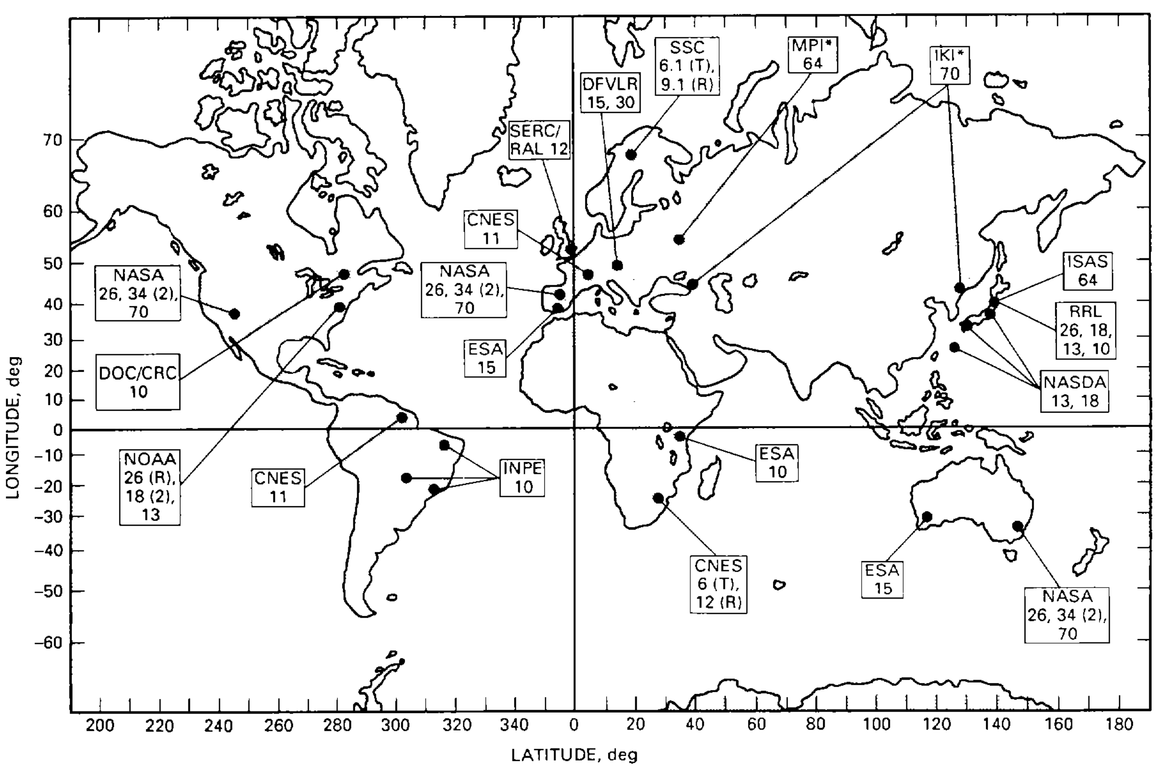


Fig. 2. Galileo tour example 87-07 telecommunications considerations.



FOREIGN AGENCIES:	DOC/CRC	CANADA	ESA	EUROPE	SSC	SWEDEN	NASDA	JAPAN	*NON-CCSDS
	CNES	FRANCE	SERC	GREAT BRITAIN	ISAS	JAPAN	IKI	SOVIET UNION	
	INPE	BRAZIL	DFVLR	GERMANY	RRL	JAPAN	MPI	SOVIET UNION	

Fig. 3. Space agency tracking station summary with station locations and diameters, m.