Reports of the Department of Geodetic Science and Surveying

Report No. 329

REFERENCE FRAME REQUIREMENTS AND THE MERIT CAMPAIGN

by

Ivan I. Mueller, Sheng-Yuan Zhu and Yehuda Bock

Prepared for

National Aeronautics and Space Administration
Goddard Space Flight Center
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Grant No. NSG 5265
OSURF Project 711055

The Ohio State University
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PREFACE

This project is under the supervision of Professor Ivan I. Mueller, Department of Geodetic Science and Surveying, The Ohio State University. The science advisor is Dr. David E. Smith, Code 921, Geodynamics Branch, and the Technical Officer is Mr. Jean Welker, Code 903, Technology Applications Center.

ABSTRACT

This report is an analysis of how satellite, lunar laser, and VLBI stations available during the MERIT Campaign in 1983/84 could contribute to the detection of short periodic variations in the rotational parameters of the earth, as well as to the determination of the differences between the various Conventional Terrestrial and Inertial Reference Frames inherent in the above systems. Specific observational requirements are given both by objective and by country. The report serves as the basis of the recommendations made by COTES (IAG/IAU Joint Working Group on the Establishment and Maintenance of a Conventional Terrestrial Reference System) to the MERIT Steering Committee (CSTG Bulletin, June 9, 1982).

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1. INTRODUCTION

1.1 Motivation

The motivation for this proposal may be found in the proceedings of the MERIT Workshop held in Grasse, France [Wilkins and Feissel, 1982], in which, on page 43 there is an account of a joint meeting of the MERIT (Monitor Earth Rotation and Intercompare the Techniques of Observation and Analysis) Steering Committee and the newly formed COTES (Working Group on the Establishment and Maintenance of a Conventional Terrestrial Reference System) on May 21, 1981, at which

> it was agreed that it would be of general benefit if the operations during project MERIT were planned in such a way as to contribute whenever possible to the establishment and maintenance of the new conventional terrestrial reference system. In particular it was noted that it would be necessary to identify precisely the coordinate systems being used implicitly by each of the networks that are participating in the MERIT project; these systems could differ even within one technique since, for example, different gravity-field models are used for different satellites. It would then be necessary to establish the relationships betweeen these systems; this might involve making observations by, for example, both laser ranging and radio interferometry at some sites.

and

> it was agreed that relevant material prepared for Project MERIT, such as contributions to the report on standards, should be made available to the new working group, which should in turn specify what extra observations should be made during the main campaign to unify the individual reference systems.

The frame of the future Conventional Terrestrial System (CTS) is to be defined by an adopted set of spatial coordinates of a global network of observing stations mainly Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), and their motion models, or by an equivalent way [Mueller, 1981; Kovalevsky and Mueller, 1981]. The stations will define the vertices of a fundamental polyhedron whose deformation and movement with respect to the frame of a Conventional Inertial System (CIS) is to be monitored through periodic re-observations. The main differences between this terrestrial system and that of the currently adopted CIO-BIH are that in defining the former, the stations cannot be assumed to be motionless with respect to each other, and that the observations will no longer be referred to the directions of the local plumblines (optical instruments), but to other terrestrial directions (baselines).

The functions of the CTS are twofold. The first, requiring only a subset of the polyhedron vertices, is to monitor the motions common to all stations (polar motion and earth rotation) of the polyhedron with respect to the frame of a CIS. The second, involving all stations, is to monitor the internal motions (or deformations) of the polyhedron, i.e., those motions not common to all stations. Of course, both functions are integrally related. The latter function raises several problems. The first is how these stations should be distributed on the surface of the earth so that the polyhedron is geometrically optimal. Of course, the distribution of stations during the 1983-84 MERIT campaign will be constrained by practical "real world" considerations. However, it still seems useful to first find the optimal distribution disregarding these constraints. Then, a "real world" network's anticipated performance can be estimated by comparing it to the optimal network.

Considering that several advanced geodetic systems are available today, the second problem is how to merge several networks, each one defining essentially its own reference frames, both CTS and CIS, into a common set. In order to accomplish this, several stations will need to be collocated, i.e., maintain different instrument types at common sites.

A third problem not addressed in this study is how well the adopted optimal polyhedron can be expected to monitor the total behavior of the earth. This would involve the incorporation of accepted earth models (e.g., a plate tectonic model), which in view of the anticipated 1983-84 "real world" constraint is not considered.

1.2 Proposal Objectives

This proposal for coordinated SLR, LLR and VLBI observations during the MERIT main campaign is an attempt to get answers to the following questions:

(1) whether the most precise observational systems available at that time (i.e., third-generation lasers, and VLBI's with Mark III receivers) will be able to detect the systematic differences between the frames of the various

Conventional Inertial Systems (CIS) and between the frames of the various Conventional Terrestrial Systems (CTS) inherent in these observational systems.

(2) whether the above observational systems will be able to detect short periodic variations in the earth's rotational vector (and how accurately).

As a byproduct, the systems also should provide an initial global network of baselines suitable to start the monitoring of the deformation of the earth.

It is emphasized that since COTES aims at the establishment and maintenance of a future CTS, the proposal is based only on the best SLR, LLR and VLBI systems in a network which in our view could be established by 1983/84 with minor modifications of existing plans set up for other purposes (e.g., NASA's Crustal Dynamics Project). Important use is made, however, of transportable SLR and VLBI systems which will be available in that time frame in Europe and the U.S.

It should also be noted that although only third-generation lasers and Mark III type VLBI are considered in this plan, other systems such as Doppler, especially when utilizing the new NOVA satellites, could also follow a similar plan for a secondary network by applying the principles described below. The Doppler systems have their own inherent CIS's and CTS's, and the establishment of the relationship between them and the others would be of scientific interest. The Global Positioning System (GPS) during the 1983-84 time frame will still be in a preliminary stage as a global system at best, and therefore except for a few baseline determinations it is unlikely to be very useful for this immediate purpose.

2. DETERMINATION OF THE CTS AND CIS RELATIONSHIPS AND SHORT PERIODIC VARIATIONS IN THE EARTH ROTATION VECTOR

2.1 The Effect of CIS and CTS Differences on Earth Rotation Parameters

The two CIS's (and two CTS's) inherent in two different techniques are generally not exactly identical. Suppose the relation between the two CIS's is

$$(\underline{X})^{II} = R_1(\alpha_1)\ R_2(\alpha_2)\ R_3(\alpha_3)(\underline{X})^{I} \quad . \tag{2.1}$$

Similarly, the relation between two CTS's is

$$(\underline{x})^{II} = R_1(\beta_1)\ R_2(\beta_2)\ R_3(\beta_3)(\underline{x})^{I} \tag{2.2}$$

where α_i and β_i are small rotation angles about the axes "i".

The transformation from CIS to CTS is [Mueller, 1969]

$$(\underline{x})^{I} = S^{I}\ N\ P\ (\underline{X})^{I} \tag{2.3}$$

and

$$(\underline{x})^{II} = S^{II}\ N\ P\ (\underline{X})^{II} \tag{2.4}$$

where common nutation (N) and precession (P) matrices are assumed to be used in both techniques. The earth rotation matrix $S = R_2(-x_p)R_1(-y_p)R_3(\theta)$, in which x_p, y_p are the coordinates of the pole and θ is the Greenwich Sidereal Time.

Substituting eq. (2.1) for the last term of the right-hand side of eq. (2.4), and eq. (2.2) for the left-hand side,

$$R_1(\beta_1)\ R_2(\beta_2)\ R_3(\beta_3)(\underline{x})^{I} \ = \ S^{II}\ N\ P\ R_1(\alpha_1)\ R_2(\alpha_2)\ R_3(\alpha_3)(\underline{X})^{I} \quad .$$

After some reduction, neglecting second-order terms,

$$\begin{aligned}(\underline{x})^{I} = {} & R_1(-\beta_1 + \alpha_1 \cos\theta + \alpha_2 \sin\theta)\ R_2(-\beta_2 - \alpha_1 \sin\theta + \alpha_2 \cos\theta)\cdot \\ & \cdot R_3(-\beta_3 + \alpha_3)\ S^{II}\ N\ P\ (\underline{X})^{I} \quad .\end{aligned} \tag{2.5}$$

Comparing eq. (2.5) with (2.3),

$$\begin{aligned}S^{I} = {} & R_1(-\beta_1 + \alpha_1 \cos\theta + \alpha_2 \sin\theta)\ R_2(-\beta_2 - \alpha_1 \sin\theta + \alpha_2 \cos\theta)\cdot \\ & \cdot R_3(-\beta_3 + \alpha_3)\ S^{II} \quad .\end{aligned} \tag{2.6}$$

Or

$$-\Delta y_p = -(y_p^{I} - y_p^{II}) = -\beta_1 + \alpha_1 \cos\theta + \alpha_2 \sin\theta \quad ,$$

$$-\Delta x_p = -(x_p^{I} - x_p^{II}) = -\beta_2 - \alpha_1 \sin\theta + \alpha_2 \cos\theta \quad , \qquad (2.7)$$

$$\omega_e \Delta UT1 = \omega_e (UT1^{I} - UT1^{II}) = -\beta_3 + \alpha_3 \quad .$$

Thus the CTS differences (β angles) cause biases in all earth rotation parameters. Because of the modulation of the earth's diurnal rotation, the effect of CIS differences (α_1, α_2) on polar motion components are diurnal terms, while the effect of α_3 on UT1 is again a bias.

The direct way to determine all the β angles is the method of station collocation. For connections of CIS's, there are a few methods such as the use of space astrometry to connect the stellar CIS and the radio source CIS, or using differential VLBI (which, for example, was used when the Viking Mars Orbiters and a quasar were near eclipsing) to connect the planetary and radio source CIS's (see [Kovalevsky and Mueller, 1981]). These are direct approaches. One indirect method is via station collocation, i.e., using the earth as an intermediate body (see [Kovalevsky, 1980]): First by station collocation one determines the CTS difference (β angles), then through the earth rotation parameter differences one finds the CIS difference (α angles). Eq. (2.7) is the basis for connecting the two CIS's via station collocations.

2.2 Station Collocation for Determining the CTS Differences

It is obvious that using the station collocation method one can solve for β_1, β_2, β_3 directly. (β_1 and β_2 can also be determined from the biases between two sets of polar motion coordinates. (See eq. (2.7).) Suppose station i is one of the collocated stations, and $\underline{x}_i^{I}$ and $\underline{x}_i^{II}$ are the two sets of "geocentric" coordinates, then

$$\Delta\underline{x}_i = \underline{x}_i^{I} - \underline{x}_i^{II} = -\begin{bmatrix}\delta_1\\ \delta_2\\ \delta_3\end{bmatrix} + \begin{bmatrix}0 & \beta_3 & -\beta_2\\ -\beta_3 & 0 & +\beta_1\\ +\beta_2 & -\beta_1 & 0\end{bmatrix}\begin{bmatrix}x_i\\ y_i\\ z_i\end{bmatrix} + c\begin{bmatrix}x_i\\ y_i\\ z_i\end{bmatrix} \qquad (2.8)$$

where $\underline{\delta}$ is the translation vector, and c is the scale difference. Eq. (2.8) can also be seen as an observation equation. One must have at least three collocated stations to solve for the above seven unknowns. If one set of coordinates is geocentric, and the other is not, as in the VLBI case, then there are two ways to proceed. For VLBI, $\Delta \underline{x}_{ij}$ is given between stations i and j at the ends of the VLBI baseline; by assigning one VLBI station an arbitrary position vector, the coordinates of other VLBI stations in the same network can be obtained. Eq. (2.8) is still used as the observation equation, but in this case the meaning of the translation vector is not "geocentric" difference, but it expresses how much the initial arbitrary position vector differs from the geocentric position vector. The other way is to solve eq. (2.8) for only four unknowns, namely the β's and c, and choose one VLBI station position vector to exactly equal the geocentric position vector of the same station as determined by means of a collocated SLR or LLR.

A simple error analysis is given below to show how well the β's can be determined by the collocation method. The third-generation SLR and LLR stations and the Mark III VLBI observatories anticipated for MERIT 1983-84 are given in Table 1. It was assumed that the internal precision σ_x for each coordinate component is 10 cm, and all correlations were neglected. The correlations might be significant, and they would degrade the results. Since the coordinate error (σ_x) is free from the rotation error, it will essentially be the same as the baseline length error (the rotation angles are the unknowns to be solved for). For VLBI and third-generation lasers, this error might be less than 10 cm. The combination of these two factors makes the final results practically more or less reasonable. According to Table 1 there exist two VLBI groups, the Deep Space Network (DSN) (Canberra, Madrid, Goldstone), and the (extended) Polaris Network, which includes the Polaris stations (Ft. Davis, Richmond, Westford) and those which might join the Polaris network for certain observations (Wettzell, Onsala, Jodrell Bank, Owens Valley). By "simultaneous" observations, these networks might be combined into one (large) VLBI network, which would bring great benefits, as will be seen later.

Cases A in Table 1 consider only seven VLBI stations (no DSN); Cases B include the combined ten VLBI stations. In Cases A there are two existing primary collocated stations (Ft. Davis and Wettzell). In Cases B there are three primary collocated stations (with the addition of Canberra). All three primary collocation sites also have LLRs, in addition to the SLRs and VLBIs.

TABLE 1 : MERIT-COTES GLOBAL NETWORK
EXPERIMENT DIRECTORY FOR REFERENCE FRAME DETERMINATIONS

PROPOSED STATIONS 1983/84	STATUS(1981)			A1	A1A	A1B	A2	A3	A4	B1	B2	B3	B4	B5	B6	B7
OPERATIONAL																
*FT.DAVIS	M3	G3	LL	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM
*WETTZELL	M3	G3	LL	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM	VLM
MAUI		G3	LL	L	L	L	L	L	L	L	L	L	L	L	L	L
GREENBELT		G3		L	L	L	L	L	AL	L	L	L	L	L	L	AL
WESTFORD	M3			V	VT	V	VT	VT	VT	V	V	VT	VT	VT	VT	VT
ONSALA	M3			V	V	VT	V	VT	VT	V	V	V	V	VT	VT	VT
OWENS VALLEY	M3			V	V	V	V	V	V	V	V	V	V	V	V	V
CRIMEA			LL													
GRASSE			LL													
CONSTRUCTION																
HERSTMONCEUX		G3		L	L	L	L	L	L	L	L	L	L	L	L	L
GRAZ		G3		L	L	L	L	L	L	L	L	L	L	L	L	L
SIMOSATO		G3		L	L	L	L	L	L	L	L	L	L	L	L	L
RICHMOND	M3			VT	V	V	VT	VT	VT	V	VT	VT	VT	VT	VT	VT
UPGRADING NEEDED																
QUINCY		G3		L	L	L	L	L	L	L	L	L	L	L	AL	AL
YARAGADEE		G3		L	L	L	L	L	L	L	L	L	L	L	L	L
JODRELL BANK	M3			V	V	V	V			V	V	V	V	V	V	V
*CANBERRA	M3	G3	LL	LM	LM	LM	LM	LM	LM	VLM	VLM	VLM	VLM	VLM	VLM	VLM
MADRID	M3							VT	VT	V	V	V	V	VT	VT	VT
GOLDSTONE	M3									V	V					
DIONYSOS		G3		L	L	L	L	L	L	L	L	L	L	L	L	L
TAHITI-MOBLAS6		G3														
STANDARD DEVIATIONS (ASSUMPTION : COORDINATE PRECISION = 10 CM)																
ROTATION(10*-2 ARCSEC)				1.1	1.3	3.1	1.0	0.9	0.8	0.4	0.34	0.30	0.27	0.28	0.26	0.25
SCALE(X 10**-8)				2.1	2.3	2.1	2.1	1.7	1.4	1.3	1.2	1.1	1.0	1.0	1.0	1.0
TRANSFORMATION ERROR(CM)				27.	31.	69.	24.	21.	15.	11.	10.	9.0	8.0	8.0	8.0	7.0

* PRIMARY COLLOCATION SITES

STATUS CODES :
- M3 - MARK III VLBI
- G3 - 3RD GENERATION LASER
- LL - LUNAR LASER

EXPERIMENT CODES :
- V - VLBI
- L - LASER
- M - LUNAR LASER
- A - VLBI MOBILE
- T - LASER MOBILE

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In both cases additional mobile TLRS's were placed at certain other VLBI sites, and mobile VLBI's at certain SLR stations, to see how the results could be improved. In the results listed, at the bottom of Table 1, three errors are given: σ_β is the root mean square of σ_{β_1}, σ_{β_2}, σ_{β_3}, the rotation angle errors; σ_{scale} is the scale factor error; $\sigma_{x'}$ is the transformation error when two CTS's are combined into a unique one by transformation; the coordinate error in this unified CTS is the combination of $\sigma_{x'}$ and σ_x.

The table clearly shows that the various combinations in Case B are much better than those in Case A. In Case A, the σ_β could reach 0".008, while in Case B it could be as low as 0".0025. Thus from this point of view, the DSN VLBI stations (especially Canberra and Madrid) are crucial. Since the purpose here is not routine earth rotation parameter monitoring, observations over a relatively short time span(s) would be sufficient. Although desirable, the observations over the different baselines do not have to be made at the same time. Experiment B7 is the recommended combination.

2.3 Determining the CIS Differences

From eq. (2.7) it is clear that once the angles of CTS differences (β_i) are known, one can estimate the CIS difference (α_i) via earth rotation parameter differences. Because the LLRs are at the same stations as the SLR's, the SLR CTS can be used in lieu of the LLR CTS. At present, with only one operational station LLR can determine only UT well, while SLR is really suitable only for determining polar motion. Therefore, at present one can estimate well only the α_3 (equinox difference) between the VLBI and the LLR CIS, and the α_1 and α_2 (equator tilt) between the VLBI and SLR CIS. It is hoped that with the addition of the LLR stations at Canberra, Wettzell, Maui and Crimea, and with improved SLR performance (including improved gravity field) this situation will change and all angles can be satisfactorily determined by 1983/84.

Estimating α_3 is straightforward, since it is a bias in UT1. Long series of $\Delta UT1 = UT1^{I} - UT1^{II}$ data could be used yielding high accuracy in α_3. It is important that ΔUT1 should be the UT1 difference during the same time period. According to the predicted accuracy of VLBI and LLR UT1, and the σ_β in Section 2.2, σ_{α_3} could be less than 0".005. It could be better than that achieved by differential VLBI data of the Viking Mars Orbiters (0."01, see [Williams, 1981]). Since any method might have some inevitable systematic error, comparing the α_3 obtained by station collocation and that obtained by, e.g., differential VLBI might give us some useful interesting information.

To estimate α_1 and α_2, high resolution polar motion data should be available from all the systems. Studying the short period real polar motion components should be one of the aims of the MERIT Main Campaign. Fortunately, the two phenomena (i.e., real vs. modulated) can be easily separated, since in the Δx_p, Δy_p (eq. (2.7)) the contribution from diurnal real polar motion is canceled.

The VLBI network should organize an intensive observation campaign of, say, 12-hour sessions each day for one to three months. Actually, from the point of view of spectral analysis, 24-hour sessions every other day would be preferred, but may not be practical. Naturally, to determine α_1 and α_2, SLR and LLR high resolution polar motion data is also required. There are two different approaches to estimate α_1 and α_2. One approach is to determine the phase and amplitude of diurnal polar motion from both VLBI and LR separately by FFT or another method. Let these numbers be denoted as A^I, ϕ^I and A^{II}, ϕ^{II}, where $x_p^I = A^I \cos(\theta + \phi^I)$, $y_p^I = -A^I \sin(\theta + \phi^I)$, etc., then from the following equation one can solve for α_1 and α_2:

$$\begin{aligned} \alpha_1 &= A^{II} \sin\phi^{II} - A^I \sin\phi^I \quad , \\ \alpha_2 &= A^{II} \cos\phi^{II} - A^I \cos\phi^I \quad . \end{aligned} \tag{2.9}$$

The advantage of this approach is that VLBI and LR data for the same time period are not necessary. But to obtain A and ϕ with adequate quality, a comparatively long period (one month or so) of continuous high resolution polar motion data is needed.

If only sparse high resolution but simultaneous polar motion data sets are provided (for LR and VLBI), then a second approach could be used. Since $\overline{\sin\theta}$ and $\overline{\cos\theta}$ (averages over some time span) are known, from each set of $(\Delta y_p, \Delta x_p)$ one can solve for α_1 and α_2 using the first two equations of (2.7), that is,

$$L_1 = \beta_1 - \Delta y_p = \alpha_1 \overline{\cos\theta} + \alpha_2 \overline{\sin\theta}$$
$$L_2 = \beta_2 - \Delta x_p = -\alpha_1 \overline{\sin\theta} + \alpha_2 \overline{\cos\theta} \tag{2.10}$$

The average of all pairs of (α_1, α_2) obtained is the final solution. The error of α_1 and α_2 depends on σ_{L_1}, σ_{L_2}, $\overline{\cos\theta}$ and $\overline{\sin\theta}$. Assuming $\sigma_{L_1} = \sigma_{L_2} = \sigma_L$, and that L_1, L_2 are independent, by simple derivation

$$\sigma_{\alpha_1} = \sigma_{\alpha_2} = \sigma_L \Big/ \sqrt{\frac{2}{(\Delta\theta)^2}\,(1-\cos(\Delta\theta))} \tag{2.11}$$

where $\Delta\theta$ is the resolution of the polar motion. For example,

$$\Delta\theta = 8^h \qquad \sigma_{\alpha_1} = \sigma_{\alpha_2} = 1.21\ \sigma_L$$
$$\Delta\theta = 12^h \qquad \sigma_{\alpha_1} = \sigma_{\alpha_2} = 1.57\ \sigma_L$$

High resolution will help to reduce $1 \Big/ \sqrt{\frac{2}{(\Delta\theta)^2}\,(1-\cos(\Delta\theta))}$, but generally the smaller $\Delta\theta$ is, the larger σ_L will be. If a few simultaneous 8^h (or 12^h) resolution VLBI and LR polar motion data sets are available with $\sigma = 0''.01$, then using this second method, α_1 and α_2 also might be determined with σ_α = $0''.01$. It is emphasized that the polar motion data from the two techniques must be (approximately) simultaneous--more than a half-hour difference might cause a significant error in α.

For calculating α_3 from eq. (2.7), the method of station collocation is necessary to first determine β_3. But to estimate α_1, α_2 or β_1, β_2, collocations are not indispensible; they can be determined from the polar motion differences observed at stations not collocated. As shown in eq. (2.9), one can determine α_1 and α_2 directly from the diurnal terms of polar motion. Also, from eq. (2.7), (as mentioned earlier) it is clear that β_1 and β_2 are biases in the polar motion differences. However, because of possible systematic errors, the β_1, β_2 angles determined from polar motion biases and those from the collocation method might be different. Since collocation is necessary anyway to obtain β_3, it might be useful to estimate two sets of β_1 and β_2 using both polar motion biases and station collocations, and then compare them.

The above requirements for high frequency observations and polar motion components for SLR's might be difficult to meet, both because of natural reasons (weather) and for economic and/or technical feasibility based on present experience. The feasibility, however, should be tested, since no one knows at present what a third-generation SLR network with improved satellite ephemerides will be able to do by 1984. Also, since the definition of the geocentric origin of the CTS depends mostly on the performance of the SLR network, participation of these systems in the campaign is indispensable in any case.

3. OPTIMAL NETWORK OF BASELINES FOR GLOBAL DEFORMATION ANALYSIS

3.1 Mathematical Model

At some fundamental epoch, the frame of the CTS is defined by a set of station coordinates adopted on the basis of an observational campaign such as MERIT 1983/84. Call this set of coordinates X_0 and its corresponding set of fundamental (polyhedron) baseline lengths D_0. At a later epoch the baseline lengths D of the polyhedron are estimated from measurements taken at all of the vertices during a short campaign. By comparing D to D_0, the deformation of the polyhedron can be estimated, i.e., a new set of coordinates, X_t.

The mathematical model is derived from the length of baseline i-j,

$$D_{ij} = [(X_j-X_i)^2 + (Y_j-Y_i)^2 + (Z_j-Z_i)^2]^{\frac{1}{2}} \tag{3.1}$$

Linearization of this model about the fundamental coordinates yields

$$D_{ij} = D_{ij_0} + \left.\frac{\partial D_{ij}}{\partial X_i}\right|_{X_i = X_{i_0}} [X_i - X_{i_0}] + \ldots + \left.\frac{\partial D_{ij}}{\partial Z_j}\right|_{Z_j = Z_{j_0}} [Z_j - Z_{j_0}] \tag{3.2}$$

Adding a residual vector V, the observation equations can be written in matrix form as

$$V = A\,X + L \tag{3.3}$$

where for the k^{th} observation (n is the number of polyhedron vertices)

$$L_k = D_{ij_0} - D_{ij} \qquad k = 1, \ldots, n(n-1)/2 \tag{3.4}$$

$$A_k = \left[\frac{\partial D_{ij}}{\partial X_i} \;\cdots\; \frac{\partial D_{ij}}{\partial Z_j}\right] \tag{3.5}$$

$$X = \begin{bmatrix} X_i - X_{i_0} \\ \vdots \\ Z_j - Z_{j_0} \end{bmatrix} \tag{3.6}$$

Thus the parameter vector X consists of the difference between the deformed coordinates and the fundamental coordinates. Then the deformed coordinates are computed as

$$X_t = X_0 + X \tag{3.7}$$

For the sake of greater generality, allow the possibility of adopting an earth deformation model that will provide information on expected station motion.

The estimation of X given in eq. (3.3) is a singular problem due to the familiar origin and orientation defects. Therefore one can adopt a pseudo-inverse approach which is equivalent to applying a set of inner constraints to (3.3) to make the resulting normal matrix non-singular [Blaha, 1971]. Define in the observation space a weighted norm,

$$||L||_P = (L^T PL)^{\frac{1}{2}} \tag{3.8}$$

where P is the weight matrix of the observed baseline distances obtained from an adjustment of the VLBI and laser data. Furthermore, in the parameter space, define the weighted norm

$$||X||_M = (X^T MX)^{\frac{1}{2}} \tag{3.9}$$

where M introduces the statistics of the adopted earth deformation model. Applying the pseudo-inverse(denoted by +) yields for the parameter vector estimate [Rao and Mitra, 1972]

$$X = -M^{-1} N(N M^{-1} N)^+ U \tag{3.10}$$

where

$$\begin{aligned} N &= A^T PA \\ U &= A^T PL \end{aligned} \tag{3.11}$$

It can be shown that $\hat{X}$ is a minimum M-norm (conditional on minimum variance), P-least squares (minimum variance), minimum bias and unique estimate which makes it very suitable for our purposes [Bock, in preparation]. Although the estimate is biased, this is not a problem as long as the linearization of (3.3) is performed about the fundamental coordinates X_0. The equivalent, but more computationally efficient innner constraint estimate is given by

$$\hat{X} = -[(N + MC^T CM)^{-1} - C^T (CMC^T CMC^T)^{-1} C] U \tag{3.12}$$

where

$$C = \begin{bmatrix} I & I & \dots & I \\ S_1 & S_2 & \dots & S_n \end{bmatrix} \tag{3.13}$$

$$S_i = \begin{bmatrix} 0 & -Z_i & Y_i \\ Z_i & 0 & -X_i \\ -Y_i & X_i & 0 \end{bmatrix} \tag{3.14}$$

and I is the 3x3 identity matrix. The constraints $CM\hat{X} = 0$ enforce the condition that the origin and orientation of the deformed polyhedron do not differ from that of the fundamental polyhedron. This is consistent with the requirement that the crust should have only deformations, i.e., no rotations and translations [Kovalevsky and Mueller, 1981]. It can be shown that with this approach the axes of the CTS are fixed in the Tisserand sense in the deformable earth [Moritz, 1980].

3.2 Optimal Polyhedra

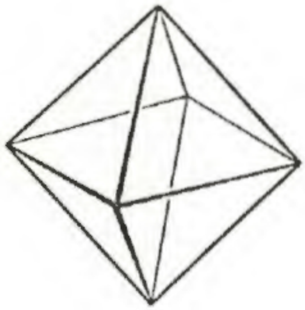
If a global network of stations is to define a reference frame, then it is plausible that choosing their optimal locations reduces to the problem of distributing n points on a sphere so that they are, in some sense, as far apart as possible from one another. On the circle, it is clear that the optimal distribution is achieved by marking off equal arc segments resulting in a regular polygon when adjacent points are connected. On the sphere, the distribution is not so obvious although a reasonable requirement is that the resulting polyhedron for a particular n value should be regular, i.e., all of its faces should be of one kind of a congruent regular polygon. Only five such polyhedra exist, the Platonic solids--the tetrahedron ($n=4$), octahedron (6), cube (8), icosahedron (12), and dodecahedron (20) (see Fig. 1). Semiregular polyhedra, that can be inscribed in a sphere as can the Platonic solids, exist for other n values (see [Pearce, 1978]). However, in general we must define a broader optimal criterion dealing with the set of baselines of a polyhedron, besides the regularity consideration mentioned above. An accepted definition for distributing n-points in a sphere so that they are as far apart as possible from each other is that the shortest distance between any two vertices is maximized [Fejes Toth, 1964]. This problem has not been solved in general, but exact solutions are available for n through 12 and $n = 24$. Near or possibly optimal solutions have been proposed for $n = 13$ through 16, 20, 42 and 122. For this study approximate solutions for $n = 14$, 18 and 32 are proposed (see Fig. 1).

The second criterion is that the average distance between vertices is maximized. It turns out that only the regular polyhedra with triangular faces ($n = 4, 6, 12$) meet both distance criteria, the cube the second, and the dodecahedron neither, though it does meet the regularity consideration. The antiprism (Fig. 1) meets the first criteria, and a distribution for $n = 20$ is proposed by [Van der Waerden, 1952] which meets both criteria. It is shown below that all of the above criteria can be taken as optimal for the deformation analysis model given by eq. (3.1) - (3.3), depending on the design measure chosen. It can be shown that the optimal distribution of stations on the sphere, in the sense of defining a reference frame and at least for A and D optimality defined below, is obtained by meeting regularity considerations. However, as mentioned above, the dodecahedron, for example, though regular is optimal for deformation analysis on the basis of only one design measure (D-optimality). Nevertheless, as we shall see below, the other design measures for the dodecahedron are very close to the optimal. Therefore, one can maintain to a very good approximation that distributing the stations so that the strongest reference frame is achieved also provides the best configuration for subsequent analysis of the deformation of the polyhedron with time.

The number of redundant baselines in the deformation analysis (number of baselines + six inner constraints - number of coordinates) is given by

Fig. 1 EXAMPLES OF OPTIMAL** POLYHEDRA

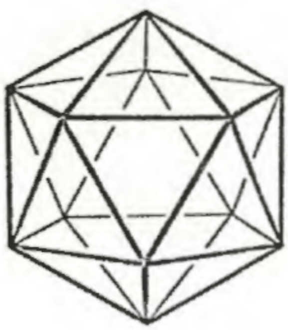
6



Octahedron

Faces:
  8 triangles
Vertices:
  6, each with 4
    edges meeting
Edges:
  12
Dihedral angle:
  109°28'

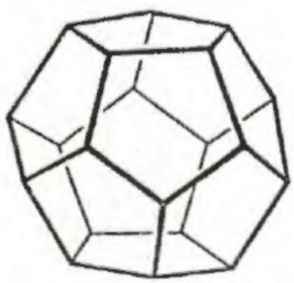
12



Icosahedron

Faces:
  20 triangles
Vertices:
  12, each with 5
    edges meeting
Edges:
  30
Dihedral angle:
  138°11'

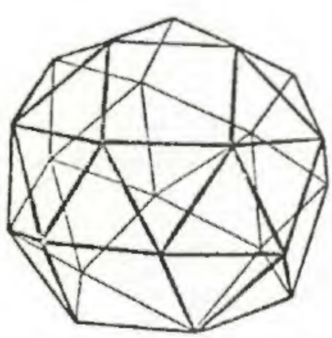
20*



Dodecahedron

Faces:
  12 pentagons
Vertices:
  20, each with 3
    edges meeting
Edges:
  30
Dihedral angle:
  116°34'

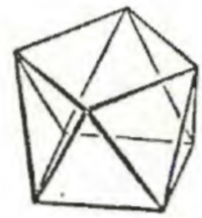
24



Snub cuboctahedron

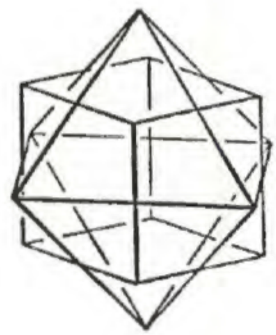
Faces:
  32 triangles] 38 total
  6 squares
Vertices:
  24, each with 5
    edges meeting
Edges:
  60
Dihedral angles:
  142°59' (square-triangle)
  153°14' (triangle-triangle)

8



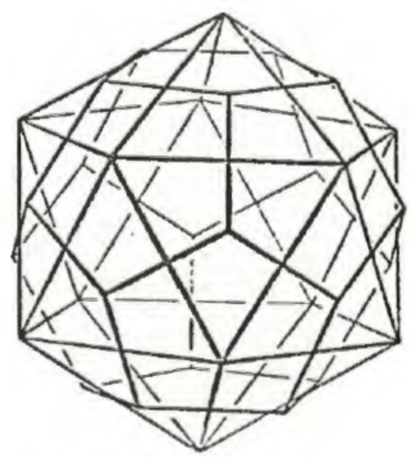
Antiprism

14*



Cube:
  6 faces, 8 vertices, 12 edges
Octahedron:
  8 faces, 6 vertices, 12 edges

32*



Dodecahedron:
  12 faces, 20 vertices, 30 edges
Icosahedron:
  20 faces, 12 vertices, 30 edges

**minimum distance maximized -

Fejes Toth, 1964, Regular Figures

* near optimal

$$\frac{(n-4)(n-3)}{2} \tag{3.15}$$

where n is the number of vertices. Therefore, it is necessary to maintain at the least, five stations. Optimal design measures were studied for nine different vertex numbers ranging from n = 6 to n = 32 (Fig. 1). Before the results are presented, the design measures used in defining optimal parameter estimation are briefly reviewed.

The corresponding covariance matrices for the parameter estimate vectors (3.10) and (3.12) are given by (assuming M =I, i.e., no a priori earth deformation model)

$$D(X) = N^{+} \tag{3.16a}$$

$$= (N + C^TC)^{-1} - C^T(CC^TCC^T)^{-1}\, C \tag{3.16b}$$

respectively. The optimal design then involves distributing n stations on the earth's surface so that (3.16) is minimized in some sense. A canonical notion of design optimality is not available, and we will briefly describe several common design criteria which have been used in this study. All of these can be expressed in terms of the reduced eigenspace of N^+, of dimension 3n-6.

<u>A-optimality</u> is defined as minimizing the average variance (the A-measure), or equivalently the spectral mean, i.e.,

$$\min \frac{1}{3n} \text{ trace } N^{+} = \min \frac{1}{3n} \sum_{i=1}^{3n} \sigma_i^2 = \min \frac{1}{3n-6} \sum_{i=1}^{3n-6} \lambda_i \tag{3.17}$$

where λ_i are the eigenvalues. <u>D-optimality</u> is given as minimizing the determinant of N^+ raised to the 1/(3n-6) power (the D-measure) or equivalently

$$\min \left[\prod_{i=1}^{3n-6} \lambda_i \right]^{\frac{1}{3n-6}} \tag{3.18}$$

<u>E-optimality</u> is defined as

$$\min_{\lambda_i} \lambda_{max} \tag{3.19}$$

We shall refer to the maximum eigenvalue as the E-measure.

Another criterion, though used usually for determining the condition of N rather than for optimal design, can be termed C-optimality, and is defined by

$$\min_{\lambda_i} \frac{\lambda\ \max}{\lambda\ \min} \tag{3.20}$$

the ratio of maximum and minimum eigenvalues. This is useful, since it is unitless and independent of scale factor, i.e., baseline precision. It should be noted that all of these criteria are rotationally and translationally invariant (isotropic and homogeneous) [Grafarend, 1974]. That is, only the relative distribution of the stations affects the optimal design.

The different design measures for the various polyhedra studied are presented in Table 2. It can be inferred by examining the polyhedra for $n = 8$ and $n = 20$ that A-optimality results from maximizing the average distance, D-optimality from regularity considerations, while E- and C-optimality result from maximizing the minimum distance. The optimal designs have been computed under the assumption that all baseline lengths have a precision of 10 cm and are uncorrelated. To relate the corresponding measures for different baseline accuracies (except for C-optimality), one has

$$D_A = \frac{\sigma_A^2}{\sigma_B^2} D_B \tag{3.21}$$

where D denotes any design measure and σ, the baseline accuracy.

In Fig. 2 the optimal design measures are plotted for the different polyhedra. The points have been connected under the assumption that the intermediate n-values will behave regularly. All four curves seem to be leveling off as n get larger so that one can make the observation that increasing the number of stations outside the range of the curves (n=32) will not yield any significant improvement. That is, the sphere is quite well covered in the geometrical sense, and the stations provide a strong reference frame and the ability to subsequently monitor polyhedron deformations.

Now that the optimal design measures are available for the best distribution of a global network, it is possible to compare the expected strength of the MERIT-COTES global network in Table 1 to this standard.

3.3 MERIT-COTES Network Simulations

The planned MERIT 83/84 campaign may be the first opportunity to investigate the frame for a future CTS, considering that approximately 20 globally distributed stations will be available with a combination of the best VLBI, SLR and LLR instrumentation. Therefore, it is appropriate to compare the planned networks to the optimal networks discussed in the previous section. First, the VLBI and laser (LLR and SLR) networks are compared separately. Second, both networks are combined into one, and the effect of different collocations schemes are studied. Table 3 summarizes again the stations involved, their status and the experiment descriptions. Four stations have been added to those in Table 1 as possible candidates for addition to the presently planned network.

The results of the single type of observations are plotted in Fig. 2. The experiment number reflects the number of participating stations. Experiment 7 includes the (extended) Polaris VLBI net described in Section 2.2. As can be seen, the network is very weak. The addition of the DSN network to the configuration (Experiment 10) greatly improves the VLBI net. It follows that the DSN sites, particularly Canberra (being a primary collocation site) should be upgraded to be compatible with Mark III equipment. Of all the stations in Table 3, the addition of a station in South America (e.g., Sao Paulo or Santiago) provides the greatest improvement as seen in Experiments 11 and 12.

Experiment 13 examines the most realistically available laser net for the MERIT campaign. It is about at the same level as the 12-station VLBI net. Again, the addition of a station in South America (e.g., Santiago) yields the greatest improvement as indicated in Experiment 14. This configuration yields a fairly close approximation to the optimal design and is best among the single experiment networks.

Combining VLBI and laser stations into one frame requires at least three collocated sites. The best scenario, of course, would be to have all sites collocated and, therefore, the optimal design curves shown in Fig. 3 are the result of each baseline being observed twice for each of the optimal polyhedra. Realistically, as mentioned, MERIT may have three primary collocation sites (Ft. Davis, Wettzell and Canberra) where both VLBI and laser (SLR and LLR) equipment may be available on a full-time basis.

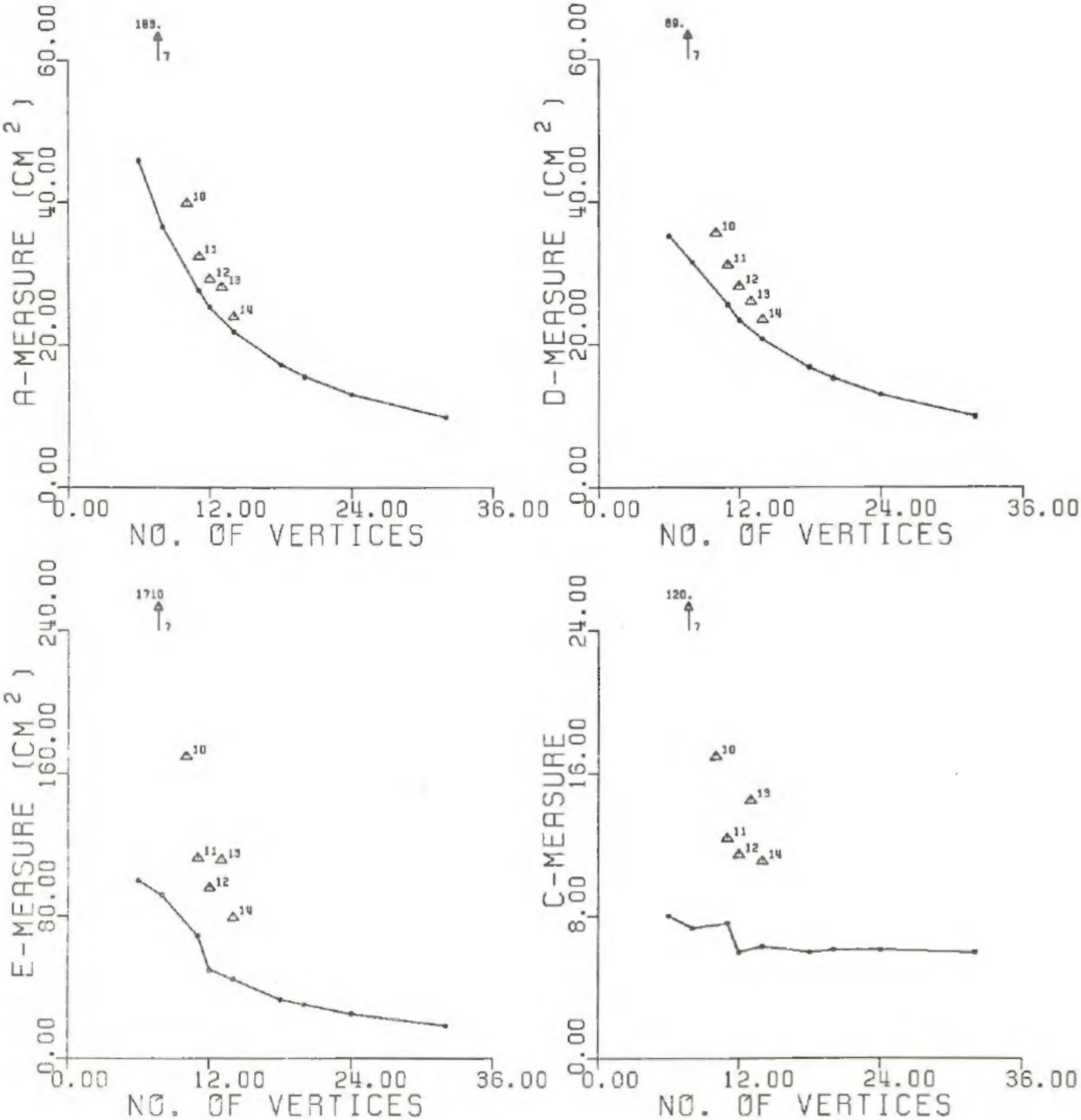
TABLE 2 : DESIGN MEASURES FOR OPTIMAL POLYHEDRA AND THE MERIT-COTES NETWORK OF STATIONS (SINGLE AND COMBINED TECHNIQUES)

EXPERIMENT		DESIGN MEASURES			
NO.	DESCRIPTION	A-MEASURE	D-MEASURE	E-MEASURE	C-MEASURE
		(CM^2)	(CM^2)	(CM^2)	(-)
		OPTIMAL POLYHEDRA			
6	OCTAHEDRON	46	35	100	6.0
8	CUBE	*36.5	*31.4	(100)	(8.0)
8	ANTIPRISM	(36.6)	(31.6)	*92	*7.3
11	ICOSAHEDRON -1	28	26	69	8.0
12	ICOSAHEDRON	25	23	50	6.0
14	OCTAHEDRON+CUBE	23	21	45	6.3
18	OCTA+ICOSAHEDRON	17	17	33	6.0
20	VAN DER WAERDEN	(15.517)	*15.178	*30.67	*6.13
20	DODECAHEDRON	*15.515	(15.182)	(30.77)	(6.15)
24	SNUB CUBE	13	13	26	6.1
32	ICOSA+DODECAHEDRON	10	10	19	6.0
		MERIT-COTES WITH SINGLE TYPE OF INSTRUMENT***			
		VLBI :			
7	EXTENDED POLARIS	183	69	1710	120
10	EXP. 7 + DSN	40	36	170	16
11	EXP.10 + SAO PAULO	32	31	112	12
12	EXP.11 + SANTIAGO	29	28	96	11
		LASER :			
13	STATUS IN 1983	28	26	112	15
14	EXP.13 + SANTIAGO	24	23	79	11
		MERIT-COTES WITH COMBINED LASERS AND VLBI'S***			
12	OPERATIONAL (9)	28	21	137	28
18A	VLBI+SLR+LLR (ALL)	11	10	45	16
18B	PRIMARY (3)	54	35	441	75
18C	CONTINENTAL (9)	26	19	181	43
18D	GLOBAL (9)	21	18	76	19
20A	EXP.18+G2SLR (ALL)	9	9	37	15
20B	PRIMARY (3)	41	30	258	48
20C	CONTINENTAL (9)	23	18	143	36
20D	GLOBAL (9)	20	17	86	22
24A	EXP.20+NEW (ALL)	7	7	20	10
24B	GLOBAL (7)	20	18	68	18

(NOS. IN PARENTHESES INDICATE NO. OF COLLOCATED SITES)

*OPTIMAL MEASURE AMONG POLYHEDRA WITH SAME NO. OF VERTICES (COMPARE TO CORRESPONDING NO. IN PARENTHESES)
**EXPERIMENT NO. CORRESPONDS TO NO. OF POLYHEDRON VERTICES
***FOR ACTUAL STATION LOCATIONS SEE TABLE 3

FIGURE 2 : DESIGN MEASURES - SINGLE TECHNIQUES



CONTINUOUS LINES : OPTIMAL POLYHEDRA

△ : MERIT - COTES NETWORK (EXP. NO. INDICATED)

(BASELINE ACCURACY ASSUMED : 10 CM)

TABLE 3 : MERIT-COTES GLOBAL NETWORKS
POLYHEDRA EXPERIMENT DIRECTORY

PROPOSED STATIONS 1983/84	STATUS(1981)	SINGLE EXPT. 7	10	11	12	13	14	COMBINED EXPERIMENTS 12	18A	B	C	D	20A	B	C	D	24A	B
OPERATIONAL																		
*FT. DAVIS	M3 G3 LL	V	V	V	V	L	L	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
*WETZELL	M3 G3 LL	V	V	V	V	L	L	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
MAUI	G3 LL					L	L	AL	AL	L	L	L	AL	L	L	L	AL	L
GREENBELT	G3					L	L	AL	AL	L	AL	L	AL	L	AL	L	AL	L
WESTFORD	M3	V	V	V	V			VT	VT	V	VT	VT	VT	V	VT	VT	VT	V
ONSALA	M3	V	V	V	V			VT	VT	V	VT	VT	VT	V	VT	VT	VT	V
OWENS VALLEY	M3	V	V	V	V			VT	VT	V	V	V	VT	V	V	V	VT	V
CRIMEA	LL																	
AREQUIPA	G2					L	L						AL	L	L	AL	AL	L
GRASSE	G2 LL					L	L						AL	L	L	L	AL	L
KOOTWIJK	G2																	
CONSTRUCTION																		
HERSTMONCEUX	G3					L	L	L	AL	L	L	L	AL	L	L	L	AL	L
GRAZ	M3 G3					L	L	L	AL	L	L	L	AL	L	L	L	AL	L
SIMOSATO	G3					L	L	L	AL	L	L	AL	AL	L	L	AL	AL	L
RICHMOND	M3	V	V	V	V			VT	VT	V	VT	V	VT	V	VT	VT	VT	V
UPGRADING																		
QUINCY	G3					L	L		AL	L	AL	L	AL	L	AL	L	AL	L
YARAGADEE	G3					L	L		AL	L	L	AL	AL	L	L	L	AL	L
JODRELL BANK	M3	V	V	V	V				VT	V	V	V	VT	V	V	V	VT	V
*CANBERRA	M3 G3 LL		V	V	V	L	L	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL	VL
MADRID	M3		V	V	V				VT	V	VT	VT	VT	V	VT	V	VT	V
GOLDSTONE	M3		V	V	V													
DIONYSOS	G3					L	L		AL	L	L	AL	AL	L	L	L	AL	L
TAHITI-MOBLAS6	G3																	
OTHERS																		
SAO PAULO				V	V				VT	V	V	VT	VT	V	V	VT	VT	V
SANTIAGO					V		T										AT	AT
FAIRBANKS																	VT	VT
SHANGHAI																	VT	VT
S. AFRICA																	AT	AT

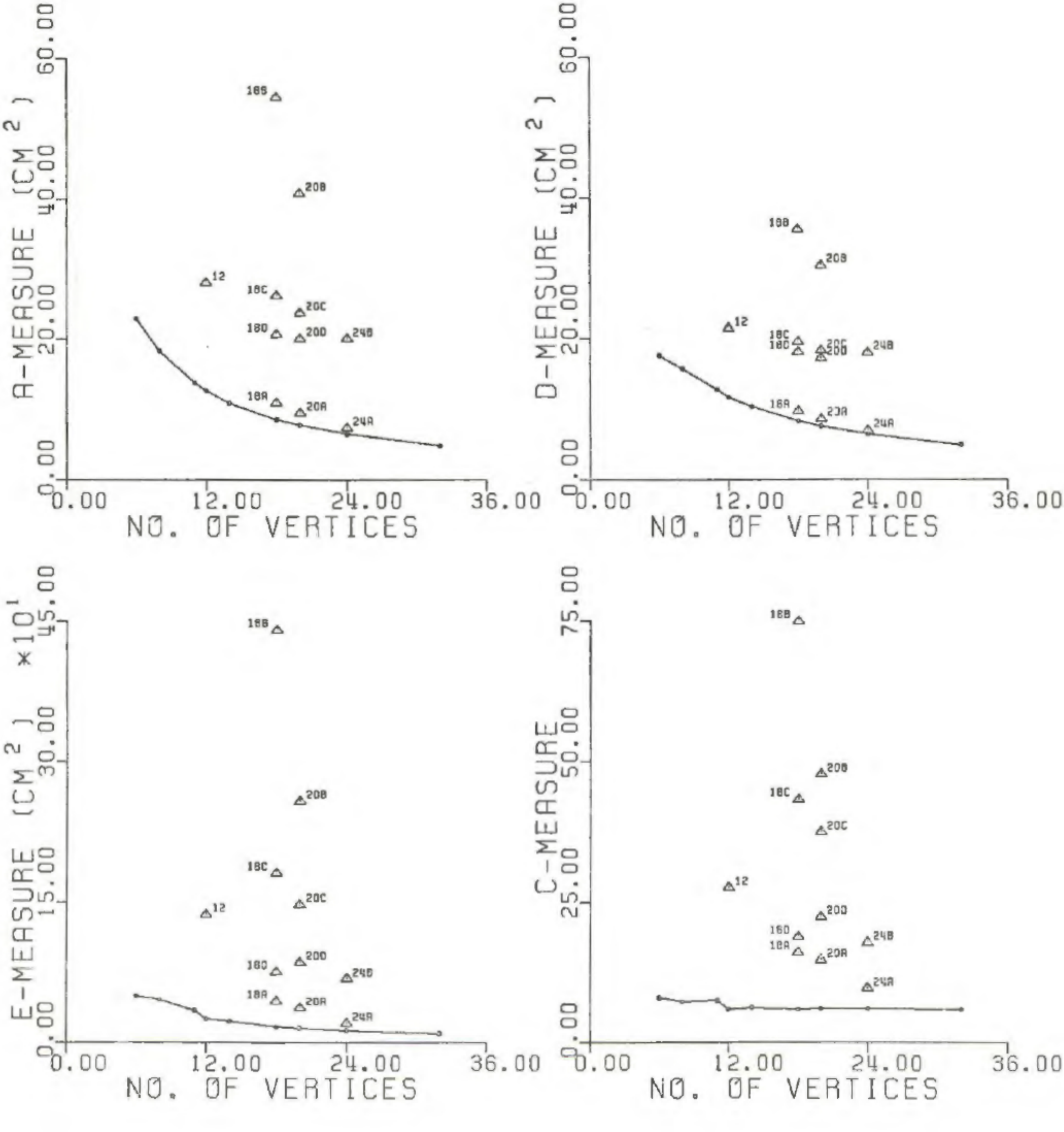
* PRIMARY COLLOCATION SITES

EXPERIMENT CODES :
V - VLBI
L - SLR, LLR OR BOTH
A - VLBI MOBILE (2)
T - LASER MOBILE (4)

STATUS CODES :
M3 - MARK III VLBI
G2 - 2ND GENERATION LASER
G3 - 3RD GENERATION LASER
LL - LUNAR LASER

8 JUNE 1982

FIGURE 3 : DESIGN MEASURES - COMBINED TECHNIQUES



CONTINUOUS LINES : OPTIMAL POLYHEDRA

△ : MERIT - COTES NETWORK (EXP. NO. INDICATED)

(BASELINE ACCURACY ASSUMED : 10 CM)

Furthermore, we again assume that the two U.S. mobile VLBI and four mobile SLR's (two U.S. and one each from FRG and the Netherlands) will be available for additional collocations or for occupying new sites. In Experiment 18A, for the purpose of comparison to the optimal, all sites are collocated. In 18B, only the primary sites are collocated. In 18C and D a comparison is made between constraining the mobiles to operate on their respective continental bases (U.S. and Europe) and allowing this deployment anywhere in the net. A similar analysis is performed in the Experiment 20 series, except that the top of the line second-generation lasers are also included at Arequipa and Grasse. In Experiments 24A and B, the possibility of adding new sites is investigated. In 24A all sites are collocated; in 24B there are only seven collocations since two of the mobiles have now been used to occupy other new sites.

The following can be inferred from the combined type of experiments. It is crucial to increase the number of collocations above the minimum three primary collocation sites. Using mobile VLBI and laser equipment is somewhat beneficial when the mobiles are deployed in their respective continental bases (see Exp. 18 and 20C). However, a much more significant improvement in the strength of the network would results from a more global distribution of these mobiles (compare 18C and D, 20 C and D). The addition of new sites into the planned network in South America, South Africa, and Alaska (in this order) would improve the strength of the network and would reduce the number of collocations necessary to achieve similar accuracy without the new sites (see Exp. 24). However, the optimal use of the planned network can also yield comparable results (compare Exp. 18D and 24B). In any case, it would be very beneficial to have several collocated sites in Australia and South America.

Based on preliminary discussions with MERIT participants, it seems that Experiment 20C represents the most realistic network available for the MERIT campaign in 1983-84 and should yield reasonable results. However, this configuration is not perfect for defining the frame of the future CTS for several reasons. First, the number of collocations are not sufficient and not optimally distributed throughout the net (compare 20A and C to D). Second, the stations do not adequately cover the tectonic plates. Considering that there are at least six major plates (N. American, S. American, African, Pacific, Eurasian and Indian-Australian) and that each one should be covered by at least three stations, it should be possible to plan a more optimal future CTS frame with about the same number of stations (18-24). (Note that Experiment 20C in Table 3 is identical to the recommended Experiment B7 in Table 1, except for Arequipa, Grasse and Sao Paulo. These stations, however, would not contribute anyway to the CTS-CIS connection problem).

4. SUMMARY OF OBSERVATIONAL REQUIREMENTS TO MEET THE COTES OBJECTIVES

1. Short Periodic Earth Rotation Parameters (ERP)

To detect short periodic ERP's, an intensive campaign of observations is needed over one to three months. As a guide, these observations should be for 12 hours daily, or for 24 hours every other day.

2. CTS/CIS Differences

(a) To determine CTS differences (β_1, β_2, β_3 angles), an appropriate number of collocated stations are needed (see Exp. B7 in Table 1 or Exp. 20C in Table 3). Mobile stations should be on these sites for a few weeks to get station coordinates or baseline components with adequate accuracy. (β_1, β_2 can also be estimated from the bias of polar motion from two techniques in which case there is no requirement for collocation.)

(b) To connect the first axes of CIS's, the angles α_3 can be obtained as a by-product of the MERIT Main Campaign, but β_3 must be known. There is no other special requirement.

(c) To detect the tilt of the CIS equators (α_1, α_2 angles), about ten 12-hour resolution simultaneous polar motion data from the various techniques are required. The 12-hour observation time spans should be synchronized within 30 minutes. β_1 and β_2 should also be known (see eq. (2.7)). An alternative to this method is participation in the intensive observational campaign (see #1 above). As a by-product, α_1, α_2 could be estimated from the differences of the diurnal polar motion components as determined by the various techniques (see eq. (2.9)). In this case, knowledge of β_1, β_2 and simultaneous observations are not necessary.

The two campaigns (1 and 2c) can be observed during the same time period (to be specified) with as many SLR's observing the same satellite passes as possible.

3. Collocated Sites

(a) The number of collocated sites within the network should be increased above the three primary collocations which have been proposed previously (Ft. Davis, Wettzell, Canberra).

(b) Using mobile VLBI and laser equipment is somewhat beneficial when the mobiles are deployed in their respective continental bases (e.g., Exp. 20C in Table 3); however, a much more significant improvement in the strength of the network would result from a more global distribution of these mobiles (compare combined Exp. 18B with C, 20C with D).

(c) The strength of the VLBI net (as well as the combined VLBI and laser net) is greatly improved with the addition of the DSN stations (Canberra, Goldstone, Madrid). (Compare single Exp. 7 and 10.) Especially Canberra, being a primary collocation site, and Madrid should be upgraded with Mark III equipment.

4. Station Upgrading and Construction Completion

Upgrading of other stations (especially Yaragadee and Quincy) to the levels indicated in Tables 1 or 3 as well as the completion of construction work at the indicated stations (Herstmonceaux, Graz, Simosato, Richmond) and the NASA, Dutch and German TLRS's by 1983 crucial (compare combined Exp. 12, 18 and 20).

5. Additional Useful Sites

For both VLBI and laser baseline networks, the greatest improvement should result from additional stations in South America (next is South Africa). This suggests the addition of, e.g., Sao Paulo to the VLBI net and a station in the southern portion of South America (e.g., Santiago) to the laser net. (Compare single Exp. 10 and 11-12; 13 and 14.)

6. Radio Satellite Tracking Participation

In order to determine the relations between the reference systems of SLR, LLR, VLBI and the Doppler satellite techniques, Doppler receivers should be collocated on the sites where the above systems will be operated. Those Doppler stations should observe simultaneously for a period of at least one month, and their positions determined with respect to the best available precise ephemeris.

A collocation campaign using the available GPS geodetic receivers is also suggested.

7. Importance of Monumentation

It is extremely important to the realization of the proposed experiments that the participating stations be unambiguously described and permanently monumented. This is particularly critical when mobile systems are to be used for collocations and there is danger that the exact position may not be recoverable after the mobile system has departed. COTES urges that MERIT establish appropriate standards concerning the geodetic surveying, data reduction, and adjustment procedures to be followed to insure that the necessary documentation is compiled and preserved. Briefly, it is urged that a "master" station mark (with suitably placed reference marks) be placed at each complex, and that the offsets of the individual measurement systems with respect to the master station mark be determined by three-dimensional geodetic surveys. The observations should be reduced and adjusted, using proven programs. The raw geodetic survey data should be considered as part of the MERIT data set and should be available to the general community for analysis and study.

5. SUMMARY OF REQUIREMENTS BY COUNTRY

All systems below should observe as per #1 and #2 in the previous section.

Australia - Canberra SLR should be upgraded to G3 and participate with LLR.

Austria - SLR construction and testing should be finished in Graz.

France - Grasse should participate with LLR and possibly G2 (G3 preferred) SLR (in South America?). MEDOC participation (see #6 in Section 4).

Federal Republic of Germany - The construction at Wettzell is to be finished. The Mark III VLBI and G3 SLR and LLR should be in full operation. The German TLRS is imperative and should be deployed as per Exp. B7 (at Madrid) in Table 1.

Greece - Dionysos should be upgraded to a G3 SLR.

Japan - SLR construction and testing should be finished at Simosato.

Netherlands - Kootwijk possibly should participate with G2 SLR (G3 preferred). The Dutch TLRS is imperative and should be deployed as per Exp. B7 (at Onsala) in Table 1.

Sweden - Onsala should be upgraded to a Mark III VLBI.

USSR - The Crimean LLR should participate.

United Kingdom - SLR construction and testing should be finished at Herstmonceaux. Jodrell Bank should be upgraded to a Mark III VLBI.

United States - (a) The Polaris network--all three stations (Westford, Ft. Davis, Richmond)--should be completed.

(b) DSN VLBIs (Madrid, Goldstone, Canberra) should be upgraded to Mark III (at least at Canberra and Madrid).

(c) Continue to operate SLR at Greenbelt and Mark III VLBI at Owens Valley.

(d) SLR's at Quincy, Yaragadee, Moblas 6 (if it is to go to the Southern Hemisphere) should be upgraded to G3. Arequipa would also be useful as a G3.

(e) TLRS's and ARIES's should be deployed at locations specified in Exp. B7 in Table 1 (TLRS's at Westford and Richmond, ARIES's at Greenbelt and Quincy).

(f) Participation by McDonald and Maui LLR's is important.

(g) GPS geodetic receiver participation would be desired as per #6 in Section 4.

(h) Doppler participation (DMA network) as per #6 in Section 4 is desired.

Miscellaneous - Additional stations as per Exp. 24 are desired, e.g., in South America, South Africa, China, Alaska (~ three per major tectonic plate).

REFERENCES

Blaha, G. (1971) "Inner Adjustment Constraints with Emphasis on Range Observations," Dep. of Geodetic Science Rep. 148, Ohio State Univ., Columbus.

Bock, Y. (in preparation) PhD dissertation.

Fejes Toth, L. (1964) Regular Figures, Macmillan, New York.

Grafarend, E.W. (1974) "Optimization of Geodetic Networks," Boll. di Geod. e Sci Aff., XXXIII, 4.

Kovalevsky, J. (1980) "Modern Approaches to Research in Dynamical Astronomy," Astronomische Gessellschaft Mitteilungen 48, Hamburg.

Kovalevsky, J. and I.I. Mueller (1981) "Comments on Conventional Terrestrial and Quasi-Inertial Reference Systems," Reference Coordinate Systems for Earth Dynamics, E.M. Gaposchkin and B. Kołaczek, eds., D. Reidel.

Moritz, H. (1980) "Theories of Nutation and Polar Motion I," Dep. of Geodetic Science and Surveying Rep. 309, Ohio State Univ., Columbus.

Mueller, I.I. (1969) Spherical and Practical Astronomy As Applied to Geodesy, Ungar Publ., New York.

Mueller, I.I. (1981) "Reference Coordinate Systems for Earth Dynamics: A Preview," Reference Coordinate Systems for Earth Dynamics, E.M. Gaposchkin and B. Kołaczek, eds., D. Reidel.

Pearce, P. and S. Pearce (1978) Polyhedra Primer, Van Nostrand Reinhold, New York.

Rao, C.R. and S.K. Mitra (1971) Generalized Inverse of Matrices and Its Applications, John Wiley & Sons, New York.

Van Der Waerden, B.L. (1952) "Punkte auf der Kugel, Drei Zusatze," Math. Ann., 125, pp. 213-222.

Wilkins, G.A. and M. Feissel, eds. (1982) "Project MERIT: Report on the Short Campaign and Grasse Workshop with Observations and Results on Earth-Rotation During 1980 August-October," Royal Greenwich Observatory, Herstmonceaux.

Williams, J.G. (1981) "Lunar and Planetary Ephemerides: Accuracy, Inertial Frames, and Zero Points," Proc. of Fourth International Workshop on Laser Ranging Instrumentation, Austin, Texas, Oct. 12-14. Publ. by IFAG, Frankfurt.