OPERATION OF THE 10-m OPTICAL TELESCOPE AND
AUXILIARY INSTRUMENTS FROM A
REMOTE SITE

(First Draft)

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December, 1980

This report is concerned with operation of the 10-m optical telescope, proposed by the University of California system, on Mauna Kea. —MAG

I. INTRODUCTION

Remote control of telescopes and instruments is a fact at large observatories. This is due in large part to the successful example provided by the pioneering work at Lick Observatory (Robinson and Walpler, 1972 a,b; Miller, Robinson, and Wampler, 1975). Communication technology makes it possible to extend the link between the telescope and control room from tens of feet to tens or thousands of miles. Early in the project Joe Wampler suggested that we might want to operate the telescope from the mainland through a satellite link. This report develops that idea and estimates the costs for alternative ways to achieve remote control.

Because of the difficulty of working effectively and efficiently at the high altitude summit of Mauna Kea, we propose a remote control center which will operate in parallel with the control room on the summit. The latter will be used for telescope maintenance, telescope safety surveillance, and to support those astronomers who either must be or want to be at the observatory during their observations. The remote control center will be used by the majority of astronomers who use observatory-supported instruments.

In Section II we consider the rationale for remote operation. The required bandpass for the communication link is derived in Section III. Three alternatives

25 METER MILLIMETER WAVE TELESCOPE
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for remote operation are described and costed in Section IV. The three alternatives are compared and discussed in Section V, and recommendations are made. Section VI lists the names, company affiliations, and phone numbers of knowledgeable people in communications.

II. RATIONALE FOR REMOTE OPERATION

A. Scientific Effectiveness and Efficiency

The hostility of the summit of Mauna Kea is masked by its stark beauty and the romantic notion of Hawaii. The elevation is 13,800', the seasonal average nighttime mean temperature is -1°C, and the median wind velocity is 10 mph (Morrison, et. al. 1973). In short, the air at the top of the mountain is cold, often moving, and very thin. People at the summit commonly experience severe headaches, altitude sickness, and a noticeable loss of ability to solve problems and make critical decisions. A repertory of amusing anecdotes has grown out of the Mauna Kea experience. These are typified by stories such as "I precessed the coordinates wrong, but it didn't matter because halfway through the plate development I realized that the darkroom lights were still on!".

The physiological effects of working at high altitudes are discussed throughly in Cudaback's report (Appendix). His report presents a sobering documentation of the physiological changes, loss of judgement, and the appreciable threat to life caused by hypoxia. Apart from people with known heart conditions, who would be ill advised to risk the physiological stresses of the summit, people in good physical condition are also at risk. Surprisingly, the risk is higher for healthy young astronomers than healthy old astronomers. Although there is no easy way to translate the measurable physiological changes into a measure of "lost science", common experience of astronomers (and construction crews at the summit) suggests that the loss will be at least as large as 20% to 30%. Unless remedial steps are taken, the world's largest telescope will operate at no more than 75% of its complete capability.

The adverse effects of hypoxia can be partially alleviated by requiring that everyone on the mountain wear oxygen masks and/or by oxygenating highly frequented rooms in the telescope building. These remedies should be implemented to accomodate the maintenance staff and those astronomers with unique instrumentation which requires their presence on the mountain. The remaining majority of astronomers and technical staff can work at high levels of efficiency by interacting with the telescope, instrumentation, and on site personnel via a high bandpass communication link to lower elevation or to the mainland.

B. Maintenance of the Observatory and Auxiliary Instruments

In accordance with present policy at Mauna Kea, we are not making any provision for a resident staff on the summit or at the Hale Pahaku midlevel facility. Although there will be facilities for on-site repairs and mirror maintenance, most major repair work, fabrication, and overhauls will be done at a sea-level facility in the islands or on the mainland.

Auxiliary instruments will be built primarily at Lick Observatory and secondarily at other UC campuses. Consequently the majority of the astronomers and engineers who are responsible for scientific instrumentation will be on the mainland.

Rather than send astronomers and engineers to the summit for trouble shooting and repair work, we propose to send the signature of the trouble to the appropriate personnel. The communication links which are described in Section IV will enable off-site personnel to exercise offending equipment with diagnostic routines and immediately see the results. Alternatively, a television picture of a mechanical assembly or of a critical operation can be inspected or monitored by off-site engineers. This high data rate trouble shooting is a natural extension of the routine telephone trouble shooting/consultation transactions between remote headquarters and observatories.

The proposed data link will minimize the down time of the telescope and instruments. On-site personnel can be *immediately* augmented and back stopped by clear headed headquarters staff. Equipment that requires more than a minor repair will be replaced from the mountain inventory of spares and sent off the mountain for repair. If a spare is not available on the mountain, a replacement can be immediately dispatched from the island headquarters or from the mainland headquarters.

III. REQUIRED BANDPASS FOR THE COMMUNICATION LINK

The bandpass of the communication link between the telescope and a distant headquarters will be determined by a compromise between cost and our requirements. The latter can be estimated by considering the data rates which are necessary to accomodate the following functions:

A. Monitoring Dome Operations and Trouble Shooting

It is highly desirable to transmit data and television pictures from the telescope to the island and mainland headquarters. These will permit staff astronomers and engineers to immediately inspect faulty equipment, view oscilloscope outputs, run diagnostics, and suggest tests (toggle switch #3, shake the signal cable, etc.). The live pictures will also permit monitoring of critical operations such as removing or replacing a segment.

The data link must have a 5 Mhz bandpass to transmit commercial quality television pictures.* Although commercial quality pictures are not necessary, the cost of a microwave link between the summit and the island headquarters is relatively independent of the bandpass. A 10 Mhz bandpass will allow transmission of the television pictures with standard analog techniques in a 5 Mhz bandpass and leave at least 2.5 Mbs for transmission of digital data with a standard microwave multiplexer.

At the present time, the cost to transmit 5 Mhz pictures to the mainland is prohibitively expensive. Fortunately we do not need broadcast quality pictures. Frame rates of a few per second and 4-bits of intensity representation (16 levels) are sufficient for our needs. Table 1 tabulates the frame rates for

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*A commercial digital television technology is emerging wherein only the difference between successive frames is transmitted. With this technique video rate pictures can be transmitted with a 1.54 Mbs bandpass.

128 x 128 and 256 x 256 4-bit pictures transmitted at the commercially available rates of 500 Kbs and 1.54 Mbs.

TABLE 1

Frame Rate Versus Bandpass

Picture Size	Bandpass 500 Kbs (s^{-1})	Bandpass 1.54 Mbs (s^{-1})
128 x 128	7.6	23.5
256 x 256	1.9	5.9

With the possible exception of the stroboscopic 2 frames/sec, all of the rates would meet our requirements.

We conclude that we should aim for a 10 Mhz bandpass in a microwave link and no less than 500 Kbs in a link to the mainland.

B. Transmission of Science Data

Charge Coupled Devices (CCDs) are likely to be the most commonly used detector in the future. This is because CCDs have very high quantum efficiency ($q_{max} \sim 0.7$), linear response over a large dynamic range, low noise performance, high resolution ($\sim 15\ \mu$), and geometrical stability. At the present time, Lick Observatory has a CCD with a 512 x 512 pixel format. CCDs with formats of 800 x 800 are being developed for the Wide Field/Planetary Camera on the Space Telescope and for the Galileo mission to Jupiter. It is likely that the CCDs with a 1000 x 1000 format will be available when the telescope becomes operational. These will be ganged together for photography and spectroscopy. For purposes of estimating the science data rate we will assume that four 1000 x 1000 CCDs are read out every 15 minutes. If a 16-bit analog to digital converter is used there will be 64 M bits of data per picture and an average data rate of 70 Kbs. The number of bits per night will be approximately 2.6 G.

The enormity of the amount of data can be appreciated by supposing that the data is written onto a high density magnetic tape or disk. If the data is written onto tape at 6400 bpi, 6.3 *miles* of tape will be needed (14 reels of tape). If the data is written onto 30 Mb disks, 85 will be needed. Clearly we must assume that the technology which will bring us 1000 x 1000 CCDs will also bring us ultra high density data storage techniques.*

The only modest number in these considerations is the average data rate of 70 Kbs. Comparison of this rate with available communication bandpasses shows the obvious solution for the problem of moving the data to the mainland. We should plan to send all the data back via our data link. The relatively low average data rate also shows that present computers can handle the reduction

*Note that archiving the data is not a problem. The 16-bits of data in each 15 μ pixel could be exposed onto a fine grain photographic emulsion as an array of 15 μ x 15 μ black or white "bits". The size of the plate with this unsophisticated scheme is then 4 times the size of the composite CCD array. The 10" x 10" plates could be exposed by imaging a high resolution CRT onto the plate. The plates could be read by imaging (and stepping) the plates across a CCD.

and analysis of the data. The primary technical problem will be one of fast access to a high density storage device.

A summary of the arguments for sending all data to the astronomers in real time are:

1. Logistics

Manpower is saved by letting each astronomer be responsible for his/her data. There are no special requirements or handling procedures for getting the data to the astronomers.

2. Real Time Assessment

A cornerstone of Lick Observatory's success in the past decade has been the real time display and assessment of data from the Robinson/Wampler scanner. The same will be true in the future. The data must go to the astronomer for real time evaluation.

The three readily available data rates which are considered in this report are listed in Table 2 along with the corresponding times which are required to transmit a composite 64 Mb picture.

TABLE 2

Time Required To Transmit A Composite CCD Picture

Data Rate (Kbs)	Time (min)
56	19
500	2
1540	0.7

The 56 Kbs rate cannot keep up with the average data rate of 70 Kbs. Even if the average data rate is decreased by increasing the exposure time, real time

assessment of the data will be hamstrung and there will be no catch-up capacity within the system.

The 500 Kbs data rate provides adequate catch-up capacity and real time capability. We conclude that the bandpass for transmitting science data should be no less than 500 Kbs.

IV. REMOTE OPERATIONS

This section discusses three options for remote operation of the telescope. A description, cost estimate, and list of principal advantages and disadvantages are given for each option. Section V summarizes the three approaches, estimates the time and money saved from reduced travel, and makes a recommendation.

The cost estimates in this report must be qualified by two considerations. First, the communication systems are relatively complicated. Precise cost estimates cannot be made without a detailed specification of our requirements and a close look at the site-specific costs. It is hoped that the cost estimates are as good as $\pm$ 25%; however, the fact that different people within the same company have given me costs which differ by a factor of two suggests that some cost uncertainties are rather large. Throughout the report I have used the most expensive estimates. Eventually we must spend money to obtain accurate costs (or at a later stage go out for bids).

A second qualification is that communication costs are likely to decrease relative to airfares. Industry observers think that this will be particularly true for wide bandpass communication, which is our primary concern. Communication costs are likely to drop because of technological advances, increasing competition, and a larger market over which to amortize satellite costs. We anticipate that it will become increasing advantageous to move the bits instead of the astronomers and engineers.

A. Observing Stations at Each Campus

Several companies sell low data rate (9600 bps and 56 Kbs) lease-line service. By buying this service we can have an "observing station" at each campus. The first possible data path is a Hawaiian Telephone Company microwave link from Hawaii to Oahu, an ATT (or RCA) satellite or cable link to the mainland,

and ATT or Pacific Telephone lines to the four UC campuses. The 56 Kbs duplex network would provide voice communication, transmission of digital data, and a limited capacity to transmit pictures.

The maximum frame rate through the system would be approximately one 128 x 128 x 4-bit picture per second (by using digital differencing the frame rate might be as high as 3 per second). This rate is adequate for verifying correct pointing of the telescope, real time centering and peak up, and guiding, though efficiency dictates using a precision programable-offset autoguider. The frame rate is probably sufficient for trouble shooting and stroboscopic viewing of dome operations. Transmission of large CCD pictures through the system would not be very practical.

Based on numerous conversations with communication specialists (cf. Section VI), the recurring lease costs for 56 Kbs duplex service are estimated to be:

			Monthly Charges
1.	Mauna Kea - Hilo - Oahu microwave service provided by the Hawaiian Telephone Company (HTC)	Mauna Kea - Hilo	$7500
		Hilo - Oahu	$5500
2.	Trunk service to the mainland provided by ATT or RCA		~$6000
3.	Mainland distribution provided by ATT or Pacific Telephone		~$2000
	Total		~$21,000

The interisland link is very expensive because the present HTC microwave link would have to be upgraded to provide 56 Kbs service with a bit error rate (BER) of 10^{-7}. The cost would be half as much if another user would buy service on the link. The cost of the Hawaiian link would be much lower if we could accept the 10^{-5} BER of the present analog system. With appropriate encoding of the data we could make a 10^{-5} BER look like 10^{-7}. However, encoding will reduce the effective data rate by 10% to 20%.

In the following section we show that buying and installing a 10 Mhz microwave link between the mountain top and Waimea is relatively inexpensive ($2600/month). A 56 Kbs satellite link between Waimea and the mainland is $8,950/month plus an $11,000 nonrecurring cost for installation of the Earth stations (5-m antennae). The total monthly cost for this system, including the tail lines on the mainland, is $13,500

In addition to the recurring costs, there are capitalization costs for five identical observing stations (one at the island headquarters and one at each campus). Each station would require the equivalent of:

1 VAX computer with 512 K of memory		
1 Dual 56 M byte disk drive		
1 9-track tape drive		
	Total	$290,000
1 High speed printer plotter		5,000
1 High resolution graphics television terminal		10,000
1 56 Kbs modem		10,000 (?)
Custom electronics		50,000 (?)
	Total	365,000
Recurring maintenance cost (7% x $315,000)		1,838/month

These capitalization costs will probably be incurred in any case. The various campuses must have data reduction facilities. It would be sensible to break with tradition and agree on common hardware. We could then easily exchange software and thus get maximum advantage from the programing efforts at the four compuses.

The 10 year amortized capitalization and maintenance cost for the five systems is 24,400 \$/month.

Advantages

- The overriding advantage of the distributed stations is convenience. Only astronomers with special requirements need travel to the islands. In as much as time is the most valuable resource within the University this is an important consideration.

Disadvantages

- The capability of the system is limited by the 56 Kbs bandpass. The data rate is too low to allow all of the data to be transmitted through the system, and is too low for effective real time assessment of large CCD pictures.

- The system is too small at the outset and provides no room for growth or cost sharing with other users.

- The system is not cost effective. It moves the least bits for the most dollars.

B. Remote Observing from the Waimea Headquarters

Several institutions with observatories at Mauna Kea are locating their island headquarters at Waimea. Assuming that we do the same, it will be relatively easy to connect the telescope and Waimea (18.3 miles line-of-sight) with a 10 Mhz duplex microwave link. The bandpass is wide enough to transmit a 5 Mhz analog, broadcast quality television picture and 2.5 Mbs of digital data with standard equipment. The bandpass is large enough to allow growth in the data rate and/or sharing the system with other users. With forethought in designing a universal data bus within the ten meter telescope building, it should be possible to link *all* data and *all* control functions to the Waimea headquarters.

The estimated cost of the microwave link is a function of cost trades between large antennae and powerful transmitters on the one hand and intermediate relay stations on the other. To avoid problems of wind and ice loads on a large antenna on the summit, we probably will want to use a relay station.

The cost breakdown per station is:

1.	Transmitter/receiver pair	$22,000
2.	Tower and antenna	$10,000
3.	Traveling Wave Tube	$ 5,000
4.	Multiplexer	$ 3,000
5.	20% Conservative Hedge	$10,000
	Total Cost Per Station	$50,000

With the exception of the tower all components in the relay station are double; thus, the relay station costs approximately $100,000 (this makes allowance for a generator at the relay station).

A site survey is necessary for licensing and to estimate power leakage, interference losses through clouds, antenna locations, etc. Site surveys usually cost ~$10,000; making allowance for travel to Hawaii, the survey might cost as much as $12,000.

The total cost sums to $212 K. My consultant thinks we could most certainly build the system for $250 K.

To estimate the monthly cost we will assume that the system has a 10-year lifetime. We further assume that maintanance requires replacing 1/4 of the system in 10 years. The amortized operating cost is then $2600/month.

The control room at Waimea will require approximately 650 square feet. Construction of a concrete block building in Hawaii is roughly $50/square foot. Amortizing the $32.5 K cost over an anticipated life of 50 years gives a negligible cost per month ($54). The 10-year amortized capital cost for the VAX computer and associated peripherals is $4880/month.

The total estimated cost for the remote control center in Waimea is $7534/month.

Advantages

- The system has a large enough bandpass to meet our needs and allow for growth or sharing (which would reduce the cost).

- The telescope will be operated at maximum scientific effeciency by astronomers at sea-level.

- The system is a cost effective way to move data off the mountain. For comparison, Hawaiian Telephone Company estimates that they will charge $7,500/month for a 56 Kbs microwave link from the summit to Hilo.

Disadvantages

- The most important disadvantage of this scheme is that astronomers still must travel to Hawaii to use the telescope. The round trip airfares of 12 people (9 astronomers and 3 engineers) and the value of 18 working days must be added to the monthly cost.

- High bandpass trouble shooting cannot be done from the mainland.

C. Remote Observing from the Mainland Headquarters

Synchronous satellites have revolutionized communications. The large bandpass relay stations in synchronous orbits make it possible to place control of the telescope and auxiliary instruments in our mainland headquarters. The bandpasses (500 Kbs to 10 Mbs) are large enough to send near video rate television pictures and large CCD pictures. Our operational capabilities would not be bandpass limited.

The cost of a satellite link depends on the bandpass, the decision to lease or buy the Earth stations (antennae plus transmitter/receivers), and the location of the island Earth station. Both Ford Aerospace and Communication Corporation and American Satellite estimate that we will need 10-m antennae to achieve a data rate of 1.54 Mbs with a BER of 10^{-7}. Ford Aerospace estimates that the cost per station will be between $250 K and $500 K, whereas American Satellite estimates the cost at $200 K per station, excluding antennae enclosures. If the data rate is 500 Kbs, American Satellite estimates that we will need 7-m antennae.

There are at least two problems in locating a large antenna on the summit of Mauna Kea. Because of wind and ice loading, the antenna must be in a radome enclosure, which increases the cost of the system by TBD$. A second problem is the environmental and aesthetical impact of a large Earth station. In recognition of the Hawaiians' desire to restrict growth on the mountain to the scientifically essential, we should locate the Earth station off the mountain.

By locating the Earth station at our Waimea headquarters we save the cost of a radome. This more than pays for the cost of the microwave link to Waimea. This plan gives us control of the telescope from both the Waimea headquarters and the mainland headquarters. The engineers and astronomers resident at Waimea are directly in the communication loop. This scheme also permits a stepwise installation of the communication link. We first bring up the microwave link and then establish the satellite link to the mainland.

The estimated satellite tariffs and nonrecurring charges for installing the Earth stations are given in Table 3. American satellite is very reluctant to consider leasing anything other than end-to-end service; that is, they are not interested in leasing the satellite transducers for use by our Earth stations.

TABLE 3

Cost Estimates for a Satellite Link to Hawaii

Bandpass (Kbs)	Monthly Tariff	Earth Station Installation Charge
56	$ 8,950	$11,000
500	$15,000	$20,000
1540	$35,000	$30,000

To arrive at a total cost for the satellite system I assume that we will lease a 500 Kbs channel. The cost of the microwave link, the Waimea control room, and the mainland control room are included in the total cost estimate. Table 4 summarizes the entire costs for the satellite link.

TABLE 4

Total Costs for a High Bandpass Link from the Summit to the Mainland Control Center

10 Mbs Microwave Link	$ 2,600
Waimea Control Room	4,934
500 Kbs Satellite Link	20,000
Mainland Control Room	4,923
Total	32,457

Note that the total cost can be reduced by as much as 40% if we share the system with another user.

Advantages

- The system capacity is large enough for mainland control of the telescopes and instruments. Most astronomers and many engineers do not have to fly to Hawaii to use the telescope or trouble shoot instruments.
- The system capacity is large enough for growth and/or sharing with other institutions.
- The system allows us to send our large volumes of data (up to 2 G bits/day) to the mainland control/(data reduction?) center electronically.
- The system is cost effective when compared to the 56 Kbs system to all campuses.

Disadvantages

- There is a minor disadvantage in that astronomers from Southern California must fly to the mainland headquarters (which is presumably on the Santa Cruz campus).

V. COST COMPARISONS AND RECOMMENDATIONS

A. Cost Comparisons

The estimated total monthly cost for each option is given in Table 5. The fourth column in the Table gives an estimate of the travel and lost workday costs which are saved with each option. I assume that 8 UC nighttime optical/infrared astronomers and 6 UC daytime infrared/millimeter astronomers use 80% of the time each month (10% of the time for the University of Hawaii and 10% for visitors). I assume that on the average, 6 of the nighttime astronomers and 3 of the daytime astronomers will choose to observe from the mainland headquarters or the campus observing stations. I further assume that 3 astronomer/engineer trouble shooting trips will be saved each month. The present round trip airfare to Hawaii plus rental car and lodging is ~$700. There is an additional savings of lost workdays. Each trip entails at least 1.5 days lost in travel and jet lag. I reckon each workday at $185. The total savings are approximately $10,000 per month for those astronomers and engineers that do not travel to Hawaii.

The cost for astronomers to travel from Southern California to the mainland headquarters at Santa Cruz is $120 airfare, $70 for a rental car, $100 for room and board, and $185 for the lost workday. Assuming that half of the 9 astronomers who choose to observe from the mainland are from UCLA or UCSD, an additional $2000 a month is saved if we have stations at each campus.

Table 5 compares the cost of all astronomers going to the summit with the three options discussed in the previous section.

TABLE 5

Cost and Efficiency Comparisons

Option	Bandpass	Cost Components	Total (dollars/mon)	Scientific Efficiency	#Bits/dollar
Observe at the summit	--	17 astronomer/engineer trips to Hawaii	$15045	≤ 75%	$1.3 \cdot 10^5$ *
Observe at each campus	56 Kbs	5 trips to Hawaii	4425		
		56 Kbs data link	13500		
		5 observing stations	24400		
		Total	$42325	≤ 85% +	$6.1 \cdot 10^4$
Observe at Waimea	10 Mbs	17 astronomer/engineer trips to Hawaii	15045		
		microwave link	2600		
		control room	4880		
		Total	$22525	100%	$1.1 \cdot 10^5$
Observe at UCSC	500 Kbs	5 trips to Hawaii	4425		
		4.5 trips to UCSC	2137		
		microwave-satellite link	32457		
		Total	$39019	100%	$6.7 \cdot 10^4$

*The 2.6 G bits/day were reduced to 2 G bits/day to allow for the presumed 75% operation efficiency.

+Less than 100% effeciency is assumed because of the inefficiency of transmitting large pictures.

B. Discussion and Recommendations

There are several "figures of merit" that can be used to choose between the alternatives in Table 5. The narrowest view would use the cost given in column 4; that is, the costs that can be charged directly to the process of observing. A somewhat better figure of merit is the number of bits/dollar. Either of these measures presently favor options 1 and 3 (traveling to Hawaii). However, it should be borne in mind that the present doubling time for airfares is less than three years. Furthermore the data link cost may decrease, and can certainly be lowered by as much as 40% if we can work out a time sharing agreement with one or more of the other groups on the mountain. The present margin in favor of observing in Hawaii, which does not reflect the value of our time at other than our salary rate, is, in my opinion, likely to vanish.

The best figure of merit is the amount of science which pushes the telescope-insturment-observer capability to the limit. If the science is divided by the *total* operating cost of the telescope (~$100,000/mon?), the balance shifts to options 3 and 4.

Based on these considerations, my recommendations are:

1. Install a microwave link between the telescope and Waimea. This covers all bets.
2. Lease a satellite link from Waimea to the UCSC mainland headquarters.
3. Make a vigorous effort to lower the cost by reaching a time sharing agreement with other groups.

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